

OHTA503

NOISE - Measurement and its Effects

STUDENT MANUAL

2023



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SYMBOLS & ABBREVIATIONS

a	- absorption. Unit: m^2 , ft^2 or metric Sabines
A	- A frequency weighting (or filter) that corresponds with the response of the human ear
A_{total}	- attenuation at each octave band for outdoor sound propagation, composed of A_{div} (geometrical divergence), A_{air} (air absorption), A_{env} (environmental effects) and A_{misc} (miscellaneous other factors). Unit: dB
ACGIH	- American Conference of Governmental Industrial Hygienists
AI	- articulation index. Unit: dimensionless
AIHA	- American Industrial Hygiene Association (USA)
AMA	- American Medical Association (USA)
ANSI	- American National Standards Institute (USA)
ARHL	- age related hearing loss
ASA	- Acoustical Society of America. Also, until 1966, American Standards Association (USA)
AS	- Australian Standard
AS/NZS	- joint Australian and New Zealand Standard
ASHRAE	- American Society of Heating, Refrigerating and Air-Conditioning Engineers (USA)
ASTM	- American Society for Testing and Materials (USA)
BOHS	- British Occupational Hygiene Society
c	- speed of sound at sea level [344 m/s , 1128 ft/s @ 20°C]. Unit: m/s , ft/s
C	- C frequency weighting (or filter) that is essentially flat over the range of interest for occupational noise
CNEL	- community noise equivalent level. Unit: dBA
CAOHC	- Council for Accreditation in Occupational Hearing Conservation
COHC	- Certified Occupational Hearing Conservationist (by CAOHC in USA)

SYMBOLS & ABBREVIATIONS (Cont'd)

cps	- cycles per second (also see hertz)
D	- noise dose as a percentage of maximum permitted daily noise dose
dB	- decibel
dBA	- decibel measured using A frequency-weighting (also see L_A). Note: may also be written as dB(A).
dB(C)	- decibel measured using C frequency-weighting (also see L_C). Note: may also be written as dB(C).
DNL	- day-night average sound level (A-weighting implicit). Unit: dBA (also see L_{dn})
EAT	- A-weighted sound exposure with measurement time period, T. E_{CT} denotes C-weighting. (Note: reporting of T is optional). Unit: Pa^2h
EC	- European Community
EPA	- Environmental Protection Agency (USA)
f	- frequency (cycles per second). Unit: hertz (Hz)
f_c	- center frequency; unit: Hz
FFT	- Fast Fourier Transform which usually transforms from time domain to frequency domain
F-MIRE	- Field Microphone in real ear
h	- hour
HCP	- hearing conservation programme
HL	- hearing level. Unit: dB
HPD	- hearing protection device
Hz	- hertz (cycles/second; also see cps)
HML	- High, Medium, Low, hearing protector rating. Unit: dB

SYMBOLS & ABBREVIATIONS (Cont'd)

I	- sound intensity. Unit: watts/m ²
I _{ref}	- reference sound intensity (10 ⁻¹² w/m ²)
IEC	- International Electrotechnical Commission
IL	- insertion loss. Unit: dB
ISO	- International Organization for Standardization
kHz	- kilohertz
L _A	- A-weighted sound level. Unit: dBA
L _{Aeq,8hr}	- A-weighted equivalent-continuous sound level, also called average sound level,-with 3-dB exchange rate, normalized to 8 hours. Same as L _{EX,8h} as defined in ISO 1999, and L _{EP,d} as defined in UK and sometimes written as L _{A8h} . Contrast with L _{eq,T} which is a non-normalized quantity. Unit: dBA
L _{AE}	- sound exposure level with A-weighting. Unit: dBA (also see SEL)
L _{Aeq,T}	- see L _{eq,T}
L _{AF(t)}	- A-weighted and fast response sound level as a function of time. Use of S instead of F denotes slow response. Unit: dBA
L _C	- C-weighted sound level. Unit: dBC
L _{dn}	- day-night average sound level (A-weighting implicit), use of L _{Adn} is optional. Unit: dBA (also see DNL), as defined by the U.S. EPA.
L _{den}	- day-evening-night noise indicator (A-weighting implicit), as specified in European Directive 2002/49/EC, and used to assess noise for overall annoyance. (Note – as of this publication date the EC has not specified the assessment method and has deferred the definition to Member States and their legislation.)
L _{eq,T}	- equivalent-continuous sound level, also called average sound level, during time period T, using a 3-dB exchange rate. Weighting must be specified separately as in L _{Aeq,T} . Contrast to L _{A8hr} for normalized

SYMBOLS & ABBREVIATIONS (Cont'd)

	average sound level, but note that for an 8-hr. measurement, $L_{A8hr} = L_{Aeq,8h}$. Unit: dB, dBA, or dBC.
$L_{EX,8h}$	- sound pressure level equivalent to the noise exposure normalized to a nominal 8-hour working day
$L_{Aeq,8h}$	- sound pressure level equivalent to the noise exposure normalized to a nominal 8-hour working day
L_F	- sound levels or sound pressure levels measured with fast time constant; 125-ms exponential weighted time average instrument response, often called "fast response." (also see L_s .)
L_I	- sound intensity level, dB
L_N	- percentile level that is exceed "n" percent of the measurement period. Unit: dBA
L_p	- sound pressure level. Unit: dB (also see SPL)
L_{ptot}	- total sound pressure level. Unit: dB (also see SPL)
$\overline{L_p}$	- average sound pressure level. Unit dB
L_{pk} or L_{peak}	- peak sound pressure level. Unit dB
L_s	- sound levels or sound pressure levels measured with slow time constant; 1-s exponential weighted time average instrument response, often called "slow response." (also see L_F)
L_W	- sound power level. Used with A or C subscript (e.g. L_{WA}) denotes use of A- or C-weighting. Unit: dB (also see PWL)
L_{Wtot}	- total sound power level. Unit: dB (also see SPL)
Log or L_g	- logarithm. When no subscript appears, base 10 is assumed. Note either term "log" or "lg" are correct and will vary based on origin of standard or reference.
m	- meter (also known as metre)

