CHAPTER NINETEEN

Industrial Noise and Conservation of Hearing

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1 INTRODUCTION

Exposure to industrial noise and the resulting effect of occupational hearing loss is a common problem across nearly all industries. High noise levels also cause interference with verbal communication and warning signals. which can have a significant impact on safety and work performance. Finally, noise can be considered as a source of stress for workers, producing unwanted physiological and psychological effects that can lead to a degraded quality of life.

Typically, noise-induced hearing loss develops slowly, and usually goes unnoticed until a significant impairment has occurred. Fortunately, occupational hearing loss is nearly always preventable. Prevention of noise-induced hearing loss benefits the employer as well as the individual employees. An effective hearing conservation program promotes good labor-management relations, which can lead to increased morale and productivity. Employers enjoy the benefits of reduced medical expenses and worker compensation payments, and employees can expect to maintain their hearing health well into their retirement years.

1.1 Terminology

This section defines terms that are useful in discussions related to the study of noise.

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Absorption Coefficient (α): The ratio of the acoustical energy absorbed by a surface to the acoustical energy incident upon that surface. The result will be a value between 0.0 and 1.0, which also can be considered as a percentage between 0% and 100%.

Acoustic Intensity: See Sound Intensity.

Acoustic Power: See Sound Power.

Acoustic Pressure: See Sound Pressure.

Ambient Noise: The overall composite of sounds in an environment.

Amplitude: An objective measure of the quantity or amount of sound generated by a source, generally described by the sound power or sound pressure measured at a specific location.

Anechoic Room: A specially-designed test room with very absorptive interior surfaces that do not reflect sound energy, and therefore prevent sound build-up or "echoes" (i.e., nearly 100% of the sound is absorbed). Any sound generated within an anechoic room is referred to as being in a free field (see definition).

Audiogram: A recording or graph of hearing levels referenced to a statistically normal sound pressure as a function of frequency.

Audiometer: An instrument for measuring hearing thresholds.

Continuous Noise: Noise with relatively small fluctuations in level within the measurement period.

Decibel (dB): A dimensionless unit that describes the logarithm of the ratio of two power-related quantities. It is normally defined as ten times the logarithm of the ratio of a measured quantity to a reference quantity. When measuring sound, different reference values have been arbitrarily established, depending on whether sound power, sound intensity, or sound pressure is to be measured.

Decibel, A-weighted (dBA): The sound level measured with the A-weighting network on a sound level meter.

Decibel, C-weighted (dBC): The sound level measured with the C-weighting network on a sound level meter.

Diffuse Sound Field: A sound field with sound pressure levels that are essentially the same throughout, with the directional incidence of energy flux randomly distributed.

Effective Sound Pressure: The sound pressure at a given location, derived by calculating the root mean square (rms) value of the instantaneous sound pressures measured over a period of time at that location.

Exchange Rate: The number of decibels that, when a sound level is increased by this amount, gives an equivalent noise exposure when the exposure duration is halved. Likewise, when a sound level is decreased by the number of decibels specified by the exchange rate, an equivalent exposure will result if the exposure time is doubled.

Free Field: A field that exists in a homogeneous isotropic medium, such as an open outdoor area without boundaries. In a free field, sound radiated from a source can be measured accurately without influence from unwanted reflections. True free-field conditions are rarely found, except in specially designed anechoic test chambers.

Frequency (f): The rate at which complete cycles of high- and low-pressure regions are produced by a sound source, measured in Hertz (Hz). In subjective terms, frequency is often referred to as "pitch," although there is not an exact correlation between the two terms.

Hertz (Hz): A unit of measurement for frequency, indicating the number of complete waves or cycles that occur in one second.

Impulse Noise: Noise that is characterized by a sharp rise and rapid decay in sound level, and is less than one second in duration.

Insertion Loss (IL): The difference in sound levels measured at a particular location before and after an acoustical treatment is installed. $\mathrm{IL} = L_{p0} - L_{p1}$, where L_{p0} is the sound level without the attenuating device, and L_{p1} is measured at the same location with the treatment in place.

Intensity: See Sound Intensity.

Level (L_x): The value of a quantity (x) when converted into decibels (e.g., sound pressure level (L_p), sound power level (L_W), sound intensity level (L_I), etc.). The letter L indicates that the value is being described in terms of a decibel level, and the subscript denotes the type of quantity under consideration.

Loudness: An observer's impression of a sound's amplitude. Although a high-intensity sound wave is perceived as being louder than a wave of lower intensity, an exact linear relationship does not exist, and the relation between loudness and intensity is not the same for all individuals.

Noise: The terms noise and sound are often used interchangeably; however, *sound* is normally used to describe useful communication or pleasant audible signals (e.g., music), whereas *noise* is frequently considered as dissonance or unwanted sound.

Noise Reduction (NR): The difference in sound levels measured on either side of a noise-reducing wall or partition. $\mathrm{NR} = L_{p1} - L_{p2}$, where L_{p1} is the sound pressure level in room 1, and L_{p2} is the sound pressure level in room 2.

Noise Reduction Coefficient (NRC): The arithmetic average of the sound absorption coefficients of a material at 250, 500, 1000, and 2000 Hz.

Noise Reduction Rating (NRR): An indication of a hearing protector's noise reduction capability (in dB).

Octave Band: A frequency bandwidth that has an upper band-edge frequency equal to twice its lower band-edge frequency.

Pascal (Pa): A unit of pressure equal to one newton per square meter.

Peak Sound Pressure Level: The maximum instantaneous level of sound that occurs over any specified period of time.

Period (T): The time (in seconds) required for one cycle of pressure change to take place (hence the period is the reciprocal of the frequency).

Pitch: The auditory sensation that depends primarily on frequency, but also on the pressure and waveform of the sound stimulus.

Power: See Sound Power.

Pure Tone: A sound wave consisting of only one single frequency.

Random Incidence Sound Field: See Diffuse Sound Field.

Random Noise: A noise made up of many frequency components whose instantaneous amplitudes occur randomly as a function of time.

Resonance: Enhancement in the response of a mechanical system to a periodic driving force when the driving frequency is equal to the natural undamped frequency of the system. A system is in resonance when any change in the frequency of forced oscillation causes a decrease in the response of the system.

Reverberation: The build-up of sound in a room due to reflections from the floor, walls, and ceiling. The reverberation time is the time required (after the source is shut off) for the sound level to decay 60 dB from its steady-state level.

Root-Mean-Square (rms) Sound Pressure: The root-mean-square value of a changing quantity, such as sound pressure, is the square root of the mean of the squares of the instantaneous values of the quantity. (See effective sound pressure).

Sound: A propagating disturbance through a physical medium. Sound is perceived by the ear as a pressure wave superimposed upon the ambient air pressure.

Sound Intensity: The average rate at which acoustic energy is transmitted through a unit area normal to the direction of propagation. The units used for sound intensity are watts per square meter (W/m^2). Sound intensity is also expressed in terms of a sound intensity level (L_I) in decibels, referenced to 10^{-12} W/m^2.

Sound Power: The total acoustic energy radiated per second by a source. Sound power is normally expressed in terms of a sound power level (L_W) in decibels. $L_W = 10 \log (W/W_{ref})$, where W is the sound power in question, and W_{ref} is the standard reference power of 10^{-12} Watts.

Sound Pressure: Oscillation of the sound wave above and below atmospheric pressure. Sound pressure level (L_p) is the rms sound pressure measured at a certain distance from a source with respect to the standard reference pressure of 20 μPa (20×10^{-6} Pa). $L_p = 20 \log (p/p_{ref})$, where p is the sound pressure in question, and p_{ref} is the standard reference pressure, which corresponds to the softest sound a normal-hearing person can detect. The symbol SPL can be used interchangeably with L_p to denote sound pressure level.

Spectrum: A distribution or range of frequencies. When performing frequency analysis, a sound may be divided into octave-band, third-octave band, or narrow-band spectrums.

Speed of Sound (c): The rate at which sound waves travel, depending on the density and elasticity of the medium. The speed of sound is usually considered to be constant under normal temperature conditions; for example, the velocity of sound is approximately 344 m/sec (1130 ft/sec) in air, 1433 m/sec (4700 ft/sec) in water, 3962 m/sec (13,000 ft/sec) in wood, and 5029 m/sec (16,500 ft/sec) in steel.

Time-Weighted Average (TWA): A single reading of noise level obtained by averaging all of the different sound levels that a worker is exposed to during the workday. The TWA represents that constant noise level in dBA that has the same severity over eight hours as the exposure to the actual workday noise.

Transmission Loss (TL): The amount of attenuation (in decibels) provided by a wall or panel, as measured in a laboratory. Transmission loss is defined as ten times the logarithm (to the base 10) of the ratio of the incident acoustic energy to the acoustic energy transmitted through a sound barrier.

Ultrasonic: Frequencies higher than those of audible sound (i.e., above 20,000 Hz).

Wavelength (λ): The length (in feet or meters) of one complete sound wave. Wavelength is calculated from known values of the frequency (f) and speed of sound (c) by: $\lambda = c/f$.

White Noise: A sound spectrum with essentially equal energy at each frequency within a specified frequency range.

2 PHYSICS OF SOUND

Sound results from oscillations in pressure in any "elastic" medium such as air, water, solids, etc., that effectively couples the sound source with the ear. When sound is transmitted through air, it is usually described in terms of variations in pressure that alternate above and below atmospheric pressure. These pressure changes are produced when vibrating objects (sound sources) cause regions of high and low pressure that propagate from the sound source. The characteristics of a particular sound depend on the rate at which the sound source vibrates, the amplitude of the vibration, and the properties of the conducting medium.

2.1 Units for Noise Measurements

2.1.1 Sound Pressure and Sound Pressure Level

The range of sound pressures encountered in many acoustical environments is usually very wide. Sound pressures as high as those produced by jet engines (about 20 Pa) are found in some work areas, whereas sound pressures down to the threshold of hearing (approximately 0.00002 Pa) are used for audiological testing. To cover this wide range of sound pressure with a reasonable number of scale divisions and to provide a scale that responds more closely to the response of the human ear, a logarithmic scale is used. This logarithmic notation was termed the Bel, in honor of Alexander Graham Bell; however, the Bel was found to be too large for practical use. Therefore, one Bel was subdivided into 10 smaller units, and the prefix "deci" was added to form *decibel* (abbreviated as dB).

Any time the word *level* is used in acoustics, decibel notation is implied. By definition, the decibel is a dimensionless unit, and is related to the logarithm of the ratio of a measured quantity to a reference quantity. The decibel can be difficult to understand and use because it is often associated with different reference quantities. Acoustic intensity, acoustic power, hearing thresholds, electric voltage, electric current, electric power, and sound pressure level may all be expressed in decibels, each having a different reference. Obviously, the decibel has no meaning unless a specific reference quantity is specified, or understood.

Most sound-measuring instruments are calibrated to provide a reading of root-mean-square (rms) sound pressures in decibels. The decibel reading taken from such an instrument is called the sound pressure level. Sound pressure level is denoted by the symbol L_p, where the capital letter L represents a decibel *level*, and the subscript p indicates sound pressure. The term level is used because the measured pressure is at a particular level above a given pressure reference. For sound measurements in air, 0.00002 Pa, or equivalently, 20 μPa, typically serves as the reference sound pressure (p_{ref}). This reference is an arbitrary pressure chosen many years ago as an approximation of the normal threshold of human hearing at 1000 Hz. Since the eardrum responds to the intensity of the sound wave, and since intensity is proportional to the pressure squared, sound pressure levels are calculated from the square of the sound pressures. Mathematically, L_p is written as follows:

$$L_p = 10 \log \left(\frac{p}{p_{ref}}\right)^2 \text{dB} \tag{1}$$

where p is the measured rms sound pressure, p_{ref} is the reference sound pressure, and the logarithm is to the base 10. Utilizing the properties of logarithms and exponents, this equation is commonly rewritten as:

$$L_p = 20 \log \left(\frac{p}{p_{ref}}\right) \text{dB} \tag{2}$$

Using this form of the equation for L_p sometimes causes confusion regarding the multiplication factor of 20 in front of the logarithm. This confusion can be eliminated by an understanding that the basic definition of the decibel is based on power-related quantities, and power is proportional to the square of the pressure (i.e., power $\propto$ pressure^2). Table 19.1 shows the relationship between sound pressure (in Pascals) and sound pressure level (in dB re 20 μPa). This table illustrates the advantage of using the decibel scale rather than the wide range of direct pressure measurements—i.e., the range of decibel values is more compact and manageable. Using decibel notation, a doubling of sound pressure is equivalent to a 6 dB change in level, and a tenfold increase in pressure raises the level by 20 dB.

2.1.2 Sound Power and Sound Power Level

Sound power was briefly mentioned in the previous section; it is defined as the amount of acoustic energy that is produced per second by a noise source. Sound power is measured in watts, and is represented by the symbol W. Power units are also frequently described in terms of decibel levels because of the wide range of powers covered in practical applications. Sound power level (L_W) is defined by:

Table 19.1. Relation between Sound Pressure and Sound Pressure Level

Sound Pressure (Pa)	Sound Pressure Level in dB re 20 μPa	Typical Environment	Average Subjective Evaluation
200	140	Near jet engine	
	130	Pneumatic chipper	Intolerable or deafening
20	120	Boiler shop; "hard rock" band	
	110	Automatic punch press; jack hammer; motorcycle	
2	100	Chainsaw; snowmobile; outboard motor	
			Very noisy
	90	Construction site; noisy urban area	
2×10^{-1}	80	Curbside of busy street; school cafeteria	
			Loud
	70	Loud radio; vacuum cleaner	
2×10^{-2}	60	Restaurant; department store	
			Moderate to quiet
	50	Conversational speech; average office	
2×10^{-3}	40	Residential area at night	
			Faint
	30	Average home	
2×10^{-4}	20	Background in TV studio	
	10	Rustle of leaves	Very faint
2×10^{-5}	0	**Normal threshold of hearing**	

$$L_W = 10 \log \frac{W}{W_{ref}} \text{ dB} \tag{3}$$

where W is the power of the source in watts (W) and W_{ref} is the standard reference power of 10^{-12} W. In air, this reference corresponds to the reference pressure of 20 μPa used for sound pressure levels.

For most hearing conservation purposes, familiarization with the concepts of sound pressure and sound pressure level is sufficient. However, it is important to understand that the measured sound pressure is actually a result of the amount of sound power generated by a source. In other words, there is a cause-and-effect relationship between sound power and sound pressure: Sound power is the "cause" of a noise, and sound pressure is the resulting "effect." Conversion from power to pressure (or vice versa) is routinely performed when developing engineering noise control treatments. Sound pressure levels can be predicted from known sound power levels, depending on the environment in which the sound source is located, the exact distance from the source, as well as other variables.

2.1.3 Sound Intensity and Sound Intensity Level

Sound intensity at any specified location may be defined as the average acoustic power passing through a unit area, in the direction of wave propagation. For a spherical or free-progressive sound wave, the intensity may be expressed by:

$$I = \frac{p^2}{\rho c} \frac{\text{W}}{\text{m}^2} \tag{4}$$

where p is the rms sound pressure, ρ (rho) is the density of the medium, and c is the speed of sound in the medium. Sound intensity, like sound power and sound pressure, covers a wide range of measurements, and it is often desirable to use decibel levels to compress the measuring scale. Sound intensity is converted into decibels through the use of the following equation:

$$L_I = 10 \log \frac{I}{I_{ref}} \text{ dB} \tag{5}$$

where I is the measured intensity at some given distance from the source and I_{ref} is the standard reference intensity of 10^{-12} W/m^2.

As mentioned previously, once the sound power level of a source is known, then the resulting sound pressure level can be predicted for any particular environment where that source may be placed. Unfortunately, there is no way to measure sound power directly. However, modern instruments have been developed to measure sound intensity, which is simply the amount of acoustic power radiated over a given surface area. Sound intensity instruments make it possible to determine the sound power of a source *in situ*, eliminating the need for special-purpose acoustical facilities such as anechoic rooms and reverberation chambers.

2.1.4 Combining Sound Levels

It is often necessary to combine sound levels—for example, individual frequency band levels may be combined to obtain the overall or total sound pressure level of a particular noise. Another example is the estimation of total sound pressure level resulting from adding a machine of known noise spectrum to a noise environment of known characteristics. However, because decibels are logarithmic quantities, they cannot be combined by simply summing up the individual sound pressure levels. Instead, the actual acoustic intensities represented by the logarithmic expressions must be determined by taking the antilogs of the level readings. Then the intensities can be added together, and the resulting level is determined from the logarithm of that sum. An equation commonly used for summing any number of individual sound levels is:

$$L_p(\text{total}) = 10 \log (10^{L_{p1}/10} + 10^{L_{p2}/10} + \ldots) \text{ dB} \qquad (6)$$

where each level to be added is arbitrarily assigned as L_{p1}, L_{p2}, etc., for as many different levels that are to be added together. An example of decibel addition using this equation follows.

Example: Add 90 dB + 95 dB + 88 dB

$$L_p(\text{total}) = 10 \log (10^{L_{p1}/10} + 10^{L_{p2}/10} + 10^{L_{p3}/10})$$

$$L_p(\text{total}) = 10 \log (10^{90/10} + 10^{95/10} + 10^{88/10})$$

$$L_p(\text{total}) = 10 \log (4.79 \times 10^{9})$$

$$L_p(\text{total}) = 96.8 \text{ dB}$$

Alternatively, a decibel addition table may be used to determine the resultant level when two or more individual levels are combined (see Table 19.2). To use a decibel addition table, determine the difference between the first two levels to be added, then find where this number falls in the left-hand column of the table. Next, move across to the right-hand column and locate the number that corresponds to this difference. Finally, determine the total sound pressure level by adding the value in the right-hand column to the higher of the two levels being added together. If more than two levels are to be added, any two may be combined first, then that result should be added to the third level, and the resultant of the three sources added to the next level, etc., until all levels have been summed. Although the order in which the levels are added usually does not matter, one typically starts with the highest levels first. This is done because once the difference between two levels is 10 dB or greater, the addition process can be discontinued since the addition of smaller values does not add significantly to the overall total.

The use of a decibel addition table may be illustrated by the following example.

Example: Add 85 dB + 87 dB + 90 dB + 71 dB

Starting with the highest levels, the difference between 90 dB and 87 dB is 3 dB. Locating this value in the left-hand column of Table 19.2 and looking across to the

Table 19.2. Table for Combining Decibel Levels of Sounds with Random Frequency Characteristics

Numerical Difference between Levels (dB)	Amount to be added to the Higher Level (dB)
0.0–0.1	3.0
0.2–0.3	2.9
0.4–0.5	2.8
0.6–0.7	2.7
0.8–0.9	2.6
1.0–1.2	2.5
1.3–1.4	2.4
1.5–1.6	2.3
1.7–1.9	2.2
2.0–2.1	2.1
2.2–2.4	2.0
2.5–2.7	1.9
2.8–3.0	1.8
3.1–3.3	1.7
3.4–3.6	1.6
3.7–4.0	1.5
4.1–4.3	1.4
4.4–4.7	1.3
4.8–5.1	1.2
5.2–5.6	1.1
5.7–6.1	1.0
6.2–6.6	0.9
6.7–7.2	0.8
7.3–7.9	0.7
8.0–8.6	0.6
8.7–9.6	0.5
9.7–10.7	0.4
10.8–12.2	0.3
12.3–14.5	0.2
14.6–19.3	0.1
19.4–∞	0.0

right side of the table, it can be seen that 1.8 dB should be added to the higher level, which gives 91.8 dB. Next, the difference between 91.8 dB and 85 dB is 6.8 dB, so according to Table 19.2, 0.8 dB should be added for a total of 92.6 dB. Finally, due to the large (i.e., greater than 10 dB) difference between 92.6 dB and 71 dB, nothing more needs to be added, and the total sound pressure level from summing all four levels is 92.6 dB.

Most industrial noises have random frequency characteristics, and can be combined as described in the preceding paragraphs. However, in the few cases when noises have a certain "pitch" or major pure tone component(s), these calculations are not accurate, and phase relationships must be considered. At zero phase difference, the resultant value of two identical pure tone sources is 6 dB greater than the value of either single level. Between 0 and 90°, the resultant is somewhere between 3 and 6 dB greater than either level. At a phase difference of 90°, the resultant is 3 dB greater than either level. Between 90 and 120°, the resultant is between 0 and 3 dB greater than either level, and with a phase difference of 120°, the resultant is equal to the individual levels. At 180°, complete cancellation of sound occurs. The fact that one sound can actually cancel out another is a very important principle in acoustics, as it forms the basis for active noise control. Noise cancellation technology, also referred to as active noise reduction, is increasingly being employed as advances in equipment and instrumentation are developed.

2.2 Frequency Analysis

The most common frequency bandwidth used for industrial noise measurements is the octave band. A frequency band is said to be an octave in width when its upper band-edge frequency f_2 is twice the lower band-edge frequency f_1:

$$f_2 = 2f_1 \tag{7}$$

Octave bands are commonly used for measurements directly related to the effects of noise on the human ear, and for general noise control purposes, because they provide the maximum amount of information with a limited number of measurements.

When more specific characteristics of a noise source are required (e.g., for pinpointing a particular noise source among a background of other sources), it is necessary to use frequency bandwidths that are narrower than octave bands. Half-octave, third-octave, and narrower bands are used for these purposes. A half-octave bandwidth is defined as a band whose upper band-edge frequency f_2 is the square root of two times the lower band-edge frequency f_1:

$$f_2 = \sqrt{2}\, f_1 \tag{8}$$

A third-octave bandwidth is a band whose upper band-edge frequency f_2 is the cube root of two times the lower band-edge frequency:

$$f_2 = \sqrt[3]{2}\, f_1 \tag{9}$$

The center frequency f_c of any of these bands is the square root of the product of the high and low band-edge frequencies (geometric mean):

$$f_c = \sqrt{f_1 f_2} \tag{10}$$

It should be noted that the upper and lower band-edge frequencies describing a frequency band do not imply abrupt cutoffs at these frequencies. These band-edge frequencies are conventionally used as the 3-dB-down points of gradually sloping curves that meet the

American National Standard Specification for Octave-Band and Fractional-Octave-Band Analog and Digital Filters (1).

3 THE EAR

Normal human ears respond to a remarkably wide frequency range that covers approximately 20 to 20,000 Hz. As might be expected, the characteristics of any individual ear are extremely complex, and large differences exist among the population. An ear's response characteristics may change as a result of physical or mental conditions, sound level, medications, environmental stresses, diseases, and other factors.

A normal healthy human ear is also capable of detecting a remarkable range of sound levels. It is sensitive to very low sound pressures that produce a displacement of the eardrum no greater than the diameter of a hydrogen molecule. At the other extreme, it can receive sounds whose sound pressures are more than one million times greater than the lower threshold value; however, exposure to high-level sounds may cause temporary or permanent damage to the hearing mechanism.

3.1 Anatomy and Physiology of the Ear

As shown in Figure 19.1, the ear can be divided into three sections: the *outer* or *external ear*, the *middle ear*, and the *inner ear* (2). Sound waves impinging on the eardrum cause it to vibrate, and these vibrations are transmitted to the fluid-filled inner ear that contains the nerve endings by which aural information is detected. The acoustic or auditory nerve carries these impulses to the hearing center in the brain.

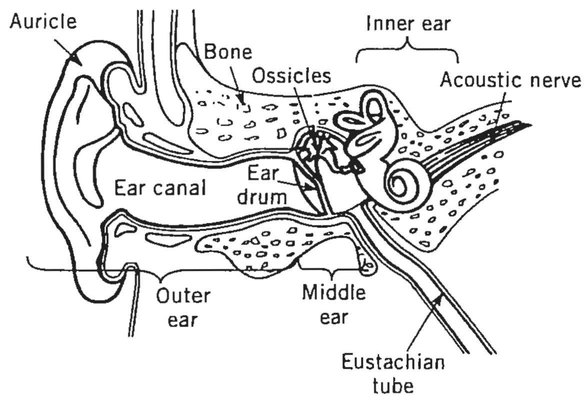

Figure 19.1. Cross-section of the ear showing the outer (external), middle, and inner ear configurations.

3.1.1 Outer Ear

Although the auricle is what most people think of when the term "ear" is used (Fig. 19.2), it plays only a limited role in the hearing process. To a certain extent, the auricle helps direct high frequency sounds into the ear canal, assisting the hearing system in determining the direction from which a sound originates. Sound waves enter the ear canal and travel towards the eardrum, which is the dividing point between the outer and middle ear regions.

Typical ear canals are about one-inch long and approximately one-quarter inch in diameter. They are seldom as straight as depicted in Figures 19.1 and 19.2, and the shape and size of ear canals differ significantly among individuals (and even between ears of the same individual). From an acoustical viewpoint, since the ear canal is closed at one end by the eardrum, it can be modeled as a cylinder with a quarter-wavelength resonance of about 3000 Hz. This resonance effectively increases the sensitivity of the ear in the higher frequencies around 3000 Hz.

Glands producing earwax or cerumen are located in the ear canal. Normally, cerumen flows outward, toward the entrance of the ear canal, carrying with it any foreign particles that may accumulate in the canal. The normal flow of wax may be interrupted by changes in body chemistry that can cause excessive wax to be produced, or the wax may become hard or "impacted." At times, the cerumen may build up to the point of totally occluding the canal, and a temporary loss of hearing will result. Any buildup of wax deep within the ear canal should be removed very carefully, to prevent damage to the eardrum and middle ear structures.

The surface of the external ear canal is extremely delicate and easily irritated. Cleaning or scratching with fingernails or other sharp objects can break the skin and cause a very painful and persistent infection. Infections can cause swelling of the canal walls and, occasionally, a loss of hearing when the canal swells shut. An infected ear should be given prompt attention by a physician.

3.1.2 Middle Ear

The air-filled space between the eardrum and the inner ear is called the middle ear (Fig. 19.3). The middle ear contains three small bones or ossicles that mechanically connect the

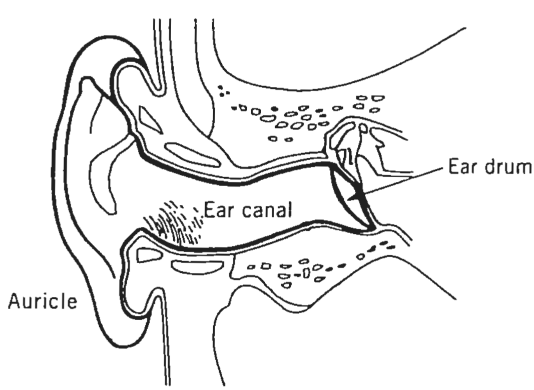

Figure 19.2. The outer or external ear.

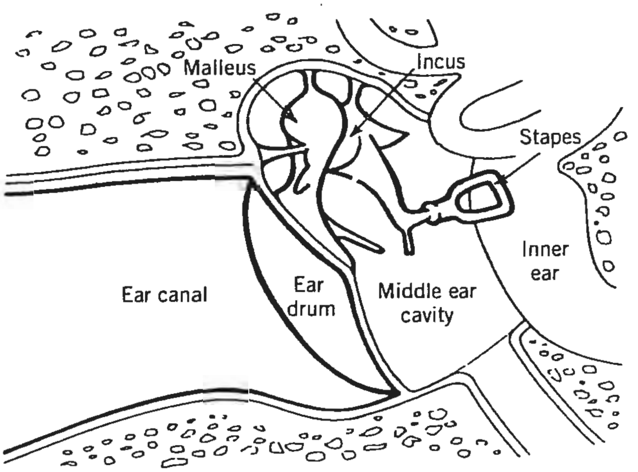

Figure 19.3. The middle ear.

eardrum to the oval window of the inner ear. Sound energy is converted into mechanical energy by the middle ear system.

The eardrum is a very thin and delicate membrane that responds to very low sound pressures at the lower threshold of hearing, yet it seldom suffers physical damage from routine exposure to continuous high-level noises. Although an eardrum may be damaged or perforated by an explosion or a rapid change in ambient air pressure, most common steady-state noise exposures do not produce a noticeable effect on the eardrum itself.

The three tiny bones or ossicles in the middle ear are commonly known as the hammer, anvil, and stirrup, although their correct anatomical names are the malleus, incus, and stapes. These three bones are connected together to form a "chain," with the handle of the malleus physically attached to the eardrum. Therefore, any movement of the eardrum is transmitted directly to the bones of the middle ear. Due to the construction of the eardrum/ossicle system, a mechanical advantage or lever action is formed, which is necessary to match the impedance of air in the ear canal with the fluid in the adjacent inner ear structure.

When an eardrum is ruptured, the attached middle-ear ossicles may be dislocated; thus the eardrum should be carefully examined immediately after the injury occurs to determine whether realignment of the ossicles is necessary. In a high percentage of cases, surgical procedures are successful in realigning dislocated ossicles or by inserting a prosthesis, so that little or no permanent loss in hearing acuity results from this type of injury.

The middle ear cavity is completely enclosed except for the small Eustachian tube that connects the middle ear to the back of the throat (see Fig. 19.1). The purpose of the Eustachian tube is to equalize the air pressure inside the middle ear space with that of the surrounding atmosphere. When flying in an airplane or when driving in mountainous territory, changes in the ambient barometric pressure are normally compensated for when the Eustachian tube briefly opens, thereby allowing air to enter or escape from the middle ear space. In this manner, the same amount of air pressure is always maintained on both sides of the eardrum.