SYMBOLS & ABBREVIATIONS (Cont'd)

m	- mass. Unit: kg, lb
MIRE	- Microphone in real ear
ms	- 1/1000 s (millisecond)
NHCA	- National Hearing Conservation Association
NIHL	- noise-induced hearing loss. Unit: dB
NIOSH	- National Institute for Occupational Safety and Health
NIPTS	- noise-induced permanent threshold shift. Unit: dB
NIST	- National Institute of Standards and Technology (USA)
NRR	- Noise Reduction Rating. Often a trailing subscript, as in NRR_{84} , is used to indicate the percentage of the population that is protected. Unit: dB
NRR(SF)	- Noise Reduction Rating (Subject Fit). Unit: dB
NRS_A	- Noise Level Reduction Statistic for use with A-weighting
OSHA	- Occupational Safety and Health Administration (USA)
p	- sound pressure. Unit: Pa
p_{ref}	- reference sound pressure (20 μ Pa)
p_{rms}	- root-mean-square sound pressure. Unit: Pa
p_{peak}	- peak sound pressure. Unit: Pa
Pa	- Pascal
PAR	- Personal Attenuation Rating
PPE	- personal protective equipment
PTS	- permanent threshold shift. Unit: dB
PWL	- sound power level. Unit: dB (also see L_W)
Q	- directivity factor. Unit: dimensionless
r	- radius, effective radius of circle or sphere, or distance from source. Unit: m, ft

SYMBOLS & ABBREVIATIONS (Cont'd)

REAT	- real-ear attenuation at threshold. Unit: dB
rms or RMS	- root-mean-square
RTA	- real time analyser
R_w	- weighted sound reduction index, used for transmission loss
s	- second
SABIN	- Unit of Sound Absorption. The unit of sound absorption is square meter, referring to the area of open window.
SEL	- sound exposure level. Unit: dB (also see L_{AE})
SLM	- sound level meter
SPL	- sound pressure level. Unit: dB (also see L_p)
STC	- sound transmission class. Unit: dB
STS	- standard threshold shift in hearing, as defined in (USA) OSHA HCA. Unit: dB
T	- is the time it takes to complete one full cycle, it is proportional to the frequency.
t	- time. Unit: s, min, h
T_e	- effective duration of the working day Unit: h
T_c	- criterion sound duration. In OSHA/MSHA practice, $T_c = 8$ h. Unit: h
TL	- transmission loss. Unit: dB
TTS	- temporary threshold shift. Unit: dB
TTS_2	- temporary threshold shift measured two minutes post-exposure. Unit: dB
TWA	- A-weighted average sound level with 5-dB exchange rate and slow meter response, applied in (USA) OSHA/MSHA practice. The TWA is normalized to 8 hours. Contrast with L_{OSHA} for a non-normalized quantity. Unit: dBA

SYMBOLS & ABBREVIATIONS (Cont'd)

W	- sound power. Unit: watts
W_{ref}	- reference sound power (10^{-12} acoustic watts)
Z	- Z frequency weighting (or filter) that is flat over the range from 10 Hz to 20KHz
λ	- wavelength. Unit: m, ft
μPa	- micropascal (10^{-6}Pa)
ρ	- density of air (ρ). Unit: kg/m^3
τ	- transmission coefficient. Unit: dimensionless
ω	- angular frequency = $2\pi f$. Unit: rad/s
ω_n	- angular natural frequency. Unit: rad/s
ζ	- ratio of viscous damping constant to critical damping value. Unit: dimensionless

1. COURSE OVERVIEW

1.1 INTRODUCTION

This Course has been delivered by OHTA approved training providers for over 10 years and reviewed by international experts on two occasions to ensure the information is accurate and current. The latest update was 2023.

The mention of any product, manufacturer or vendor as examples in this manual should not in any way be construed as either endorsement or recommendation of such by either OHTA, authors, contributors, or editors of this manual.

1.2 AIM OF COURSE

To provide the student with an appreciation of the nature of noise hazards in the workplace and the effects of noise on people. It also details the approach in carrying out noise assessments in the workplace and in the general environment, and to determine the significance of measurement data in relation to the various standards for compliance.

1.3 LEARNING OUTCOMES

On successful completion of this module the student should be able to:

- Describe the consequences to health and well-being of excessive noise exposure;
- Understand the measurement (including dosimetry) of noise in relation to current standards;
- Conduct surveys in the workplace to assess risks from noise;
- Advise on the need and means of control, including personal protective equipment;
- Understand when to recommend the need for audiometry based on the outcome of the exposure assessment.

- Evaluate effectiveness of hearing protection if worker experiences a temporary or permanent hearing threshold shift.
- Appreciate and advise on environmental noise assessment and concerns; and
- Understand current standards and good practice in these fields.

1.4 FORMAT OF MANUAL

This manual has been designed to follow the learning outcomes. Similarly, the material provided in this manual has been aligned with the presentations for each topic so students can follow the discussion on each topic.

It should be recognised that the format presented in this manual represents the views of the editors and does not imply any mandatory process or format that must be rigidly observed. Presenters using this manual may well choose to alter the teaching sequence or course material to suit their requirements. In this regard the case studies and exercises are provided as illustrative examples and alternate material relevant to a particular industry may be used if desired.

The manual refers frequently to ANSI standards. Readers should also refer to their national standards and be aware of the exchange rate i.e. 3 or 5dB(A) exchange written into the national standards and legislation.

In the final outcome, the aim of this manual is to transmit the principles of noise measurement and an understanding of the effects of human exposure to noise.

2. THE PHYSICS OF SOUND

In order to understand occupational noise, it is important to build an understanding of sound and its interaction with the ambient environment. Noise is a subjective. Noise to one person may not be conceived as noise by another. Yet, everyone is exposed to noise at work, home, recreation, hobbies, etc. The effect of loud noise over time can be damaging to a person's hearing. This course will focus on noise measurement to evaluate exposure to unwanted sound.

2.1 SOUND PROPAGATION

Sound is generally defined as fluctuations in pressure above and below the ambient pressure of a medium that has elasticity and viscosity. The medium may be a solid, liquid, or gas. Sound is also defined as the auditory sensation evoked by the oscillations in pressure described above (ANSI S1.1-1994 (R2004)). For assessing the nature of workplace noise, the medium of primary concern is air. Noise is often used to describe unwanted sound, but it is also often used interchangeably with sound as in “sound source” or “noise source”.

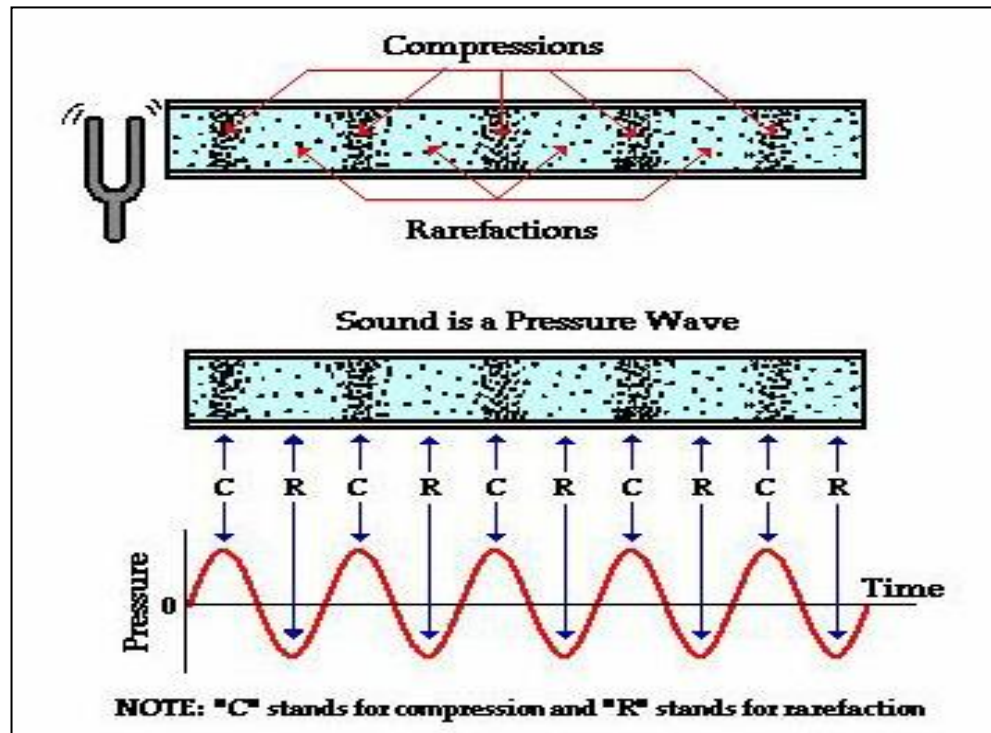
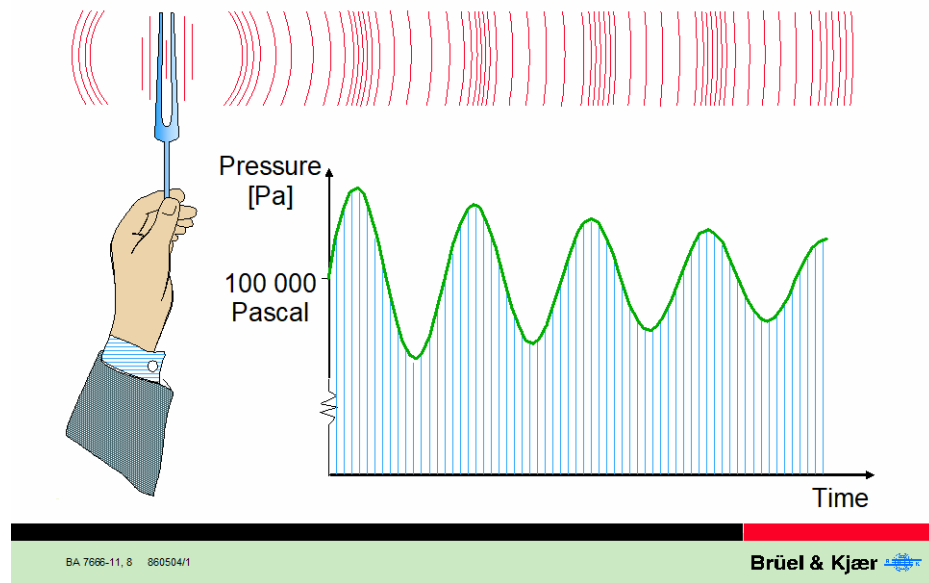


Figure 2.1 – A vibrating tuning fork sets air molecules into motion as illustrated in the top image, which results in positive (compression) and negative (rarefaction) excursions around atmospheric pressure as shown in the bottom illustration.

Sound perceived by the ear results from fluctuations in the pressure of the air. These fluctuations are usually initiated by a vibrating surface or object, such as the casing of a machine, or by air flow such as from compressed air exhaust. In the example in Figure 2.1 the sound is created by the vibrating prongs of a tuning fork pushing molecules forwards and backwards like the pendulum of a clock

As each molecule is set into vibration, it pushes against the adjacent molecule, i.e. the air is compressed, and so the next molecule is set into vibration. In this manner the sound wave is transmitted through the air. As the direction of motion of the air molecules is the same as the direction of motion of the wave front this is a longitudinal wave. This is unlike the wave in water where the water molecules move up and down at right angles to the propagation of the water wave, a transverse wave. For ease of presentation the airborne sound wave is usually drawn as a sine wave, as shown in Figure 2.2.

Sound Pressure



(Source: Brüel & Kjaer)

Figure 2.2 – Sound Pressure

2.2 PROPERTIES OF SOUND

The properties of sound waves are characterized by frequency, wavelength, period, amplitude, and speed. Amplitude and Period are illustrated in Figure 2.3 and described below for a simple sine wave.