Occasionally, the Eustachian tube will remain closed as a result of an infection or an allergy, resulting in a pressure imbalance between the middle ear and the outside air. This situation may produce a temporary loss of hearing sensitivity and extreme discomfort for the individual. Even a healthy ear may suffer a loss of hearing if the Eustachian tube becomes blocked, but this loss of hearing can often be quickly restored simply by yawning, swallowing, or chewing gum, which allows the Eustachian tube to open momentarily.

3.1.3 Inner Ear

As illustrated in Figure 19.1, the inner ear is completely surrounded by bone; a close-up of the inner ear is shown in Figure 19.4. One end of the inner ear is shaped like a snail shell, and is called the cochlea. The other end of the inner ear contains three semicircular loops or canals. The fluid-filled cochlea serves to detect incoming sound signals and to translate them into nerve impulses, which are then transmitted to the brain. Although they are located in the inner ear, the semicircular canals are balance organs, and not actually part of the hearing mechanism.

Mechanical energy from the middle ear is transferred to the inner ear by the stapes, whose footplate rests on the oval window of the cochlea (see Fig. 19.4). Movement of the stapes forces the oval window in and out with the dynamic characteristics of the incident sound, setting the fluid of the cochlea into motion, thereby transforming these mechanical vibrations into hydraulic energy. Thousands of hair cells located along the two-and-one-half turns of the cochlea detect these motions and translate them into nerve impulses. A sound is "heard" when this neural energy is sent along the acoustic or eighth cranial nerve up to the auditory center of the brain.

3.2 How Noise Damages Hearing

Noise-induced hearing loss may be temporary or permanent depending on the level and frequency characteristics of the noise, the duration of exposures, and the susceptibility of

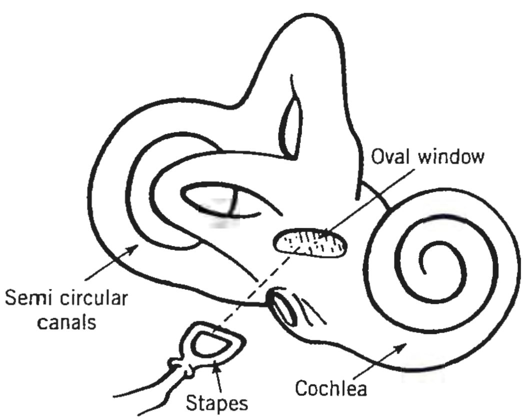

Figure 19.4. The inner ear.

the individual (3). After a temporary hearing loss occurs, the original sensitivity is usually restored within a matter of hours; however, in some cases temporary losses may last for days or weeks. Permanent losses result when these temporary losses do not recover completely. A permanent noise-induced hearing loss is not reversible and cannot be corrected by conventional medical or surgical procedures.

A noise-induced hearing impairment generally occurs with the hair cells located in the cochlea, and is called a sensorineural hearing loss. For commonly encountered noise exposures, hearing acuity is generally affected first in the frequency range from 3000 to 6000 Hz, with most affected persons showing a loss or "dip" in sensitivity at 4000 Hz. If high-level exposures are continued, the loss of hearing generally increases around 4000 Hz and spreads to adjacent frequencies. For noise exposures having significant components concentrated in narrow frequency bands below 4000 Hz, impairments usually are found about one-half to one octave above the predominant exposure frequencies.

Noise-induced hearing loss is an insidious problem, because a person does not necessarily have to experience pain or even be immediately aware that severe hearing damage has taken place. The damage may occur instantaneously or over a long period of time, depending upon the noise characteristics. Generally, impulsive or impact noises are most likely to produce significant losses with short exposure periods, and steady-state continuous noises are responsible for impairments that develop over a long period of time. Additionally, workers suffering from noise-induced hearing loss may hear a continuous "ringing" in their ears, which is called tinnitus.

Even after a significant amount of damage, a person with noise-induced hearing loss is able to hear low-frequency (vowel) sounds very well, but the high frequencies (consonants) in speech are not clearly heard. Loudness levels may be nearly normal, but intelligibility may be poor since the consonant sounds carry most of the distinguishing characteristics of speech, and degraded high frequency hearing will cause misunderstanding or confusion between similar-sounding words. A noise-induced hearing loss becomes particularly noticeable when verbal communication is attempted in noisy or reverberant areas. Speech is "masked" or obscured most effectively by background noises containing the speech frequencies, such as the sounds encountered in a crowd of people, where many are talking simultaneously.

3.3 Combined Effect of Noise and Other Agents

Research has shown that exposure to some chemicals or other industrial substances may exacerbate the effect of high-intensity noise (3). Agents such as solvents, heavy metals, and asphyxiants can increase the amount of hearing loss a worker may incur, beyond the amount expected from any one of the physical agents alone. Further research is needed to accurately define the combined effects of noise exposure and other hazardous substances.

4 HEARING MEASUREMENT

The only way to monitor the overall effectiveness of a hearing conservation program is to periodically check the hearing of all persons exposed to potentially hazardous noise. Hearing thresholds at 500, 1000, 2000, 3000, 4000, and 6000 Hz must be checked in each ear, in order to determine whether employees are losing some of their hearing ability. Hearing loss due to medical conditions unrelated to occupational noise exposure may also be identified from periodic hearing tests.

To ensure the accuracy of hearing tests, audiometric equipment must be periodically calibrated, a quiet test environment must be maintained, and a well-trained audiometric technician or hearing conservationist must perform the hearing tests. Requirements for audiometer performance and for the background noise limits in test rooms have been specified in standards published by the American National Standards Institute (ANSI S3.6-1996 and S3.1-1991) (4, 5). Guidelines for training Occupational Hearing Conservationists have been established by the Council for Accreditation in Occupational Hearing Conservation (CAOHC) (6).

4.1 Audiometers

An audiometer is the instrument used for measuring pure tone, air conduction hearing thresholds. It may be designed for manual or automatic operation; most of the newest audiometers are microprocessor-based, and can be used in conjunction with a computer for data storage.

ANSI S3.6-1996 provides the specifications that audiometers must meet to provide accurate hearing threshold information (4). Instrumentation inaccuracies are seldom obvious, and there is a strong tendency to automatically accept dial readings as being accurate. Therefore, strict attention should be given to equipment calibration. Modern audiometers are much more stable than their older counterparts; however, they may lose their specified accuracy if not cared for properly. Earphones are particularly susceptible to damage from rough handling. Unseen damage could occur during shipment, so that even a new instrument may be out of calibration when initially received. The normal aging of components and exposure to temperature extremes may also cause changes in audiometer accuracy. Dust or dirt inside the audiometer can cause dials and switches to produce electrical noise or to wear excessively. Poor electrical contacts may produce intermittent operation or poor accuracy. For this reason, dust covers should always be used to protect the instrument when not in use, and the exterior of the audiometer should be cleaned periodically to prevent dust and dirt from getting inside the case.

The Occupational Safety and Health Administration (OSHA) requires that functional or biological calibration checks (audiograms taken on persons with known stable hearing thresholds) be performed before each day's use (7). Accuracy checks should also be made any time there is a reason to suspect a problem. The person used for daily biological calibration checks does not need to have perfectly normal hearing; the main consideration is that this individual's hearing thresholds do not fluctuate. A baseline hearing test is established immediately following a comprehensive or exhaustive electro-acoustic calibration of the audiometer. Subsequent daily tests should not deviate by more than 10 dB if the audiometer remains correctly calibrated.

Hearing sensitivity may temporarily decrease as much as 20 dB because of allergies, colds, or other causes; therefore, it is strongly recommended that at least two individuals be made available for biological tests. Alternatively, an "electroacoustic ear" may be used in place of a live human subject. An electroacoustic ear (sometimes called a bio-acoustic simulator) is an instrument that is calibrated to take a hearing test and respond as a person would. The audiometer's headphones are placed on the instrument, and a normal hearing test is run. Test results are compared to the electroacoustic ear's baseline to determine whether a change in calibration has occurred, just as would be done for a human listener. The advantage to using an electroacoustic ear is that this instrument will always be available for daily biological calibration checks, and will not respond differently on successive hearing tests.

The technician should also check the audiometer periodically using the following additional procedures:

1. Check all control knobs on the audiometer to be sure that they are tight on their shafts and not misaligned, and make sure all cable connections between the audiometer and jack panel are correct and secure. Visually inspect the earphones for correct headband tension, missing parts, and serviceability of the cushions. Cushions should be replaced if they are not resilient or if cracks, bubbles, or crevices develop. A new acoustic calibration is not required when replacing earphone cushions.

2. Straighten the earphone cords so that there are no sharp bends or knots. Cords with worn or cracked insulation should be replaced. With the audiometer set to 1000 Hz and 60 dB, test the earphone cords for electrical continuity by listening while bending the cords along their length. Typical trouble spots are where the cord connects to the earphones, or at the other end where the cord attaches to the jack. Any static, intermittency, or change in test tone indicates a need for new earphone cords. A new acoustical calibration is not required when replacing only the earphone cords.

3. With the frequency set to 1000 Hz, check the linearity of the hearing level control by listening to the earphone while slowly increasing the hearing level. Each 5-dB step should produce a steady increase in loudness without changes in tone quality or any other audible extraneous noise.

4. With the audiometer set at 1000 Hz and 60 dB, test the operation of the tone interrupter by listening to the earphones and operating the interrupter several times. No audible noises (such as clicks or scratches) or changes in tone quality should be heard when the interrupter switch is used.

5. With a steady 60 dB tone coming from the right earphone, cover that earphone with the palm of your hand and listen for extraneous noises from the left earphone. No tones or noises should be heard in the non-test earphone. Repeat this procedure with the tone coming from the left earphone.

6. With the hearing level set to 60 dB, check for the presence of a tone at each test frequency. There should be a noticeable difference between each frequency, without any wavering or abrupt changes in tone quality.

According to Appendix E in the OSHA Hearing Conservation Amendment, audiometer calibration should be checked "acoustically" once per year, or sooner if the functional check indicates a deviation of 10 dB or more between the dial setting and actual output of the audiometer. The two main checks performed during an acoustic calibration are a sound pressure output check and a linearity check. When any of the measured sound levels deviate by ±3 dB at any test frequency between 500 and 3000 Hz, 4 dB at 4000 Hz, or 5 dB at 6000 Hz, an exhaustive calibration is *advised*. An exhaustive calibration is *required* if the deviations are 15 dB or greater at any test frequency.

An exhaustive calibration is typically done by an authorized repair service or the audiometer's manufacturer. This is the only stage at which changes to the audiometer are made, in order to exactly meet the requirements in the ANSI S3.6 standard. This type of comprehensive electroacoustic calibration must be performed at least every two years, regardless of whether any discrepancies have been noted in the functional or acoustical calibration checks.

4.2 Test Rooms

The sound pressure level of the background noise in rooms used for measuring hearing thresholds must be limited to prevent masking effects that cause misleading, elevated threshold values. In particular, an individual's hearing thresholds at 500 Hz may be artificially elevated (i.e., appear worse than they really are) due to interference from the background noise. Maximum allowable octave-band sound pressure levels for audiometric test rooms, as specified in Appendix D, Table D-1, of the OSHA Standard, are contained in the following chart (7):

500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
40 dB	40 dB	47 dB	57 dB	62 dB

It should be noted that the maximum background levels specified by OSHA are not low enough to permit testing down to 0 dB hearing threshold level. More accurate tests can be obtained if the test room meets the criteria established in ANSI S3.1-1991, American National Standard Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms (5). These background noise levels are more stringent than those specified by OSHA, but they are difficult to obtain in noisy areas, and may be below the practical limit for ambient noise in many industrial locations. Typically, audiology clinics or otologist offices are the only testing locations that meet the ANSI S3.1 background levels.

In addition to meeting OSHA's background noise level requirements, subjective tests should be made inside the test booth on-site to determine that no noises (e.g., talking and heel clicking) are audible. In particular, short impulse-type noises may be heard even though the measured sound pressure levels are below the limits in the table. Any of these extraneous noises may distract the subject and interfere with the hearing threshold measurements. If possible, these nuisance sounds should be eliminated, or the tests must be delayed until they no longer present a problem.

The noise reduction provided by a good prefabricated audiometric test booth should be adequate when the booth is placed in a reasonably quiet area of the plant or facility. However, it is recommended that the burden of on-location performance be placed on the booth supplier, to ensure that an acceptable booth is obtained. The vendor should be willing to guarantee in writing the performance of the test room or booth when installed at the specified test site, particularly if some on-site assembly is required. Attention must also be paid to proper vibration isolation for permanently installed booths.

In addition to the attenuation characteristics, several other factors should be considered when selecting a test booth or room:

1. What size booth is necessary—one person, two person, four person, etc.?
2. Will opening and closing the door result in wearing of contact material (seals), necessitating frequent replacement?
3. Are the interior surfaces durable and easily cleaned?
4. Is the door easily opened from the inside, so that subjects will not feel "locked in?"
5. Do the observation window and seating arrangement provide an easy view of the subject, but block the subject's view of the audiometer controls?
6. If the booth is equipped with a ventilation system, is the interior noise level below the limits specified for the room?
7. If the booth must be moved occasionally, is it portable?

4.3 Hearing Threshold Measurements

Normally, the purpose of audiometric testing in industrial hearing conservation programs is to monitor the effectiveness of hearing conservation procedures. Unless the test results are to be used for another purpose, there is no need for detailed diagnostic information that would require the use of sophisticated audiometric techniques and/or specialized equipment. Pure tone, air conduction hearing thresholds obtained via standard audiometric earphones are usually adequate for industrial monitoring purposes.

The conventional technique for obtaining hearing threshold levels is referred to as the modified Hughson-Westlake method (8). In this procedure, the initial tone is presented to the subject at a level well above the anticipated threshold, then decreased in 10 or 15 dB steps until it is no longer audible. Next, the level is increased in 5 dB steps until the patient responds. After a positive response, the tone is lowered by 10 dB and testing resumes, with the level again raised in 5 dB steps until another positive response occurs. This "up 5 dB, down 10 dB" approach is referred to as an ascending bracketing technique. The hearing threshold is then defined as the level at which the subject responds 50% of the time, with a minimum of two out of three positive responses at a single level. Initially, audiometers were operated manually using this technique; however, microprocessor-based audiometers programmed to conduct the hearing test in a similar manner are now more commonly used.

4.4 Records

Records must be complete and accurate if they are to have medicolegal significance. Records should be kept in ink, without erasures. If a mistake is made in recording, a line should be drawn through the erroneous entry, and the initials of the person making the correction should be placed above the line along with the date. The original entry must not be obliterated.