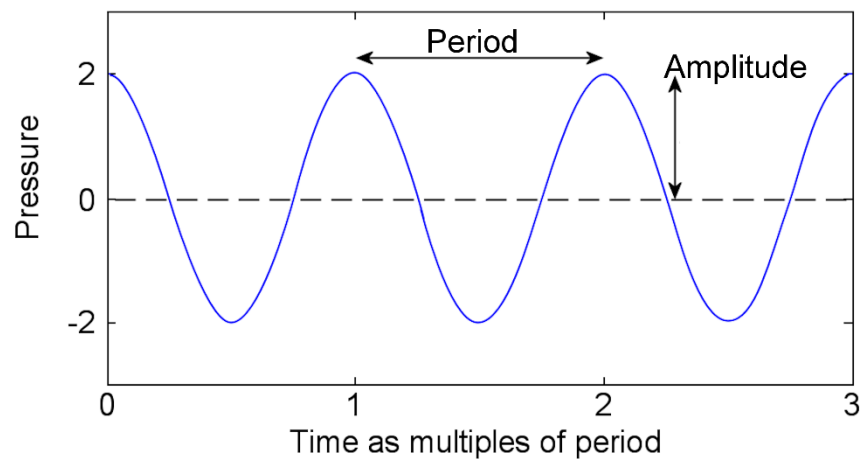


Figure 2.3 - Sound wave, pressure variation around atmospheric pressure

(used with permission of William J Murphy, CDC-NIOSH)

Amplitude is the maximum pressure variation above and below ambient or atmospheric pressure. The higher the amplitude, the greater or louder the sound level will be.

Period (T) is the time it takes to complete one full cycle, it is proportional to the frequency.

Frequency (f) of a sound is the number of times per second a complete wave passes a point. The number of cycles per second is termed Hertz (Hz).

The Period and the frequency are simply related by the following equation

$$T = 1/f \text{ (seconds)}$$

Speed (c) of sound in air is governed by density and air pressure which in turn relates to temperature and elevation above sea level. A detailed discussion of the various other mediums and their elasticity and density is beyond the scope of this Manual, and the reader is referred to more advance texts should additional details be desired. The speed of sound in air is approximately 343 m/s at standard room temperature and pressure. Thus sound travels about 1 kilometre in air in 3 seconds.

Wavelength (λ) is the length of one complete cycle, and is measured in metres (m). It is related to the frequency (f) and speed of sound (c) by:

$$\text{Wavelength } (\lambda) = c/f \text{ metres}$$

Table 2.1 shows the relationship between wavelength and frequency. Note that the higher the frequency, the shorter the wavelength; or conversely, the lower the frequency, the longer the wavelength. This is important when selecting appropriate noise control measures.

Table 2.1 - Wavelength in air at standard atmospheric conditions

Frequency	Wavelength
100 Hz	3.44 m
1000 Hz	0.34 m
10,000 Hz	0.034 m

Sine wave

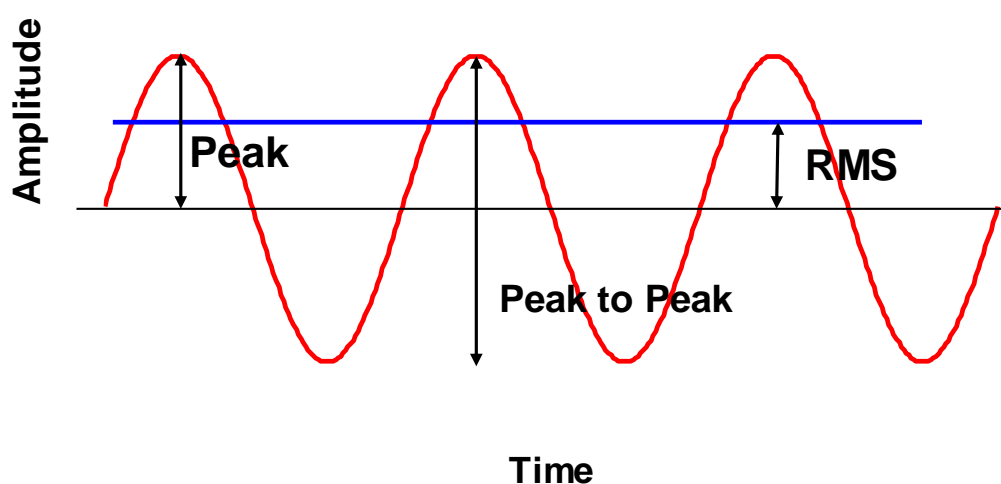


Figure 2.4 - various options for measurement of amplitude of the sound wave which is represented here as a sine pressure wave. The peak pressure is the greatest pressure for the sound wave

If the volume of a tone generator is turned up, the amplitude of the sound pressure is increased - the sound becomes louder. Amplitude is thus a convenient measure of the magnitude of the sound and can be related to its intensity and loudness and ultimately the effect it has on the human ear.

From consideration of the waveform, shown in Fig 2.4, there are various options for determining the amplitude. The peak value occurs only for a very short time period and so may not be very closely related to the subjective impression of the sound. While an average may be more appropriate, due to the symmetrical shape of the pressure wave the times the amplitude is positive equals the times the amplitude is negative and so the resultant 'average' is zero. The average amplitude takes into account the magnitude of the sound pressure fluctuations but not their direction (positive and

negative). The one most commonly used is the root-mean square (or RMS) sound pressure. This can best be described by looking at the waveform shown in the diagram below.

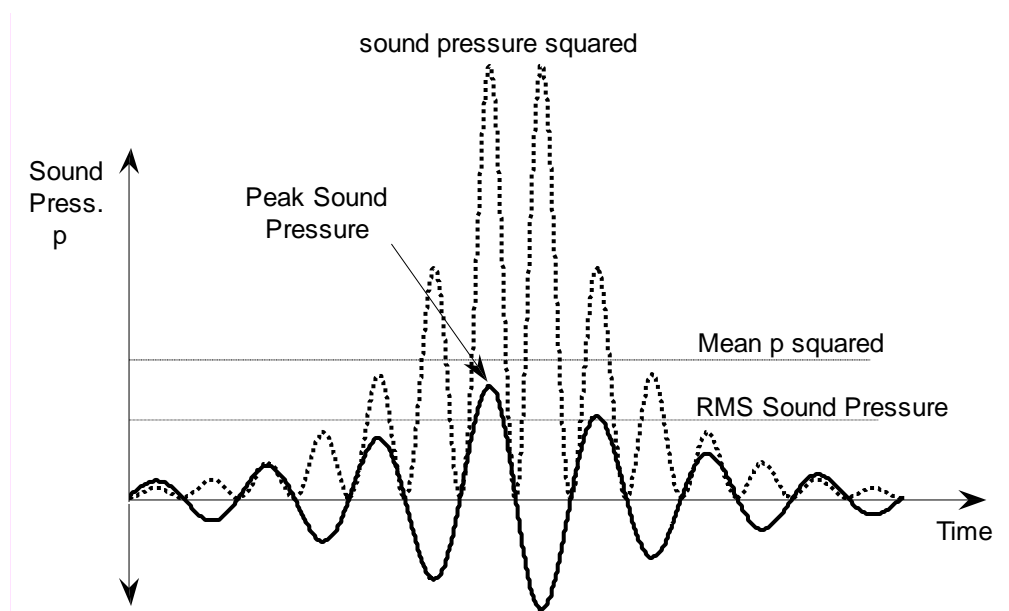


Figure 2.5 - Comparison of the pressure and the pressure squared signal with time

In effect the signal is first "squared", that is multiplied by itself. This has the effect of producing a pressure squared waveform, which is always positive. The next stage is to take the average (or mean value) of this pressure squared waveform - called the "mean pressure squared". Finally, by taking the square root of this value, we get back to a pressure - the root mean square pressure (strictly the square root of the mean pressure squared) referred to as RMS pressure.

Most sound level meters have electronic circuits which convert the microphone signal into an RMS value corresponding to the RMS sound pressure. The RMS pressure is used because it can be related to the average intensity of the sound and to the loudness of the sound. For more complex signals, there is no simple relationship between the two.

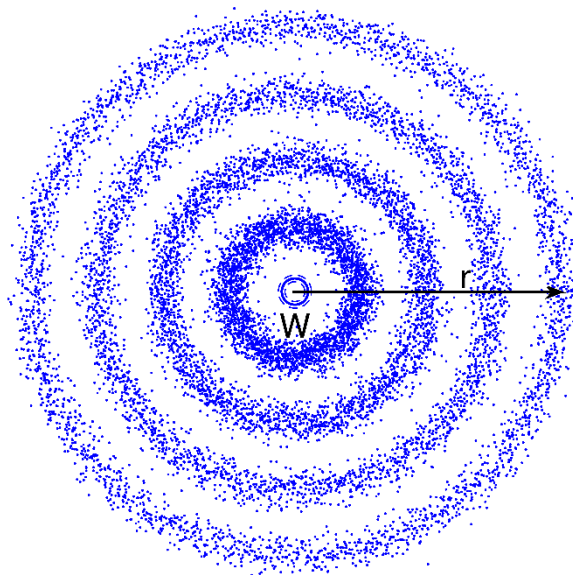
For a pure (simple sine wave) tone it can be shown that the peak pressure and the RMS pressure are simply related:

$$p_{\text{RMS}} = \frac{p_{\text{peak}}}{\sqrt{2}} = 0.707 \times p_{\text{peak}}$$

Despite what has been said above, there are occasions when it is important to measure the peak value of a complex sound waveform, or the peak to peak value, In particular for loud impulsive noise, such as gunfire, explosions or punch presses. The Crest Factor (CF) is the ratio of the peak amplitude of a waveform to the RMS value. It is a measure of the sharpness of the peak and short intense impulses will have high values of crest factor.

2.3 SOUND PRESSURE, POWER, AND INTENSITY

Sound Power - Sound power is defined as the total sound energy generated by the source per unit of time. Sound power is expressed in units of watts (W). It is important to keep in mind that for all practical situations the sound power of a source output is constant regardless of its location (i.e. inside versus outside). Conversely, the sound intensity and sound pressure will change as a function of the environment in which it is located.



Point Source Radiation

Figure 2.6 - Sound radiating out from source
(used with permission of William J Murphy, CDC-NIOSH)

Sound Intensity - is defined as sound power per unit area (watts/m²). Sound intensity is a vector quantity, in other words, it is specified by direction. A point sound source will radiate sound power evenly in all directions, assuming there are no reflective surfaces present. As the power spreads spherically from its origin, the surface area increases and so the power per unit area decreases. The total power remains the same, but the enclosing area is increasing, which results in a decrease in the sound intensity. This is known as the *inverse-square law*.

Surface area of sphere = $4\pi r^2$

At 1 metre from source, $r = 1$ and the power will be spread over a sphere whose surface area is $4\pi \times 1$

At 2 metres, $r = 2$ and the surface of the sphere will be $4\pi \times 4$, i.e. 4 times as large

At 3 metres the surface will be $3^2 = 9$ times bigger,

Therefore, as the distance from source spreads, the energy per unit area diminishes.

Sound Pressure - The variation of pressure superimposed on the atmospheric pressure within the sonic range is called the *sound pressure*. Sound pressure is expressed as force per unit area, and the preferred unit is the Pascal (Pa). Keep in mind sound pressure is the “effect” of a disturbance. The actual “cause” of the disturbance, and the resulting reaction effect, is due to the driving force or sound power.