Whether hand-written or maintained in a computer database, the model, serial number, and calibration dates of the instrument should be recorded on each audiogram. Records should also be kept of periodic noise level measurements in the test booth. In addition to the threshold levels, an audiogram should have space provided for the recording of pertinent medical and noise exposure information. Some typical questions asked of test subjects are given on the form depicted in Figure 19.5.

5 NOISE MEASUREMENT

A wide variety of new sound-measuring equipment has been made available over the past several years. Some sound level meters provide only the basic measurements required by OSHA, while others provide a very wide range of functions including integration for dose and impulse noise measurements. Sophisticated measuring equipment can be used to obtain an enormous amount of data in a relatively short period of time. The weak link in sound

Name ______ Date ______ Recorded by ______ Employee inital ______

History	YES	NO	Comments
Have you had a previous hearing test ?			
Do you now have any trouble hearing ?			
Have you ever worked in a noisy industry ?			
Do you think you can hear better in your Right ear?			
or Left ear?			
Have you ever had noises in your ears ?			
Have you ever had dizziness ?			
Have you ever had a head injury ?			
Has anyone in your family lost his hearing before age 50 ?			
Have you ever had measles, mumps, or scarlet fever?			
Do you have any allergies ?			
Are you now taking or have you regularly taken drugs, antibiotics, or medication?			
Have you ever had an earache ?			
Have your ears ever run ? Right ear ?			
Left ear ?			
Have you been in the Military service ? Describe			
Have you been exposed to any sort of gunfire ? Describe			
Do you have a second job ? Explain			
What hobbies do you have ?			

Figure 19.5. Sample medical history form.

measuring equipment, the microphone, has also been much improved in both performance and durability in recent years. Even with this advanced technology, however, careful consideration of the objectives of the measurement must be made prior to equipment selection. In all cases, accurate sound level measurements require a well-trained operator and calibrated instruments.

5.1 The Sound Level Meter

The basic sound level meter consists of a microphone that converts the pressure variations into an electrical signal, an amplifier/filter, an exponential time-averaging circuit, a device to determine the logarithm of the signal, and an indicating meter or digital display. All instruments used for hearing conservation purposes should conform to the American National Standard Specification for Sound Level Meters (ANSI S1.4-1983 R1997) (9).

Most instruments present the sound pressure level in terms of its rms value. The rms value is useful for hearing conservation purposes because it is related to acoustic power, which forms the basis for decibel notation. Further, it must be kept in mind that an ordinary arithmetic averaging process will actually yield a value of zero for sound pressure fluctuations. The rms values cannot be used to describe prominent peak pressures of noise that extend several decibels above a relatively constant background noise; peak values are used for this purpose. On the other hand, peak readings are of relatively little value for measuring sustained noises unless the wave form is known to be sinusoidal, because the relationship between the peak reading and the acoustic power changes with the complexity of the wave. As the waveform becomes more complex, the peak value can be as much as 25 dB above the measured rms value.

The two primary classifications of sound level meters used in industrial noise monitoring are the precision (Type 1) and the general purpose (Type 2). Generally, the main difference between these instruments is simply a matter of how accurate the sound level readings are. According to ANSI S1.4, the allowable tolerances across the measurement range are approximately one decibel for the type 1 and two decibels for the type 2 instruments. Most regulations require the use of a type 2 meter; type 1 instruments are used when a greater degree of accuracy is required.

Two meter-response settings are usually available on a sound level meter. The "fast" response is used to follow rapid changes in level, while the "slow" response essentially slows the meter's display down and is intended to provide an averaging effect that makes widely fluctuating sound levels easier to read. The fast response uses a one-eighth second time constant, and the slow response has a time constant of one full second. Neither of these settings actually affect the signal itself; "fast" and "slow" refer only to the speed with which the display indicator on the meter moves. The OSHA regulation states that the slow response setting is to be used for industrial noise monitoring purposes (7). When impulse or impact noise (i.e., a transient sound less than one second in duration) is present, a measurement of the true peak sound pressure level is required. Some sound level meters have an "impulse" setting; however, this is not suitable for industrial noise measurements, because it is not designed to actually measure the true unweighted peak sound level.

General-purpose sound level meters are normally equipped with one or more filters or frequency-weighting networks, designated by the letters A, B, and C (see Table 19.3).

Table 19.3. Relative Response as a Function of Frequency for A, B, and C Weighting

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
1,000	0	0	0
1,250	+0.6	0	0
1,600	+1.0	0	−0.1
2,000	+1.2	−0.1	−0.2
2,500	+1.3	−0.2	−0.3
3,150	+1.2	−0.4	−0.5
4,000	+1.0	−0.7	−0.8
5,000	+0.5	−1.2	−1.3
6,300	−0.1	−1.9	−2.0
8,000	−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

Readings obtained using any of these weighting scales are termed sound levels rather than sound pressure levels, and the particular weighting network used must always be indicated. The A, B, and C weighting curves were chosen because they approximate the response characteristics of the ear at various sound levels, and in the earliest sound level meters they could be easily produced with a few common electronic components. Empirically, the A-weighting has been found to give a good estimation of the hearing-damage risk potential from exposure to continuous noise. Therefore, OSHA specifies that the A-weighting scale be used for industrial noise measurements (7). The B-weighting is seldom used, and the C-weighting is used when assessing hearing protector effectiveness.

Figure 19.6 illustrates the frequency response characteristics of the A- and C-weighting networks. A linear or flat response, also included on some sound level meters, does not apply any correction values (i.e., it weights all frequencies equally) and would correspond to the 0 dB line in Figure 19.6.

In use, the frequency distribution of noise energy can be estimated by comparing the levels measured with each of the frequency weightings. For example, if the noise levels measured using the A and C networks are approximately equal, it can be reasoned that most of the noise energy is above 1000 Hz, because this is the only portion of the spectrum in which the weightings are similar. On the other hand, a large difference between these readings indicates that most of the energy will be found below 1000 Hz.

The rough estimate of frequency-response characteristics provided by the weighting networks of a sound level meter is not always adequate, particularly for engineering noise control work. In such cases, frequency analyzers are used. The most common types are the octave band (commonly abbreviated as 1/1), one-third octave band (abbreviated as 1/3), and narrow-band analyzers using filters or Fast Fourier Transform (FFT) digital calculations. Table 19.4 shows the range encompassed by each octave and one-third octave band, as defined by ANSI S1.11. Normally, the full octave bands provide adequate spectral information to solve most hearing conservation and noise control problems, and one-third

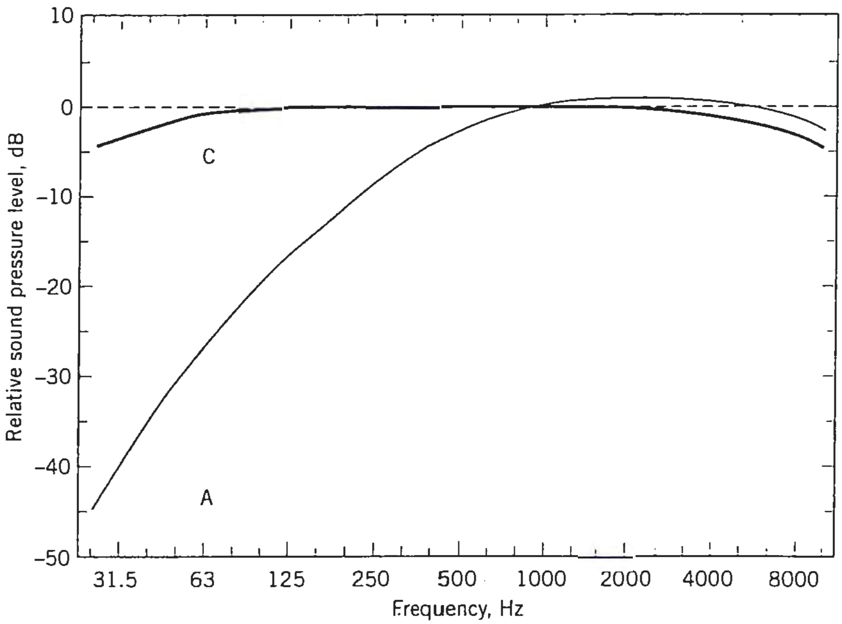

Figure 19.6. Sound level meter weighting curves.

Table 19.4. Center and Cutoff Frequencies for Full Octave and Third Octave Bands

1/1 Octave Bands			1/3 Octave Bands		
Lower	Center	Upper	Lower	Center	Upper
22.4	31.5	45	22.4	25	28
			28	31.5	35.5
			35.5	40	45
45	63	90	45	50	56
			56	63	71
			71	80	90
90	125	180	90	100	112
			112	125	140
			140	160	180
180	250	355	180	200	224
			224	250	280
			280	315	355
355	500	710	355	400	450
			450	500	560
			560	630	710
710	1000	1400	710	800	900
			900	1000	1120
			1120	1250	1400
1400	2000	2800	1400	1600	1800
			1800	2000	2240
			2240	2500	2800
2800	4000	5600	2800	3150	3550
			3550	4000	4500
			4500	5000	5600
5600	8000	11,200	5600	6300	7100
			7100	8000	9000
			9000	10,000	11,200
11,200	16,000	22,400	11,200	12,500	14,000
			14,000	16,000	18,000
			18,000	20,000	22,400

octave bands are used when more detail is required. However, significantly more measurements are necessary to cover the overall frequency range when smaller bandwidths are used; thus a compromise must be reached between the resolution required and the number of measurements that must be taken.

5.2 The Noise Dosimeter

A noise dosimeter consists of a miniature microphone connected to a small microprocessor-based sound level meter, which stores the noise data. The microphone is positioned at the top of the employee's shoulder, and the sound level meter control unit is clipped to the wearer's belt or placed in a pocket. Noise dosimeters continuously measure and process sound levels obtained near a worker's ear (i.e., hearing zone), then produce an average level of noise exposure that occurred throughout the individual's workday. Specifications for these devices are contained in ANSI S1.25-1991 (R1997), American National Standard Specification for Personal Noise Dosimeters (10).

A dosimeter is essentially identical to any other sound level meter, with the addition of an integrating function that keeps track of the noise level as well as the accumulated exposure time. Dosimeters have made it much more convenient to measure and assess employees' noise exposures, by eliminating the need for the surveyor to follow a worker throughout the workday with a sound level meter and a stopwatch to keep track of the exact amount of exposure to different noise levels. Many of the new instruments can continuously log or store the employee's noise exposure at one-minute, 10-second, or even one-second intervals. This noise exposure history information can be printed out and analyzed in any number of ways to help pinpoint periods of high noise levels or other significant occurrences during a workshift. Most regulatory inspectors use dosimeters to determine compliance with the applicable noise standards.

5.3 Instrument Calibration

It is very important to carefully read and understand the operator's manual prior to using any sound level meter or dosimeter. One of the critical points of interest is the proper calibration procedures for the particular instrument. If valid data are to be obtained, it is essential that all equipment for the measurement and analysis of sound be in calibration. When equipment is purchased from the manufacturer, it should have been calibrated to the pertinent ANSI specifications. However, it is the responsibility of the user to keep the instrument in calibration by conducting periodic checks.

Acoustic calibrators are available for checking the overall acoustical and electrical performance at one or more frequencies. Specifications for acoustical calibrators can be found in ANSI S1.40-1984 (R1997) (11). Calibration checks should be made according to the manufacturer's instructions at the beginning and end of each day's measurements, using a calibrator specifically designed for the sound level meter or dosimeter microphone. A battery check should also be done at these times. These calibration procedures cannot be considered to be of high absolute accuracy, nor will they allow the operator to detect changes in performance at frequencies other than those used for calibration. Nevertheless, they do serve as a warning for most common instrument failures, thus helping operators to avoid making invalid measurements.

Periodically, sound-measuring instruments should be sent back to the manufacturer or to a competent laboratory for a comprehensive re-calibration. This includes sound level meters, dosimeters, and their calibrators. How frequently these complete calibrations should be performed depends on the purpose of the measurements and how roughly the instruments are handled. In most cases, it is good practice to have a complete calibration performed at least once a year, and at any time an unusual reading is suspected or found.

6 ASSESSMENT OF NOISE EXPOSURE

6.1 Harmful Noise Exposures and Damage-Risk Criteria

Four major factors contribute to the development of noise-induced hearing impairment (12): (*1*) the overall noise level, (2) the frequency content, (*3*) the duration of exposure, and (*4*) the susceptibility of the individual. Studies leading to the development of comprehensive damage-risk criteria require complex statistical evaluations of large groups over long periods of time. Many different factors can compromise the accuracy of these studies, since there is a very large number of different combinations of noise levels, frequency component distributions, and exposure duration. In addition, there are wide differences in the susceptibility of individuals to noise-induced hearing impairment. Also, hearing losses found in a study may be due in part to noise exposures away from work that are not considered. Therefore, it is impossible to set a particular exposure level as the dividing line between safe and unsafe conditions that apply for all individuals. Damage-risk criteria are also influenced by practical limits. Typically, exposure level limits are established as a compromise between (*1*) the amount of hearing impairment that may result from a specified exposure dose and (2) the economic or other impact that may result from noise control expenditures.

6.2 Noise Regulations

The Safety and Health Standards for Federal Supply Contracts (Walsh-Healy Public Contracts Act), U.S. Department of Labor, was revised on May 20, 1969, to include the first national noise exposure regulation in the United States (13). This regulation stemmed from the Social Security Act of 1935, which expressed the philosophy that a worker has the right to earn a living in an environment that does not endanger his or her health. The Occupational Safety and Health Act of 1970 created the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH) (14). OSHA is responsible for the establishment and enforcement of regulations for most industries (one exception is mining, where the Mine Safety and Health Administration has responsibility). NIOSH conducts research and develops criteria in all areas of occupational safety and health for both general industry and mining.

The OSHA Occupational Noise Exposure Standard (29 *CFR* 1910.95) was released in 1971, and was designed to protect workers exposed to hazardous noise environments from incurring permanent hearing loss (7). This regulation set the maximum levels of industrial noise to which an employee may be exposed, which is 90 dBA, measured with the slow meter response, for an 8-hour workday. Higher levels are permitted as long as the exposure time is less; a 5 dBA increase is allowed for each halving of exposure time (i.e., 95 dBA for 4 hours, 100 dBA for 2 hours, 105 dBA for 1 hour, 110 dBA for 30 minutes, and 115 dBA for 15 minutes or less). Additionally, the OSHA regulation states that exposure to impulsive or impact noise should not exceed 140 dB peak sound pressure level. A new MSHA noise regulation (that will become effective in the year 2000) is expected to closely follow the OSHA regulation, and will essentially replace the existing four different mining operation standards.

It is important to note that most noise regulations are designed to keep damage risk within "acceptable limits," which means that some people are likely to incur a hearing loss even when exposed to less than the maximum daily amount of noise specified in the regulation. NIOSH has recently revised its occupational noise exposure criteria, and, if incorporated into the OSHA standard, adherence to these criteria would reduce the "excess risk" of incurring noise-induced hearing loss from 25% down to 8% (15). Excess risk is defined as the percentage with material impairment of hearing in an occupational noise-exposed population, after subtracting the percentage who would normally incur such impairment from other causes in a population not exposed to occupational noise.

Based on the above information, many companies find it prudent to adopt the more stringent criteria and use exposure limits lower than OSHA's wherever possible. Obviously, the lowest feasible noise exposure levels are desirable for the health, safety, and well-being of workers. Moreover, these lower limits are of significant value to employers because they help maximize morale and work productivity and minimize the number of compensation claims for noise-induced hearing impairment.

When an employee's daily noise exposure is composed of two or more periods of exposure at different levels, the combined effect is determined by adding the individual contributions as follows:

$$D = \frac{C_1}{T_1} + \frac{C_2}{T_2} + \frac{C_3}{T_3} + \cdots\cdots + \frac{C_n}{T_n} \times 100\% \qquad (11)$$

where D represents the noise dose (in %), the values C_1 to C_n indicate the total time of exposure at a specific noise level, and the corresponding values of T indicate the total number of hours of exposure permitted at each of these levels. Values of T can be obtained from Table G-16 in the OSHA noise regulation, which is based on the equation

$$T_n = \frac{8}{2^{(Ln-90)/5}} \text{ hours} \qquad (12)$$

where L_n is equal to the A-weighted sound level that corresponds to each of the exposure time intervals. If the sum of the individual contributions exceeds 1.0, (i.e., the value for D exceeds 100%), then the mixed exposures are considered to exceed the overall limit value. For example, if a person were exposed to 90 dBA for 5 hours, 95 dBA for 2 hours, and 100 dBA for 1 hour during an 8-hr working day, the times of exposure are $C_1 = 5$ hours, $C_2 = 2$ hours, and $C_3 = 1$ hour. In this example, the corresponding time limits (or reference durations) for these exposures are $T_1 = 8$ hours, $T_2 = 4$ hours, and $T_3 = 2$ hours. Therefore, the total dose for this combined exposure is $5/8 + 2/4 + 1/2 = 1.625$ (about 163%), which exceeds the specified limit of 1.0 (100%).

In cases where employees are subjected to sound exceeding permissible exposure levels, feasible administrative or engineering controls must be used (7). Administrative controls usually involve an attempt to lower daily noise exposures by rotating employees through a "less noisy" work station; however, this practice is seldom feasible due to production constraints and/or employee training requirements. Engineering controls would work better in most circumstances, although they may be considerably more expensive to implement. If noise controls fail to sufficiently reduce exposure levels, personal protective equipment (i.e., hearing protection) must be provided.

A significant Hearing Conservation Amendment was added to the OSHA Occupational Noise Exposure Standard in 1983 (16). No changes were made to the original regulation—i.e., the same exposure limit still applies—and administrative or engineering controls are still required before the use of hearing protection is to be considered. The Amendment gives directions for administering a hearing conservation program, which must be implemented when employee noise exposures equal or exceed an 8-hour time-weighted average (TWA) sound level of 85 dBA. This 85 dBA TWA is referred to as the "Action Level," which is equivalent to a dose of 50%, and is computed without regard to any attenuation provided by the use of personal hearing protection. An employee's TWA may be determined from the following equation:

$$\text{TWA} = 16.61 \log\left(\frac{D}{100}\right) + 90 \text{ dBA} \tag{13}$$

where D is the percentage dose obtained from equation (11). Alternatively, the corresponding TWA for a particular dose can be obtained from Table A-1 in Appendix A of the OSHA noise regulation.

6.3 Noise Exposures Outside the Workplace

High-level noise exposures outside of the workplace can be just as harmful as those obtained in the workplace, so all exposures must be considered in order to get an accurate assessment of daily noise exposure. Potentially hazardous noises away from work may result from exposures to noises from chainsaws, snowmobiles, lawn mowers, motorboats, motorcycles, automobile or motorcycle races, farm equipment, loud music, shooting hobbies (skeet, targets, etc.), and shop tools. Even riding in a car at legal speeds with the window down may be harmful to some noise-sensitive individuals.

6.4 Ultrasound Limits

Exposure to high intensity sound in the upper sonic range (10,000 to 20,000 Hz) or ultrasonic range (above 20,000 Hz) is not common, although it does occur in certain industries. Ultrasonic equipment (e.g., cleaners, welders) will often emit subharmonics of the fundamental ultrasonic frequency, which fall into the audible range of human hearing. These subharmonics (rather than the ultrasonic sound itself) are of concern for potential noise-induced hearing loss or other health effects such as nausea and headaches. The OSHA noise exposure regulation does not specifically address ultrasonic frequencies, although technically they should be considered along with any other noise in the work environment. However, frequencies above 10,000 Hz cannot be reliably measured with a standard Type 2 sound level meter, due to its inherent design tolerances. Instead, a Type 1 or better instrument should be used for ultrasonic measurements. The American Conference of Governmental Industrial Hygienists (ACGIH) has published threshold limit values, or

TLVs, for one-third octave-bands of sound from 10,000 to 100,000 Hz (see Table 19.5) (17). These TLVs represent conditions under which it is believed that nearly all workers may be repeatedly exposed without adverse effect on their ability to hear and understand normal speech. The 8-hour TWA values are an extension of the ACGIH TLV for noise, which is an 8-hour TWA of 85 dBA for sound below 10,000 Hz.

7 NOISE CONTROL TECHNIQUES

From an engineering perspective, an ideal engineering noise control solution focuses directly on the actual source of the noise. Eliminating the noise-generating mechanism altogether obviates the need for further hearing conservation considerations. However, in cases where this is not practical nor possible, engineering controls must be oriented toward blocking the path that the sound waves travel toward employees, or a method must be provided for protecting the employees from exposure to the harmful noise. More than one

Table 19.5. Permissible Airborne Upper Sonic and Ultrasound Acoustic Radiation Exposure Levels[a]

Mid-Frequency of Third-Octave Band (kHz)	One-Third Octave-Band Level: Measured in Air in dB re: 20 μPa; Head in Air		Measured in Water in dB re: 20 μPa; Head in Water
	Ceiling Values	8-Hour TWA	Ceiling Values
10	105[b]	88	167
12.5	105[b]	89	167
16	105[b]	92	167
20	105[b]	94	167
25	110[c]	—	172
31.5	115[c]	—	177
40	115[c]	—	177
50	115[c]	—	177
63	115[c]	—	177
80	115[c]	—	177
100	115[c]	—	177

[a]From ACGIH, 1998.
[b]Subjective annoyance and discomfort may occur in some individuals at levels between 75 and 105 dB for the frequencies from 10 kHz to 20 kHz, especially if they are tonal in nature. Hearing protection or engineering controls may be needed to prevent subjective effects. Tonal sounds in frequencies below 10 kHz might also need to be reduced to 80 dB.
[c]These values assume that human coupling with water or other substrate exists. These thresholds may be raised by 30 dB when there is no possibility that the ultrasound can couple with the body by touching water or some other medium. [When the ultrasound source directly contacts the body, the values in the table do not apply. The vibration level at the mastoid bone must be used.] Acceleration Values 15 dB above the reference of 1g RMS should be avoided by reduction of exposure or isolation of the body from the coupling source. (g = acceleration due to the force of gravity, 9.80665 meters/second; RMS = root-mean-square.)

noise control treatment may be necessary if source treatment alone does not provide sufficient sound attenuation.

No single approach to noise control is applicable in all situations. Practical noise control solutions combine the exact science of acoustics with any production, maintenance, and economic constraints imposed upon a particular situation. Successful noise control projects are usually the result of a joint effort involving individuals from engineering, operations, and management. A compromise or balance must be struck between what is technically possible and what is truly feasible in each circumstance.

7.1 General Considerations

The first step in a noise control project is to accurately define the problem and determine its extent. In most cases, the problem will be the potential for employees to sustain a noise-induced hearing loss, although issues of verbal communication or simply complaints of annoyance often necessitate a reduction in noise levels. Area sound levels and employee noise exposures should be thoroughly measured at the outset of the project, and the data obtained will form the basis for future decisions. Questions such as "how many and/or which employees are affected?" and "exactly how much noise reduction is required?" must be answered before any other work is done.

After determining that a noise problem exists, the actual noise source(s) or "root cause" of the problem must be identified. Although this seems somewhat elementary, in reality this is often the biggest challenge encountered throughout the entire project. Noise may be produced by mechanical impacts, vibrating surfaces, exhaust gases, rotating machinery, etc. There may be hundreds of potential noise-generating mechanisms within a relatively small space in a plant or factory, and the difficulty arises when attempting to pinpoint the *exact* source of the excessive acoustical energy. Generally, it is not sufficient to simply state that the noise is coming from the "assembly line" or a particular machine—precisely what part of the equipment that is responsible for the high noise level must be known in order to implement an effective control. The services of an acoustical consultant or noise control engineer may be invaluable for this purpose; however, many noise problems can be successfully solved in-house by individuals without extensive acoustical training. The key is to systematically track down the noise source by turning different equipment (or individual components) on and off, or by using temporary controls and observing their effects.

The noise produced by one source can be distinguished from another by analyzing the differences in the octave or third-octave band spectrums. More sophisticated approaches to source identification involve using vibration measurements or performing calculations based on rotational speed, physical dimensions, or other known characteristics of the equipment in question.

Another problem encountered early in the noise control process is the prioritization of engineering control treatments. Installing a noise control device on a particular piece of equipment simply because it is "easy" or relatively inexpensive may be ineffective because the device might not affect the overall noise level, depending on what else in the immediate area is also generating noise. As a rule of thumb, when multiple noise sources are present, the loudest source(s) must be reduced first. For example, three noise sources of 91 dBA, 96 dBA, and 102 dBA combine to create a noise level of 103 dBA. If only the 91 dBA source is removed, no overall reduction would occur, since the sum of the 96 dBA and 102 dBA sources is still 103 dBA. Obviously, if the 91 dBA and 96 dBA sources are eliminated, only a one decibel reduction would occur since the overall level would be 102 dBA due to the lone remaining source. However, if the 102 dBA source is removed, the 91 dBA and 96 dBA sources added together produce 97 dBA, which results in a 6 dBA decrease from the original level of 103 dBA. When multiple noise sources are present, this type of analysis should be applied to determine how much noise reduction is necessary to meet the intended goal.

Further, it should be pointed out that successful noise control efforts do not always involve the purchase of "soundproofing" materials or products. Excessive noise levels are often produced by machinery when it is in need of adjustment, alignment, or repair (18). Therefore, restoring equipment to its optimum performance condition should be completed before investing in any noise control treatment(s). Rotating members should be dynamically balanced, with bearing and other rotating contact surfaces properly maintained. Further, no machine should be operated at an unnecessarily high speed. In many instances, a significant reduction in noise can be achieved by using a larger machine that can do the same job while operating at a lower speed. Also, it may be necessary to periodically inspect and/or replace existing noise control devices, since items such as pneumatic silencers will eventually become plugged and be rendered ineffective. Wherever possible, other maintenance-related controls should be investigated. Attempts should be made to prevent or reduce mechanical impacts between machine parts; replace metal components with quieter plastic parts; and reduce the amount of force, pressure, air velocity, etc. to the absolute minimum amount required to perform the task. Relocating noisy equipment (e.g., motors, pumps, fans) to unoccupied areas of the plant (e.g., rooftops or warehouse areas) can greatly reduce the amount of ambient noise. Even simple measures such as tightly closing access doors/panels will keep noise from "leaking out."

A successful noise control program also gives consideration to the initial procurement of noise-generating machinery and equipment. Purchase orders for new equipment should include noise limits, with the intent that noise control features will be designed and built into noisy equipment from the start. The desired sound levels may not always be met, but these specifications will provide an incentive for the development of quieter products in the future. Although the process of building quieter equipment generally increases its cost, the cost of retrofitting that piece of equipment is usually several times greater than if the same noise controls were purchased and installed in the first place.

The American National Standard Guidelines for the Specification of Noise of New Machinery (ANSI S12.16-1992, R1997) provides guidelines for obtaining noise level data from manufacturers of stationary equipment (19). This standard references existing American National Standards Institute, trade, and professional association measurement standards and techniques, to aid in formulating and submitting requests for manufacturer's noise level data. Appendices in ANSI S12.16 provide guidance for interpretation of the data received from the manufacturer.

7.2 Noise Control Materials and Products

When it is not economically feasible to replace an older, noisy machine with a new quieter unit, and it is impossible to move the noise-generating equipment away from employee workstations, many noise control problems can be effectively solved through the proper selection and installation of appropriate commercially available noise control devices, systems, or materials. Once the dominant sources are treated, the new noise environment should be evaluated to determine whether any additional noise control measures are warranted. If sufficient noise reduction is not achieved, the process should be repeated, focusing on the noise sources that have been "uncovered" by the first application of noise control treatments. Standard noise control techniques include the use of sound-absorbing materials, sound-attenuating materials/barriers, mufflers/silencers, vibration isolation devices, and damping treatments. Monthly publications such as *Sound and Vibration* periodically publish a listing of manufacturers of currently-available noise control materials (20).

7.2.1 Absorptive Materials

Absorptive materials convert sound energy into small amounts of heat. The amount of heat generated is quite small since the acoustic power is normally very small. Porous materials such as glass fiber (e.g., standard building insulation), open-cell foam, and acoustical ceiling tile are all examples of sound-absorbing materials. Acoustical performance of these materials is determined by their absorption coefficient (α), which is the fractional amount of sound energy absorbed by a surface. Absorption coefficients are determined by specific laboratory procedures, and are designated as a value between 0.0 and 1.0, which also can be considered as a percentage between 0% and 100%. Materials that are good sound absorbers have absorption coefficients approaching unity. In general, most materials perform better at higher frequencies and are less able to absorb low-frequency sound. The arithmetic average of the sound absorption coefficients of a particular material at 250, 500, 1000, and 2000 Hz provides a single-number rating of the acoustical performance of that material, called the noise reduction coefficient (NRC).

Noisy machinery is often located in large, acoustically reflective areas that reverberate and build up the sound level in the room. Sound-absorbing materials on walls and ceilings are often used to reduce this effect. However, the amount of reduction close to the actual noise source(s) may be slight, because most of the sound energy comes directly from the machines and not from the reflecting surfaces. The type, amount, configuration, and placement of absorption materials depends on the specific application. Correct selection of sound-absorbing materials can be guided by reviewing the absorption coefficients listed in manufacturer's brochures. The National Institute for Occupational Safety and Health (NIOSH) published a very useful *Compendium of Materials for Noise Control* in 1980, and this publication contains data tables as well as further explanation of acoustical absorption applications (21).