2.4 LEVELS AND DECIBELS

2.4.1 The Decibel Scale and Use of Levels

The intensity of the faintest sound a person with sensitive hearing can detect is about 0.000,000,000,001 watts/m², while the intensity of the sound produced by a Saturn rocket at liftoff is greater than 100,000,000 watts/m². This is a range of 100,000,000,000,000,000. This is an extremely large range in values. The human ear does not respond in a linear way but more

like in a logarithmic way. By applying logarithms¹, and a reference value, a new measurement scale is formed such that an increase of 1.0 represents a tenfold increase in the ratio, also called a 1.0 Bel increase. The term Bel was named by Bell Laboratories in honor of Alexander Graham Bell. The application of logarithms has evolved to the use of 10 subdivisions of a log value, or 1/10th of a Bel, which is the term you may be familiar: decibels (10 dB = 1 Bel). The decibel is abbreviated dB and is a dimensionless quantity independent of the system of units used. The dB scale is related to the way the human ear responds to sound as 1 dB change in level is a just noticeable difference under ideal listening conditions.

For sound in air, the expression for each acoustical property is as follows:

$$\text{Sound Intensity Level: } L_I = 10 \log\left(\frac{I}{I_{\text{ref}}}\right), \text{ dB}$$

$$\text{Sound Power Level: } L_W = 10 \log\left(\frac{W}{W_{\text{ref}}}\right), \text{ dB}$$

$$\text{Sound Pressure Level: } L_p = 10 \log\left(\frac{p^2}{p_{\text{ref}}^2}\right) = 20 \log\left(\frac{p}{p_{\text{ref}}}\right), \text{ dB}$$

The “L” in each expression stands for “Level,” and the I, W, and p terms represent intensity, power, and pressure, respectively. Quite often the terms L_W and L_p are correspondingly abbreviated PWL and SPL. The reference quantities are also related to human hearing as they nominally correspond to the threshold of hearing at 1000 Hz:

$$\text{Reference intensity } (I_{\text{ref}}) = 10^{-12} \text{ w/m}^2$$

$$\text{Reference power } (W_{\text{ref}}) = 10^{-12} \text{ w}$$

$$\text{Reference pressure } (p_{\text{ref}}) = 2 \times 10^{-5} \text{ N/m}^2, \text{ or } 20 \text{ } \mu\text{Pa}$$

Keep in mind sound power propagates in the form of pressure fluctuations in air, and the *root-mean square* (rms) value of Intensity is

¹ Note: Unless stated otherwise, all logarithmic functions are to the base 10 (\log_{10}) throughout this manual.

$$I = \frac{W}{4\pi r^2} \text{ (where } r \text{ is distance from source),}$$

And pressure fluctuations are found by:

$$I = p^2 / \rho c \text{ (where } \rho \text{ is air density, and } c \text{ is speed of sound)}$$

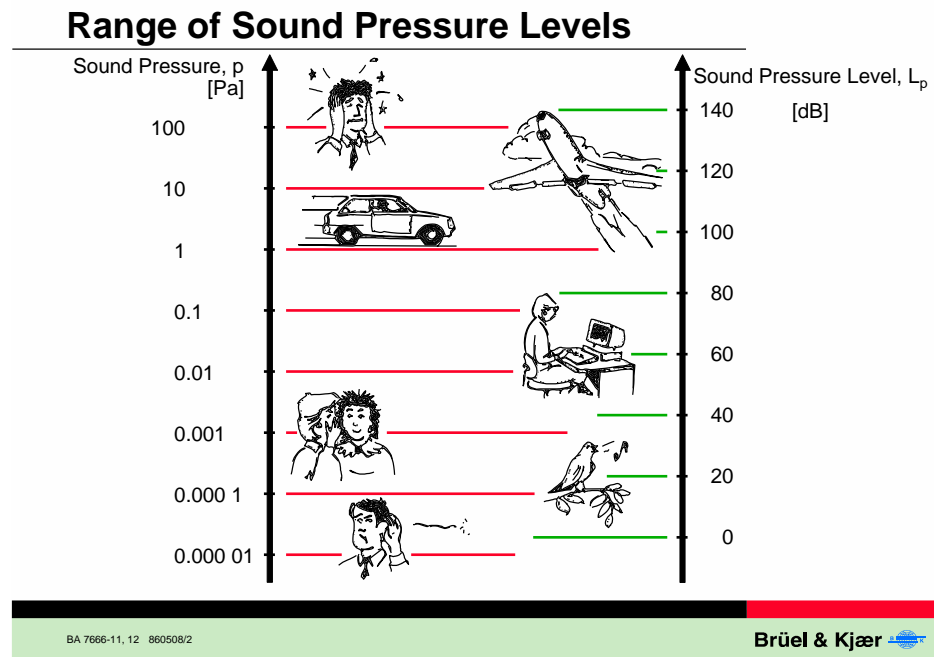
Therefore, the two expressions may be equated and represented as:

$$p^2 = \frac{W\rho c}{4\pi r^2}$$

Which illustrates where the p^2 is inversely proportional to r^2 (distance). This becomes an important factor when estimating the noise level at distance from a sound source.

2.4.2 Common Sound Levels

Perceived noise is dependent on both ambient air temperature and pressure as well as specific output of frequencies for each source. Each noise source has a unique footprint or range of frequencies that are specific to the equipment or machinery. Changing the atmospheric conditions or the location of the noise source will affect the sound being heard. Figure 2.7 presents a comparison of decibels and sound pressure.



(Source: Brüel & Kjær)

Figure 2.7 - Typical range of sound pressure levels for some common sounds

2.4.3 Quantifying Sound Levels

At this point it is useful to simply quantify how the human ear subjectively assesses relative changes in sound intensity. A 1 dB change is barely perceptible to a listener with very good hearing acuity. However, the ear does not respond linearly to changes in sound level. For example, a 3 dB difference would be just perceptible to the average listener, a 5 dB change clearly noticeable, and a 10 dB increase would typically be perceived as twice as loud. The study of the human perception of sound is complex and often referred to as Psychoacoustics.

2.4.4 Decibel Addition, Subtraction, and Averaging

Workplace noise environments often include more than one noise source. Therefore, it is important to understand the overall noise setting, and how levels vary as new equipment is added or removed. Also, when desired, it is useful to know how to average sounds or multiple sound measurements, since workplace noise exposure is almost never constant throughout the day.

Because levels are logarithmic values, it is not possible to arithmetically add or subtract them. Only the underlying physical quantities can be manipulated. Since levels are represented by logarithmic expressions, it is necessary to take the antilog of each level to determine the actual acoustic intensity. This calculation is a fairly straightforward procedure using a spreadsheet with the logarithmic formulas embedded. However, when using a spreadsheet, it is important to understand how these quantities are generated and learn alternative methods for manipulating decibels.

a) Decibel Addition

The expression for adding two or more unrelated sound pressure levels is as follows:

$$L_{pt} = 10 \log \left(\sum_{i=1}^n 10^{L_{pi}/10} \right), \text{ dB}$$

Where,

L_{pt} = total SPL, dB

L_{pi} = each individual (i^{th}) SPL, dB

n = the total number of values or levels

Adding multiple sound power levels follows the same format:

$$L_{Wt} = 10 \log \left(\sum_{i=1}^n 10^{L_{wi}/10} \right), \text{ dB}$$

Where,

L_{Wt} = total PWL, dB

L_{wi} = each individual (i^{th}) PWL, dB

n = the total number of values or levels

Example – Determine the total SPL for $L_{P1} = 85.0$ dB, $L_{P2} = 89.0$ dB, and $L_{P3} = 90.0$ dB.

These values are added using the expression:

$$L_{pt} = 10 \log \left(\sum_{i=1}^n 10^{L_{pi}/10} \right), \text{ dB}$$

And the individual SPLs are inserted as follows:

$$L_{pt} = 10 \log \left(10^{85/10} + 10^{89/10} + 10^{90/10} \right) = 93.2 \text{ dB}$$

Besides using the formula above, Table 2.2 may be used as a good estimate of the overall level due to two or more sources:

Table 2.2 - Combining Decibel Levels for Unrelated Sounds

Numerical difference between levels L_{P1} and L_{P2} (dB)	Amount to be added to the higher of L_{P1} or L_{P2} (dB)
0	3.0
1	2.5
2	2.1
3	1.8
4	1.5
5	1.2
6	1.0
7	0.8
8	0.6
9	0.5
10	0.4
greater than 10	0.0 for all practical purposes

To use the table method, first determine the numerical difference between two levels to be added. Next, in the second column of Table 2.2 look up the corresponding value to be added for this difference, and then simply add this value to the higher of the two levels to obtain the resultant level (L_{P3}). Repeat this process for each of the remaining unrelated sound sources to be combined.

Note: it is best to rank order the noise sources from lowest to highest, and then begin Step 1 using the two lowest levels, working down through the list to each successively higher number.

The table method above is often useful as a quick means to estimate the total SPL due multiple noise sources without having to use a pocket calculator or a spreadsheet with the requisite formulas embedded.

Example – Use Table 2.2 to estimate the total SPL for the addition of three sound levels of 85 dB, 89 dB, and 90 dB. (The final result will be L_{Pt}).

Step 1: Rank ordering these values from low to high gives us 85, 89, and 90 dB.

Step 2: The numerical difference between the two lowest levels 85 and 89 is 4 dB. From column 2 in Table 2.2 the corresponding value to add to the higher level, 89 dB is 1.5 dB, so the total for these two levels is $89 + 1.5 = 90.5$ dB.

Step 3: Now we combine the 90.5 dB with the third sound level of 90 dB. The difference is 0.5 dB so from Table 2.2 we see the amount to be added for a difference of 0.5 falls between 3 and 2.5. By interpolating between these numbers we can determine that the amount to be added is 2.8, which is added to the 90.5 giving an overall total of 93.3 dB which represents the total sound level for the three sounds.

This process can also be used to calculate the overall sound level if the data for the sound level in separate frequency bands is known. Each sound level is considered as a separate value and then they are added in pairs to provide the overall or total sound level for that sound. It can be important to ensure that the effect of the combination of the sound levels with lower value are properly taken into consideration so it is good practice to rearrange the numbers in ascending order before commencing the addition process. The table is an example of a typical layout to assist with this calculation, however it is also possible to set up a spread sheet for this determination.

Example - Determine the overall sound level for a sound source with the following spectrum.							
Frequency, (Hz)	63	125	250	500	1000	2000	4000
SPL (dB re 20 μ Pa)	95	72	85	80	86	82	79
Rearranging in ascending order	72	79	80	82	85	86	95
Difference		7	0	1	0.5	2	4.9
Add		0.8	3	2.5	2.5	2.1	1.2
Cum. level dB		79.8	83	85.5	88	90.1	96.2
Thus the overall sound level for this sound is 96 dB							

For quick additions of decibels a simplified version of the table can often provide the answer with sufficient accuracy for the purpose.

Table 2.3 - Simplified version of the table for addition of decibels

Difference in levels	Amount to add to the higher level
0, 1	+3
2,3	+2
4,5,6,7,8,9	+1
10 and greater	0

b) Decibel Subtraction

It can be necessary to estimate the reduction in noise level when some noise sources are removed from an area. The Table 2.2 can also be used in an iterative manner for subtraction of decibels as shown in the following example.

Example – Use Table 2.2 to estimate the remaining SPL if the combined sound pressure level for two sources is 96 dB and one source, that is known to be 94 dB, is to be removed.

Step 1: Let the unknown source remaining be X dB. The 94 + X must combine to be 96 dB, that is the unknown source has led to an overall increase in level of 2 dB

Step 2: From Table 2.2 an increase in overall level of 2 dB occurs when the difference in levels of the individual sources is 2 dB. So X must be 94-2 dB, i.e. 92 dB

Step 3: Checking this; for the addition of 94 + 92 dB, the difference is 2 dB so from Table 2.2 the total combined noise level is 2 dB higher than the higher source which in this example is 94 dB, giving a total of 96 dB.