7.2.2 Noise Barriers, Enclosures, and Pipe Lagging

Sound is attenuated or "blocked" by materials that have high transmission loss (TL) values. Transmission loss is calculated in decibels, and measurements to determine the TL characteristics of a material must be done in a laboratory, according to specific test procedures. Heavy, dense materials such as concrete, steel, and thick plywood are effective as noise barriers or enclosure walls because they restrict the amount of acoustical energy that can pass through the material to the other side. Also, commercially available heavy acoustic blankets or loaded vinyl curtains are commonly used for partitions and enclosures. The main precaution that must be taken with any enclosure or barrier system is to be sure that there are no unnecessary openings. The effectiveness of an acoustical wall or barrier can be severely degraded even with only a small percentage of open area in an otherwise solid barrier.

The amount of noise reduction that can be attained with a simple noise barrier wall depends on the characteristics of the noise source, the configuration and materials used for the barrier, and the acoustic environment on each side of the barrier. Free-standing noise barrier walls are usually not very effective in indoor situations, due to the ability of the sound to reflect off of nearby surfaces (e.g., the building's walls and ceiling). Essentially, the sound bounces over the barrier with little or no attenuation. Therefore, partial or complete enclosures are used instead to contain the noise produced by both small and large noise sources inside buildings.

Noise radiated from pipelines, valves, and ducts is controlled by wrapping a barrier material around the noise source, which is essentially the same as installing a close-fitting enclosure. This technique is called acoustical lagging, which actually consists of a combination of sound absorption and sound attenuation materials. Typically, a resilient absorptive material is covered with a high transmission loss outer shell, where the absorptive layer essentially de-couples the barrier material from the pipe surface. Often, the entire length of a noisy pipeline or duct must be covered for the treatment to be effective.

7.2.3 Acoustical Silencers

Silencers, also referred to as mufflers, baffles, or sound traps, are installed in air ducts or pipelines to attenuate the noise present in a flowing medium. There are three distinct types of acoustical silencers, although two of the types may be combined into a single device to achieve a particular result. The first type, called absorptive or dissipative silencers, contains a fibrous or porous filler material that absorbs noise energy, without significantly restricting the flow through the silencer. These silencers are used to reduce broadband noise, with greater noise reduction in the higher frequencies, since the internal packing materials are typically better at absorbing high frequency sound waves.

The second type of acoustical silencer is called reactive silencers, which do not contain any kind of absorptive filler. Instead, they cause the sound waves to cancel out by reflecting them back toward the source. Reactive silencers are used in applications such as automotive exhausts, since most absorptive filler materials would eventually disintegrate or become clogged by a high-temperature, particulate-laden exhaust stream. Reactive silencers are useful for reducing low frequency noise, and are often designed or "tuned" to eliminate a certain frequency range.

The third type of commercially available silencers employs active noise cancellation technology, where loudspeakers installed in the pipe or duct produce an inverted sound wave (i.e., 180 degrees out of phase) that reduces the noise through destructive interference with the original wave pattern. These systems are best suited for very low frequency applications, and are particularly effective at reducing pure tones that may be present.

7.2.4 Vibration Isolation

Most industrial equipment and machinery vibrates during operation, and these vibrations can be felt and heard throughout a plant or factory. Vibrations can travel very long distances through solid support columns and beams, and eventually be re-radiated as sound through adjoining walls, ceilings, and floors. Therefore, it is important that the vibrating equipment be adequately isolated from the building structure. Vibration isolators are used to reduce the transmission of shaking forces to an acceptable level. A wide variety of these devices are available as off-the-shelf items or they can be specially designed for a particular application.

Three factors need to be considered when selecting the correct vibration isolator for a specific application: the size and weight of the machine, its movements and speed, and the magnitude of the vibrations it produces. Small machines might only require a cork, felt, or rubber pad for proper isolation, while a large machine may be mounted on specially designed steel springs. In any case, the product supplier or a knowledgeable engineer should be assigned to select the correct vibration mount, since the incorrect use of an isolator can actually make the vibration problem *much worse* if a resonance condition develops.

7.2.5 Vibration Damping

Metal panels or an entire machine casing may generate noise (i.e., the surface may "ring" or resonate) when excited by internal or external vibrations. A damping material may be attached to a vibrating panel or surface in order to reduce the panel motion, and thus reduce the amount of sound that can be radiated. Damping treatments may be thought of as "absorbing" solid-borne sound, by converting the vibrational energy into small amounts of heat. Both steady-state and impact-type noises can be reduced by applying the correct damping treatment.

There are two types of damping treatments: extensional (also known as free-layer or homogeneous) and constrained-layer. The first type is generally used for panels less than one-quarter inch thick, and is typically a sheet of viscoelastic material or a compound that is troweled or sprayed directly onto the vibrating surface. Vibratory energy is dissipated through extension and compression of the damping material as the panel or machine casing bends and flexes. Constrained-layer damping consists of a damping material being "sandwiched" between the vibrating panel and a stiff outer retaining layer, such as aluminum or steel. In this configuration, the damping material dissipates vibratory energy through shear deformation, rather than extension and compression. Constrained-layer systems are usually used for treating very stiff structures, or when the vibrating panel is thicker than one-quarter inch.

8 HEARING PROTECTORS

8.1 General

If personal hearing protectors are properly selected, fitted, and worn, they can provide adequate protection against noise-induced hearing impairment in a high percentage of industrial work areas. In many cases, however, the protective devices are not worn effectively, if at all. Since noise does not have to be painful to be potentially harmful, many employees do not understand the need for wearing hearing protectors. A significant effort must be made to instruct and motivate employees in order to develop and maintain an effective hearing protector management program.

8.2 Types of Hearing Protectors

Hearing protectors usually take the form of either insert-type earplugs that are inserted into the ear and seal against the ear canal walls, or muff-type devices that seal against the head around the ear. There are also concha-seated protectors that provide an acoustic seal right at the entrance to the external ear canal. There is no single "best" type for all individuals or situations. However, some types are better than others for use in specific noise environments, for some work activities, or for some environmental conditions. The 1994 publication "The NIOSH Compendium of Hearing Protection Devices" contains descriptions and laboratory attenuation data for all the HPDs currently marketed in the United States (22).

8.2.1 Insert-Type Earplugs

Several different styles of insert-type earplugs may be required to fit the wide differences in ear canal configurations. This is because ear canals differ in size, shape, and position among individuals and even within the same individual. Typically, ear canals are elliptical-shaped, although some are round, and many have only a small slit-like opening that may open into a larger diameter. Some canals are directed in a straight line toward the center of the head, but most are directed toward the front of the head, and they may bend in various ways. Ear canals can be opened and straightened by pulling the auricle upward and backward, or directly away from the head, making it possible to seat the earplug securely. All earplugs must fit snugly and have an air tight seal to be effective.

8.2.1.1 Molded Earplugs. Molded (or premolded) earplugs are constructed of soft and flexible materials that conform to the shape of the ear canal for a snug, airtight fit. Molded plugs are usually made of a silicon-type material and are available in a variety of styles. Often, these earplugs utilize one or more circular flanges to provide a seal against the canal walls (see Fig. 19.7). Different sizes of molded plugs are available from many manufac-

Figure 19.7. Example of molded earplugs.

turers, since a single size may not adequately fit all ear canal sizes and shapes. Molded earplugs are usually reusable, and will retain their size and flexibility over long periods of time if kept clean with soap and water.

8.2.1.2 Malleable Earplugs. Malleable (or formable) earplugs are made of materials such as silicone putty, wax-impregnated cotton, glass wool, and mixtures of these materials. Typically, a small cone or sphere of the material is hand-formed and inserted into the ear with sufficient pressure so that the material conforms to the shape of the canal and holds itself in position. The manufacturer's instructions should be followed regarding the depth of insertion of the plug into the canal. In all cases, care should always be taken to avoid deep insertions that may cause the material to touch the eardrum. Malleable plugs have the obvious advantage of fitting almost any ear canal, eliminating the need to keep a supply of various sizes, as is necessary for most other types of earplugs.

8.2.1.3 Foam-Type Earplugs. Earplugs made of cylindrical or tapered foam are very popular (see Fig. 19.8). Generally, these plugs must be rolled down and inserted so that most of the plug is in the canal, then held in place while they expand to fill the canal. This insertion process allows the plugs to provide the rated protection level. If these plugs are not inserted properly, their performance may drop significantly. It may not be possible to insert foam plugs properly into some small, sharply bending, or slit-shaped ear canals.

Foam plugs are typically composed of either vinyl or urethane-based material. The vinyl plugs are usually stamped out of sheets of foam material into cylinders, or less commonly, into hexagon-shaped plugs. The urethane plugs are usually tapered and manufactured through a molding process. Both of these materials provide excellent noise attenuation when the plugs are fitted and worn properly. Urethane plugs are typically somewhat softer than the vinyl plugs but may be more expensive due to the more complicated manufacturing process. Foam earplugs are generally comfortable to wear, and are reusable on a limited basis.

8.2.1.4 Custom-Molded Earplugs. A custom-molded earplug is manufactured from an exact impression of the wearer's ear. When made properly, these protectors can be expected to provide among the most consistent protection levels in daily use of all protector types. The initial cost of individually molded protectors is relatively high, but most should last

Figure 19.8. Example of foam-type earplugs.

a long period of time. A unique advantage of custom-molded hearing protectors is the capability of venting the protector to adjust the level of attenuation provided. The venting process involves manufacturing the plugs with a small hole completely through the plug, and inserting various types of dampers in the hole. These vented plugs can enhance communication in moderate-level noise environments where maximum attenuation is not required.

8.2.2 Concha-Seated Protectors

Protectors that provide an acoustic seal in the concha (i.e., the bowl part of the external ear) and/or at the entrance to the ear canal can be referred to as "canal caps," or concha-seated, semi-aural, or semi-insert, devices (Fig. 19.9). This class of hearing protectors makes use of various plug shapes attached to a lightweight headband that holds the plugs at the entrance of the external ear canal. The performance and comfort of this kind of protector varies significantly among different models.

8.2.3 Earmuffs

Many manufacturers of muff-type hearing protectors (Fig. 19.10) offer a choice of two or more models having different physical characteristics. Generally, larger and heavier earmuffs provide greater protection, but may not be comfortable to wear for long periods of time. Conversely, lightweight protectors may be accepted by the wearer more readily than

Figure 19.9. Example of concha-seated hearing protectors.

Figure 19.10. Example of earmuffs.

the larger ones, but may not provide as much attenuation. The force applied by muff suspensions is often directly related to the level of noise attenuation provided. On the other hand, the wearing comfort of a muff-type protector is generally inversely related to the suspension forces—thus a compromise must be made between performance and comfort.

Earmuff cushions are generally made of a smooth, plastic envelope filled with a foam or fluid material. Because skin oil and perspiration can have adverse effects on cushion materials, these cushions can tend to become stiff or brittle over time and require periodic replacement. Earmuffs normally provide less protection when worn over hair or glasses. If long coarse hair or other significant obstructions cannot be avoided, it may be advisable to use earplugs.

Earmuffs are sometimes chosen because their use can be monitored from greater distances than insert-type protectors. They are also easier to fit than insert types because one size fits most wearers. Comfort is also better for muff-type protectors in some work areas; however, earmuffs may be very uncomfortable to wear in hot work areas, particularly when the work involves a vigorous activity. Muff-type protectors may also be a poor choice when work is performed in areas having limited headroom.

In addition to the standard passive-attenuation earmuffs, several types of electronic earmuffs are currently available. These include muffs with electronic clipping circuits and those with noise-canceling circuits. The clipping circuits typically have a microphone on the outside shell of one or both muff cups; this microphone senses the sound outside the protector and provides input to an internal amplifier. The amplifier is connected to a speaker inside the earcup to let the wearer hear the ambient sounds at a safe level (usually limited to about 85 dBA). In some of these devices, equalization is performed on the signal to enhance the speech frequencies. Noise-canceling or active noise reduction (ANR) earmuffs use a microphone to sample the noise, then reverse the phase of the sampled signal and play back the out-of-phase signal into the earcup through a small speaker. The magnitude of the attenuation provided by noise-canceling circuits is greatest at low frequencies, and there are usually no noise-canceling effects at frequencies above about 1000 Hz. In fact, some of these devices unintentionally provide a small amount of amplification in a narrow frequency range at around 1000 Hz. Active noise cancellation is an evolving technology, and the future will likely bring better performance with a lower cost for these devices.

8.2.4 Advantages and Disadvantages of Protector Types

Earplugs, earmuffs, and canal caps all have distinct advantages and disadvantages. Insert-type protectors are convenient to carry and store, and can be worn effectively without interference from eyeglasses, headgear, earrings, or long hair. They are practical to wear in hot environments and do not restrict head movement in close quarters. The initial cost of earplugs is usually significantly less than muffs or canal caps, although in the long-term the overall cost depends on how often employees replace their earplugs. Plugs may not be appropriate for use in very dirty areas since dirt or foreign substances from one's hands may be introduced into the ear canal during insertion. For this reason, malleable and foam-type plugs (and to a somewhat lesser extent, all earplugs) may be a poor choice if the work area is excessively dirty, and intermittent noise levels make it desirable to frequently remove HPDs. Also, earplug use is more difficult for supervisors to monitor because earplugs cannot be easily seen from a distance.

Almost all insert protectors require more time and effort for proper fitting than do earmuffs, and a small percentage of employees cannot effectively wear any off-the-shelf plugs due to an improper fit. The amount of protection provided by earplugs is more variable between wearers than that of muff-type protectors. On the other hand, muffs are usually easy to fit properly and they provide relatively consistent attenuation across users. However, in addition to being uncomfortable in hot environments, muff-type protectors may be inconvenient to wear with safety glasses, welding helmets, etc. Also, earmuffs may feel cumbersome or restrict head movement in close quarters. Misuse of muffs has been documented, with users deliberately bending the headband to reduce pressure on the skull, which can lead to a significant reduction in the amount of protection. Concha-seated ear canal caps also tend to exert a substantial amount of pressure on the head, and therefore are usually better suited for brief, intermittent noise exposures. If individuals are permitted to fit themselves, they often select the type/size of hearing protector on the basis of comfort rather than on the amount of protection provided.

8.3 Hearing Protector Ratings

In most cases, hearing protector attenuation is determined by conducting tests on human subjects, where hearing tests are taken by a panel of listeners with and without the protector in place. This test method is referred to as Real-Ear Attenuation at Threshold (REAT). First, thresholds are determined with a listener's ears open, then another hearing test is administered with the subject's ears occluded by the HPD being evaluated. The decibel difference between the open-ear threshold and the occluded-ear threshold indicates the amount of sound attenuation provided at each test frequency. A detailed description of the test facility and procedures required to accurately use this technique can be found in ANSI S12.6-1997, "Methods for Measuring the Real-Ear Attenuation of Hearing Protectors" (23).

In 1975, NIOSH published a "List of Personal Hearing Protectors and Attenuation Data" which contains attenuation rating methods known as NIOSH methods #1, #2, and #3 (24). Method #1 (a.k.a "long method") is generally regarded as the most accurate, although it is the most complex method since it uses the largest amount of spectral information from the actual noise environment. The steps for calculating the amount of protection provided by a hearing protector using NIOSH method #1 are as follows:

1. Measure and record the octave band exposure levels.
2. Adjust the octave band values with the A-frequency weightings. The overall A-weighted sound exposure level (L_A) for unprotected ears is equal to the logarithmic sum of the octave band levels.
3. Record the mean hearing protector attenuation values supplied by the protector manufacturer and two times the corresponding standard deviation value.
4. Subtract the mean attenuation values from the corresponding A-weighted sound levels, then add the two standard deviations to the result to obtain the A-weighted exposure levels under the protector.

5. Combine the A-weighted exposure levels to obtain an estimate ($L_{A(\text{protector})}$) of the highest sound pressure level to which a population of wearers of this protector would be exposed 97.5% of the time if the protectors are fitted and worn properly.

A simplification of the second NIOSH method (NIOSH method #2) was adapted by the Environmental Protection Agency (EPA), and is called the Noise Reduction Rating (NRR). The NRR is a single-number rating that is required by law to be shown on the label of each hearing protector sold in the United States (25). It is intended to describe how much noise reduction a particular protector can provide. The values of sound attenuation used for calculation of the NRR are determined in accordance with ANSI S3.19-1974, "Method for the Measurement of Real-Ear Hearing Protector Attenuation and Physical Attenuation of Earmuffs" (26). It should be noted that ANSI S3.19 was revised and published in 1984 as ANSI S12.6, "Method for the Measurement of the Real-Ear Attenuation of Hearing Protectors" (27). Further, ANSI S12.6 was updated in 1997 and renamed "Methods for Measuring the Real-Ear Attenuation of Hearing Protectors," which contains the most current methodology (23). However, even the earlier version of ANSI S12.6 was adopted after the EPA hearing protector labeling laws were written, and since the EPA regulations did not make any provision for adopting newer standards, hearing protector manufacturers must still use the older S3.19 method for labeling purposes.

To determine the NRR, the experimenter (not the test subject) must fit the hearing protector for each occluded test run. The formula for calculating the NRR is

$$\text{NRR} = L_{C(\text{pink noise})} - L_{A(\text{protector})} - 3 \tag{14}$$

The first term of the equation ($L_{C(\text{pink noise})}$) is always 107.9 dBC, which is obtained by assuming a level of 100 dB SPL in each of the nine octave bands from 125 to 8000 Hz, subtracting the C-weighting corrections, and logarithmically summing to calculate the overall C-weighted level at the unprotected ear. Next, A-weighting corrections are subtracted from the pink noise octave band levels to calculate the A-weighted octave band levels at the ear. Two standard deviations are subtracted from the average attenuation at each frequency, which yields the protected A-weighted octave band level at the ear. (An adjustment of two standard deviations provides an NRR that 97.5% of the subjects will theoretically meet or exceed, provided that the wearers use the HPD in the manner that the laboratory subjects did.) The overall protected A-weighted level at the ear is determined by adding the individual octave band levels. Finally, the NRR is computed by subtracting 3 dB from the difference between the unprotected C-weighted and the protected A-weighted levels at the ear. Subtracting this additional 3 dB accounts for spectral uncertainty, since the pink noise used in the calculations may not actually match the noise environment where the hearing protector is being worn.

A worker's noise exposure when wearing the hearing protector is estimated by subtracting the NRR from the ambient C-weighted sound level (not the A-weighted sound level). For example, if a protector has an NRR of 20 dB and is used in a work area where the noise level is 95 dBC, the amount of noise entering the ear could be expected to be 75 dBA or lower in 97.5% of the cases.

Accuracy is lost when calculating hearing protection if only A-weighted sound pressure levels are known, since the NRR is based on a flat spectrum. When only A-weighted ambient noise levels have been measured, a 7 dB safety factor must be subtracted from the NRR to determine the exposure under the hearing protector. In this case, a person working in 93 dBA noise while wearing an HPD with an NRR of 20 dB can be expected to be receiving 80 dBA at the ear.

Hearing protectors are often selected with consideration being given only to the magnitude of the NRR. Although a single-number rating is useful in initiating a program when more precise octave-band noise measurement data are not available, its use requires significant safety factors because of the inherent lack of precision. A fundamental weakness of the NRR is that it can end up being based on just one or two of the nine one-third octave-band test signals used in the laboratory measurements. Generally, the controlling test signals are at or below 1000 Hz, and performance levels for other test signals may have little or no effect on the NRR. For example, two protectors may have the same NRR because of their limiting attenuation values at 250 or 500 Hz, but one of these protectors may provide 15 dB greater protection than the other at higher frequencies. The NRR values in this example would be a reasonably accurate assessment of protector performance if the primary noise source were centered at 250 or 500 Hz; however, if the noise exposures contain prominent high-frequency components, the NRR values may be very misleading.

Another limitation of the NRR is that attenuation values obtained from laboratory testing tend to over-estimate the amount of protection received by individuals during everyday use. This is not surprising, considering that well-trained and highly motivated individuals are normally used in the laboratory as subjects, and the experimenter directly fits the HPDs prior to testing. This discrepancy has led to the development of de-rating procedures that are applied to laboratory data. A prior OSHA directive called for dividing the labeled NRR by two (i.e., a 50% de-rating) before calculating exposure under the protector (28). The *Criteria for a Recommended Standard: Occupational Noise Exposure*, published by NIOSH in 1998, suggested de-rating the NRR on earmuffs by 25%, formable/foam earplugs by 50%, and molded earplugs by 70% (15). Currently, OSHA's Technical Manual permits the NRR Subject Fit (SF) value to be used for hearing protector evaluation, without any de-rating factor applied (29).

The NRR (SF) is determined from Method B procedure (which is outlined in the newest version of ANSI S12.6), and typically yields lower protection values that are expected to be closer to the "real-world" values than those obtained with ANSI S3.19. A significant difference between the older S3.19 and the S12.6 Method B procedures is that the test subjects don the protectors themselves according to the manufacturer's instructions, and testing is conducted with minimal experimenter involvement. Another feature of S12.6 Method B is that since the NRR (SF) is based on A-weighted sound levels, the 7 dB A-weighting-to-C-weighting correction is not necessary, and HPD selections can be based directly on A-weighted exposure measurements.

European hearing protector tests are performed according to the International Standard ISO 4869-1 (30). In Europe, the most common single-number rating of hearing protector performance is the Single Number Rating (SNR). The SNR has the same pitfalls as the NRR, although it is somewhat less sensitive to outlier data during the laboratory testing. The European market also utilizes a three-number rating system, called the high-middle-low, or HML, system. The three numbers in the HML rating estimate the attenuation provided in the high test frequencies, middle test frequencies, and low test frequencies, respectively. The HML values are used in conjunction with measurements of A- and C-weighted sound pressure levels to obtain the HPD attenuation that can be expected in specific noise environments.

8.4 Performance Limitations

A primary limitation to protection afforded by a hearing protector is the way it is fitted and worn. Other important limitations of a hearing protector depend upon its construction and on the physiological and anatomical characteristics of the wearer. Sound energy may reach the inner ears of persons wearing protectors by four different pathways: (*1*) by passing through bone and tissue around the protector; (*2*) by causing vibration of the protector, which in turn generates sound into the external ear canal; (*3*) by passing through leaks in the protector; and (*4*) by passing through leaks around the protector. These pathways are illustrated in Figure 19.11.

Even if there are no acoustic leaks through or around a hearing protector, some noise reaches the inner ear by bone and tissue conduction or protector vibration if noise levels are sufficiently high. The practical limits set by the bone- and tissue-conduction threshold vary significantly among individuals and among protector types, generally from about 40 to 55 dB. Limits set by protector vibration also vary widely, generally from about 25 to 40 dB, depending upon the protector type and design and on the materials used. Contact surface area and compliance of materials are major contributing factors. If hearing protec-

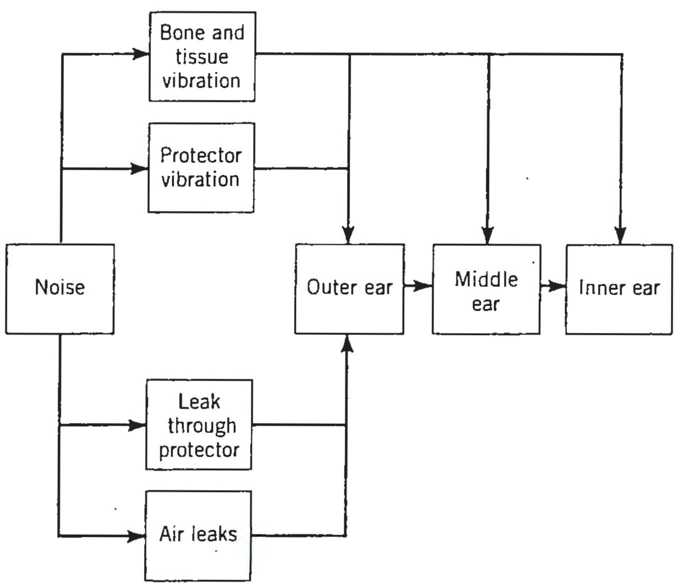

Figure 19.11. Noise pathways to the inner ear.

tors are to provide noise reduction values approaching practical limits, acoustic leaks through and around the protectors must be minimized by proper fitting and wearing.

Perhaps the major reason why hearing protective devices fail to protect employees from noise exposure is because the protector is not always worn when it should be. Workers fail to wear hearing protection for reasons of comfort or communication, or because the HPDs were misplaced or forgotten. Whatever the reason, failure to wear hearing protection for even a small fraction of a workshift will greatly reduce the effective protection. For instance, an HPD with a Noise Reduction Rating (NRR) of 25 not worn for 30 minutes out of an 8-hour workday will lose nearly 8 decibels of effective attenuation (see Fig. 19.12).

8.5 Moderate Attenuation and Flat Attenuation Hearing Protectors

Many purchasers of hearing protection have fallen into the trap of thinking that a higher NRR is always better. However, a moderate amount of attenuation rather than using a device with the highest available NRR may afford adequate protection in many industrial noise environments. In most cases, moderate attenuation protectors are more likely to be acceptable for use in noises having major components above 1000 Hz. The simplest of these devices are vented with a small hole through the protector, permitting low frequencies (below about 1000 Hz) to pass without significant attenuation.

More recently, flat (or uniform) attenuation hearing protectors have been introduced, in both muff and insert styles. A flat attenuation device "distorts" the incoming sound less than a conventional HPD since approximately equal attenuation is provided across all frequencies. This is in contrast to most hearing protectors, where more attenuation is provided in the high frequencies, and, consequently, the balance between the low and high

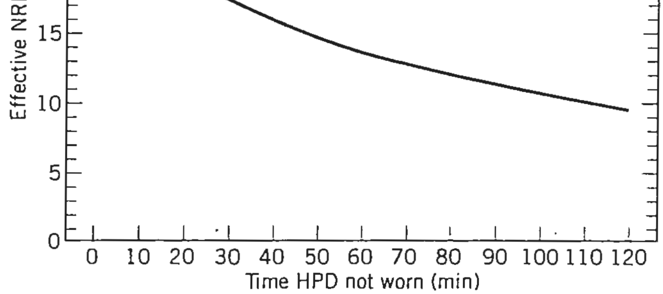

Figure 19.12. Effective NRR when an HPD with an NRR of 25 dB is not worn full-time.

frequencies is altered. Flat attenuation earplugs are sometimes referred to as musician's plugs, as they are intended to maintain the music's spectral balance while providing a moderate amount of sound attenuation. Thus, the resulting effect is that all frequency components of the music are heard, but at a uniformly reduced level. Industrial workers can also benefit from these types of HPDs, since machine/equipment sounds can essentially be heard undistorted. It is important to note that if these protectors are not fitted properly, it is likely that the low-frequency attenuation will decrease, and the overall attenuation will not be as uniform as intended.

8.6 Double Hearing Protection

The combined attenuation from wearing both a muff-type and an insert-type protector cannot be accurately predicted because of complex coupling factors. It is not correct to simply add the two NRRs to determine the overall expected noise reduction. If the attenuation values of the muff and insert protectors are about the same in a frequency band, the combined attenuation should be approximately 3 to 6 dB greater than the higher of the two individual values. If one of the two protectors provides significantly greater attenuation in a specific frequency range, the increased attenuation provided by double protection in that range will be minimal. In practice, 5 dB is typically added to the higher labeled NRR value to determine the protection afforded by wearing double hearing protection.

8.7 Hearing Protectors and Communication

Performance and safety aspects of a job often depend on a worker's ability to hear warning signals, machine sounds, and speech in the presence of high noise levels. Therefore, interference with communication is one of the most common and legitimate complaints related to hearing protector use. The effect of noise on communication depends to a large extent on the spectrum of the noise, the hearing ability of the worker, and the attenuation characteristics of the particular hearing protectors in use.

Hearing protectors attenuate both speech and background noise by equal amounts, and therefore should not adversely affect the speech reception ability of normal-hearing listeners. In fact, wearing hearing protection in high noise areas (above 85 dBA) actually improves speech recognition by lowering the overall sound level reaching a listener's ear, which reduces the potential for auditory distortion. There are situations, however, where a particular hearing protector may attenuate high frequencies substantially more than the low frequencies. In these cases, the residual low frequency sounds will mask or obscure the high frequency components, and cause the important consonant sounds to be unintelligible. Similarly, when hearing-impaired employees wear hearing protection, the higher-frequency sounds may be attenuated to a point below the level of audibility. Therefore, too much attenuation (i.e., inadequate hearing protector selection, or the use of hearing protection in areas with sound levels below 80 dBA) may be the cause of communication problems for normal-hearing as well as hearing-impaired employees. Optimal communication is usually achieved when the protector's attenuation characteristics are matched to those of the noise spectra.

To address the above issues, hearing protectors should be selected that provide sufficient protection against noise-induced hearing loss without unnecessarily inhibiting the natural perception of warning signals, machine operating sounds, speech, etc. Unfortunately, until recently, few hearing protectors were selected and purchased with any thought being given to user communication. Overprotection may be considered as acceptable, even desirable, against many health and safety hazards, but overprotection against noise exposure may cause significant communication problems and can also lead to the deliberate misuse or rejection of hearing protectors.

One European guidance document, EN 458, entitled "Hearing Protectors-Recommendations for Selection, Use, Care, and Maintenance," addresses the issue of selecting hearing protectors that maximize the ability to communicate in a noisy environment (31). This document includes several methods of HPD selection, including the octave band method, the HML method, the HML Check, and the SNR method. Recommendations for hearing protector attenuation are based on the relationship between exposure under the protector and allowable exposure criteria in dBA. Five HPD selection categories ranging from insufficient protection to overprotection are described, depending on how closely the exposure under the protector and allowable exposure criteria are matched. The underlying principle for these guidelines is that properly fitted individuals are more likely to wear their protectors consistently since they will not be unnecessarily "isolated" from other workers, and they will be less likely to intentionally disable protectors to decrease attenuation.

8.8 Field Monitoring Systems

For insert-type protectors, field monitoring systems are available that essentially replicate the laboratory tests as defined in ANSI S3.19-1974, except that the stimuli are presented via headphones instead of through loudspeakers in a diffuse sound field. Hearing thresholds of the HPD wearer are measured at selected test frequencies with and without the HPD in place, and the difference in hearing threshold at each test frequency is equal to the amount of noise attenuation provided by the hearing protector. For muff-type protectors, existing field measurement systems include a hand-held microprocessor-based unit that utilizes two microphones, one located at the entrance to the ear canal and the second located outside the cup of the muff. A digital readout displays the difference in sound pressure level between the two microphones. These units are designed to be used at the employee's workplace; therefore, the attenuation measured will be accurate while the wearer is in that particular noise exposure. Use of the protector in noises with differing spectral characteristics will affect the amount of noise attenuation provided.

Field monitoring systems for hearing protectors are designed to allow the measurement of attenuation provided by hearing protectors *on the individual wearer*. This personalized approach eliminates the need for single-number ratings (e.g., NRR) and the rough approximations associated with them. Again, the NRR is derived from laboratory test methods designed to estimate attenuation afforded to a population, not to an individual. Current laboratory performance ratings represent a best-fit situation using trained and motivated subjects under closely supervised conditions, and do not always correlate with the attenuation achieved in field situations.

Individual measurement systems are, in general, well-received by HPD wearers. The employees are typically interested in how the protectors function, and they appreciate the attention to their individual needs. Individual HPD attenuation measurements are particularly valuable as a training tool during the initial selection of insert-type HPDs. Assistance can be provided to the wearer during initial fitting, and an on-the-spot attenuation measurement can be obtained. If the measured attenuation is insufficient, the employee should re-fit the HPD and repeat the measurement procedure until a satisfactory result is achieved. These measurements document that adequate and proper protection was provided to the worker,, and empower employees to take on the responsibility of effective HPD usage.

Field measurement systems perform several functions for the industrial hearing conservation program administrator, including: (*1*) training of wearers in correct fitting procedures, (*2*) random as well as routine (e.g., annual) field sampling of protector effectiveness, (*3*) documentation that training was provided and that proper protection was provided to the employee, and (*4*) identification of failing or deteriorating protectors and changes in ear physiology. Careful hearing protector selection and periodic checks with a field monitoring system should result in a successful hearing protector management program.

9 HEARING CONSERVATION PROGRAMS

9.1 Specific Requirements

The objective of a Hearing Conservation Program (sometimes referred to as a Hearing Loss Prevention Program) is to prevent noise-induced hearing loss. This obvious fact is often forgotten, or ignored, when pressures are applied for compliance with local, state, or federal noise regulations. Simply handing out earplugs or providing yearly hearing tests is not sufficient to conserve employees' hearing. As described in the OSHA Hearing Conservation Amendment, an effective hearing conservation program should provide for (7):

1. The identification of noise hazardous areas, and the determination of employee noise exposures.
2. The measurement of exposed persons' hearing thresholds through monitoring audiometry.
3. The establishment of a personal hearing protection plan, including provisions for evaluating the effectiveness of hearing protectors.
4. The training of employees about the need for hearing conservation, and the instruction of employees in the use and care of personal hearing protectors.
5. The maintenance of accurate and reliable records of hearing tests and noise exposure measurements.

9.1.1 Identification of Noise Hazardous Areas and Employee Monitoring

Noise exposure monitoring is necessary to identify employees that should be included in the hearing conservation program. Whenever employee noise exposures equal or exceed the action level (i.e., 8-hour TWA of 85 dBA, or, equivalently, a dose of 50%), they must be included in the program. Although a specific sampling strategy is not described in the regulation, the monitoring procedures must be able to identify noise-exposed employees and also enable the proper selection of hearing protectors. If employees are stationary throughout their workshift and the noise environment does not fluctuate, area monitoring is sufficient to characterize the daily noise exposure. However, a more likely scenario is that employees will be mobile and sound levels will vary somewhat, which makes personal dosimetry sampling a more practical method. All continuous, intermittent, and impulsive sound levels from 80 to 130 dBA must be integrated into the noise measurements. Monitoring must be repeated whenever a change occurs in the production process, equipment, or noise control devices, which could change the number of exposed workers or require the use of a different type of hearing protector.

9.1.2 Audiometric Testing Program

A baseline audiogram must be established within six months of an employee's first exposure at or above the action level. All subsequent audiograms are compared to the baseline audiogram to determine if changes have occurred in the worker's hearing ability. When mobile test vans are used to conduct hearing tests, the employer has one full year to establish the baseline audiogram. If the baseline is not obtained within the first six months of that year, employees must wear hearing protection for the remaining time period until the baseline audiogram is obtained. Employees must avoid occupational as well as non-occupational noise for at least 14 hours prior to baseline testing. If this is not possible, hearing protection should be worn to reduce any noise exposures before the baseline audiogram is conducted.

Annual audiograms must be administered to all employees who are exposed to an 8-hour TWA of 85 dBA or greater. Annual hearing tests provide the most information when conducted sometime during the middle of the workshift. The reason for this is that incorrectly fitted hearing protection may cause the employee to sustain a temporary threshold shift (TTS) that day, which can be identified when a comparison to the baseline audiogram is made. Identifying this temporary condition at the time of the annual hearing test and re-instructing the individual on the proper use of hearing protection can help prevent a permanent threshold shift (PTS) in the future.

As defined by OSHA, a Standard Threshold Shift (STS) is a persistent change in hearing threshold relative to the baseline audiogram of an average of 10 dB or more at 2000, 3000, and 4000 Hz in either ear. Allowances for age corrections are permitted when determining an STS, according to the procedure described in Appendix F of the OSHA regulation. If an STS occurs, the employer may obtain a retest within 30 days, and consider those results as the annual audiogram. In practice, a retest is justified in most cases when a STS is found, because there are many common reasons why a temporary loss of hearing sensitivity may occur. However, if the retest confirms the STS, it must be reported in writing to the affected employee within 21 days. Also, unless a physician determines that the STS is not work-related, the employer must ensure the following steps are taken:

1. Employees not currently using hearing protection must be fitted with hearing protectors, trained in their use and care, and be required to use them.

2. Employees already using hearing protection must be refitted and retrained in the use of hearing protectors, and be provided with protectors offering greater attenuation, if necessary.
3. Employees must be referred for a clinical audiological evaluation or an otological examination (as appropriate) if additional testing is necessary or if the employer suspects that a medical pathology of the ear is caused or aggravated by the wearing of hearing protectors.
4. Employees must be informed of the need for an otological examination if a medical pathology of the ear that is unrelated to the use of hearing protectors is suspected.

New baselines may be established if the audiologist or physician in charge of the hearing conservation program determines that an STS is persistent, or if the annual audiogram indicates significant improvement over the baseline audiogram.

9.1.3 Hearing Protectors

According to the OSHA standard, hearing protection must be made available to employees when their daily noise exposures equal or exceed the 85 dBA action level. The regulation specifies mandatory hearing protection for those employees with a daily noise dose equal to or greater than 100%, which is equivalent to an 8-hour TWA of 90 dBA. Hearing protection is not absolutely required for employees with TWAs less than 90 dBA; however, it is mandatory for employees with a daily exposure between 85 and 90 dBA who have experienced an STS.

Job performance, worker health and safety, morale, and the overall effectiveness of a hearing conservation program may be adversely affected if attention is not given to correct hearing protector selection. Employees must be given a choice of different types of protectors, although the regulation does not explicitly state exactly how much of a variety should be provided. Typically, an employer will offer two or more types of earplugs, and at least one style of earmuff. Whichever type is selected, the employer must ensure proper fitting and usage, and provide training and supervision to employees. Further, the employer must evaluate hearing protector attenuation for the specific noise environments in which the protector will be used. Hearing protectors must attenuate employee exposures down to a TWA of 90 dBA, or 85 dBA for workers who have previously suffered an STS. Appendix B in the OSHA regulation describes the acceptable evaluation methods that can be used. The most convenient method is to use the protector's NRR, and perform a few simple calculations either using A- or C-weighted noise measurements. The adequacy of hearing protector attenuation must be re-evaluated whenever employee exposures increase to the extent that the current devices may no longer provide sufficient attenuation.

9.1.4 Training Program

A hearing conservation program cannot be entirely effective unless each individual limits his or her noise exposure both at work and away from work. All hearing conservation programs must emphasize the need for constant awareness of noise hazards through a continuing education effort. The OSHA standard requires employers to institute a training program for all employees who are exposed to noise at or above the 85 dBA action level. This training must be repeated annually, and should be updated to be consistent with changes in available hearing protection and on-site work processes. Instruction must be provided on:

1. The effects of noise on hearing,
2. The purpose of hearing protectors, the advantages, disadvantages, and attenuation of various types, and instructions on selection, fitting, use, and care,
3. The purpose of audiometric testing, and an explanation of the test procedures.

Hearing conservation measures away from work can be encouraged or assisted by lending or giving hearing protectors to employees for use during noisy activities at home. The cost of supplying hearing protectors for non-occupational uses may be far less than potential worker's compensation costs, and often directs more positive attention to the hearing conservation program at work.

9.1.5 Recordkeeping

OSHA requires that audiograms be retained for the length of employment for the affected employee. Audiometric records must include the employee and examiner's names, employee's job classification, date of the audiogram, date of the last equipment calibration, and the employee's most recent noise exposure assessment. The employer must also keep a record of the background sound pressure levels in the audiometric test room.

According to the regulation, noise exposure measurements must be retained for two years. In many cases, companies will save records indefinitely, even after an employee is terminated. These records could be invaluable if there is ever a question of legal responsibility for an employee's hearing impairment, or if the employee is expected to return to this job in the future. Both the employer and employee benefit from having complete medical records retained after the employee is terminated, for reasons including compensation claims and general health references.

9.2 Setting up a Hearing Conservation Program

Setting up a hearing conservation program entails the development and maintenance of all of the factors mentioned in the preceeding sections. Ideally, a team made up of management, industrial hygiene, preventive medicine, safety, and production personnel will work together toward building an effective hearing conservation program. The first objective for this group would be to become aware of their specific problem areas within the facility, and to consider possible ways of limiting noise exposure levels as much as is practical.

In practice, these teams may function only as advisors on general items such as company policy. Many successful hearing conservation programs have been highly dependent upon the competence and dedication of one single person who is given the time and support required to develop and maintain the program. This individual must be motivated and knowledgeable, and be respected by both management and workers. Extensive formal training in any specific field is not usually necessary, but he or she must have a good practical knowledge of noise-induced hearing impairment, hearing testing requirements, and personal hearing protectors. If a single dedicated person is not available for this job, it may be necessary to use a hearing conservation committee to establish general policies and to appoint different individuals to be responsible for carrying out particular assignments. Generally, it is highly desirable to have well-defined tasks given to each individual.

The development of effective and practical hearing conservation programs has proven to be difficult. Many ineffective programs remain even after years of effort. Two major reasons for poor programs are

1. The responsibility for the program is given to a person within the company who is already overburdened with other tasks, and essentially no support is allotted for a hearing conservation program.

2. The responsibility for the hearing conservation program is contracted to an outside firm, and nobody within the plant acknowledges ownership of the program. One of the apparent reasons for hiring an outside firm is to transfer responsibility for the hearing conservation program to the contractor. However, problems may arise when the employer does not take the time to fully understand the requirements of a comprehensive hearing conservation program. This often leads the employer to believe that the contractor is handling the entire program, but in reality the contractor satisfies only one or two requirements (e.g., hearing tests, noise measurements), and the remainder of the program is left incomplete. Money is spent inefficiently and, without the benefit of a complete program, employees may continue to suffer hearing impairment.

Outside firms can be useful for specific jobs, such as conducting annual hearing tests, noise exposure measurements, or noise control projects, although the responsibility for developing an effective hearing conservation program must be accepted by the employer. At least one person within the company who has overall knowledge of the essential components of the company's operations must work with any outside contractors that are used. The company representative must have knowledge of internal production processes, work schedules, company politics, and so forth. An outside firm or individual cannot be expected to know these things, nor is an outside party likely to have the deep interest in the employees' or the company's well-being that an employee should have. Also, an employee is usually the only logical person to maintain the program continuously after it is first established.

Personnel and work conditions may vary widely between plants, or from one work area to another within the same facility. Significant differences are found in management/employee relationships, and in motivation, education, and communication skills of hearing conservationists from one location to another. As a result, a program that works well in one place may fail in another. Therefore, it is generally necessary to develop a unique program for each situation, if it is to be effective.

Obviously, top management must support the program, and others in middle management should be enthusiastic and knowledgeable. Perhaps even more important are the shift supervisors, safety officers, and the plant nurses. These key individuals often have the respect of all workers, and they may be the only persons at the plant with whom some employees will communicate freely. The first-line supervisor must be genuinely concerned about the health and safety of the employee and be able to answer questions about the effects of noise exposure, the use of safety equipment, and the overall importance of the program.

9.3 Hearing Conservation Program Evaluation

The OSHA noise regulation does not prescribe a method to determine absolutely whether a hearing conservation program is effective or not. At a minimum, an audit of all essential elements should be conducted, and a checklist should be used to ascertain compliance with the OSHA regulation. However, the real test of effectiveness is to look closely at the amount of hearing loss that is occurring. Ideally, the number of STSs will be zero, which generally indicates a successful program.

Evaluating the hearing conservation program from a group perspective rather than looking at each individual may help to identify an ineffective program before large threshold shifts occur for many individuals. Audiometric database analysis (ADBA) techniques have been developed for this purpose, and are presented in ANSI S12.13-1991, Draft American National Standard for Evaluating the Effectiveness of Hearing Conservation Programs (32). The scope of this standard, as well as other epidemiological methods, is to specify procedures for systematically assessing the effectiveness of hearing conservation programs in preventing noise-induced hearing loss based on the results of regular monitoring audiometry for noise-exposed employees. When ADBA results show undesirable trends, the follow-up action involves changes in overall program policies or procedures, rather than changes in the treatment of individual employees.

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