Thus removing the source known to be 94 dB will lead to an overall level of 92 dB in the area.

c) Decibel Averaging

At times it is useful to average decibels, especially for repeated measurements conducted at the same position over time. This method can be used to survey and collect multiple samples over a brief time period or evaluate multiple noise sources at different time varying intervals to estimate the overall exposure rather than collecting full-shift samples. The formula for averaging measured SPLs is as follows:

$$\bar{L}_p = 10 \log \frac{1}{n} \left(\sum_{i=1}^n 10^{L_{p_i}/10} \right), \text{ dB}$$

Where,

\bar{L}_p = average SPL, dB

L_{p_i} = each individual (i^{th}) SPL, dB

n = the total number of values or levels

Example – Determine the average SPL for $L_{P1} = 81$ dB, $L_{P2} = 86$ dB, $L_{P3} = 82$ dB, and $L_{P4} = 84$ dB.

These values are averaged using the expression:

$$\bar{L}_p = 10 \log \frac{1}{n} \left(\sum_{i=1}^n 10^{L_{P_i}/10} \right), \text{ dB}$$

And the individual SPLs are inserted as follows:

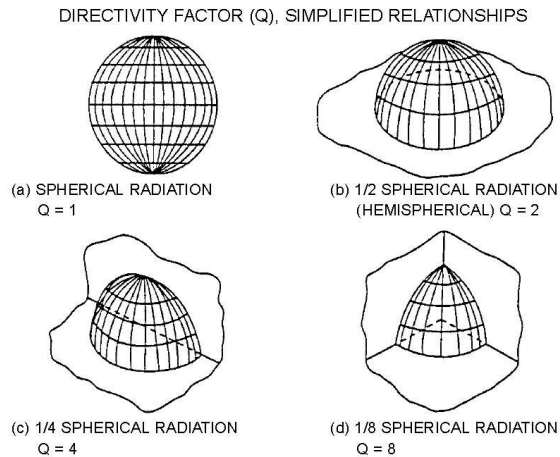
$$\bar{L}_p = 10 \log 1/4 \left(10^{81/10} + 10^{86/10} + 10^{82/10} + 10^{84/10} \right), \text{ dB}$$

$$\bar{L}_p = 83.7 \text{ dB which rounded off would be } 84 \text{ dB}$$

Note that when there is only a few dB difference in the individual levels the logarithmic average is similar to the arithmetic average. In the above example the range from the lowest to the highest is 5 and the arithmetic average of $81+86+82+84$ is 83.2 which would round off to 83.

2.4.5 Directivity of Sound Sources

Sound sources do not all radiate sound equally in all directions – this is referred to as source directivity. Also the location of a source can affect the level and distribution of the sound. The additional reflected sound from a source placed against one reflecting surface, such as a hard floor, can lead to a 3 dB increase in sound level. The same source located near 2 reflection surfaces could be 6 dB higher and in a corner with 3 reflecting surfaces could be 9 dB higher. Figure 2.8 shows this graphically for pure spherical radiators and Table 2.4 shows the relationship between the directivity factor and directivity index, which is in dB. In practice the increase in level is not as great as these theoretical values.



(Source: The Noise Manual, 5th Ed., Am. Ind. Hyg. Assoc.)

Figure 2.8 - Directivity factor, Q, for varying boundary conditions

Table 2.4 - Comparison of Directivity Factor and Directivity Index

Source Location	Directivity Factor, Q	Directivity Index (dB)
Suspended in space	1	0
On floor of large room	2	3
At intersection of one wall and floor	4	6
In the corner of a room	8	9

2.4.6 Frequency Characteristics of Sound

The frequency of sound is the number of times per second a disturbance passes through both its positive and negative excursions around atmospheric pressure, expressed in units of Hz. Workplace sounds are invariably comprised of a broad spectrum of frequencies, which can be divided into smaller bandwidths to assist the analysis for risk assessment, noise control, evaluation of hearing protection, etc. For this purpose, the sound level meter may contain a filter set to measure the select bandwidths of concern or a frequency analyser can be used. The most common bandwidth for noise measurement is the octave band.

An octave band is defined as a range or band of frequencies where the upper end frequency, f_2 , is two times the lower end, f_1 :

$$f_2 = 2 f_1, \text{ Hz}$$

Full octaves are often expressed as 1/1 octave bands, although you will also see in the literature full octaves simply referred to as “octave bands,” where the 1/1 ratio is implied.

Many times, especially for noise control purposes, more detailed definition of the frequency characteristics of a sound is required. In these instances, the most common measure will be to sub-divide the full octave in thirds, called 1/3 octave bands. Here the upper band edge, f_2 , is the cube root of two times the lower band edge, f_1 :

$$f_2 = \sqrt[3]{2}f_1, \text{ Hz}$$

Table 2.5

Nominal center and approximate band edge frequencies for contiguous octave and 1/3 octave bands (values in Hz).

Band	1/1 Octave Bands			1/3 Octave Bands		
	Lower	Center	Upper	Lower	Center	Upper
10				9.2	10	10.9
11				10.9	12.5	14.3
12	11	16	22.4	14.3	16	17.9
13				17.9	20	22.4
14				22.4	25	28
15	22.4	31.5	45	28	31.5	35.5
16				35.5	40	45
17				45	50	56
18	45	63	90	56	63	71
19				71	80	90
20				90	100	112
21	90	125	180	112	125	140
22				140	160	180
23				180	200	224
24	180	250	355	224	250	280
25				280	315	355
26				355	400	450
27	355	500	710	450	500	560
28				560	630	710
29				710	800	900
30	710	1000	1400	900	1000	1120
31				1120	1250	1400
32				1400	1600	1800
33	1400	2000	2800	1800	2000	2240
34				2240	2500	2800
35				2800	3150	3550
36	2800	4000	5600	3550	4000	4500
37				4500	5000	5600
38				5600	6300	7100
39	5600	8000	11200	7100	8000	9000
40				9000	10000	11200
41				11200	12500	14000
42	11200	16000	22400	14000	16000	18000
43				18000	20000	22400

(Source: The Noise Manual, 5th Edition, Am. Ind. Hyg. Assoc., and AIHA Press.)

Each frequency range has a centre frequency, f_c , equal to the geometric mean of the upper and lower band-edge frequencies:

$$f_c = \sqrt{f_1 f_2}, \text{ Hz}$$

For example, the bandwidth for $f_c = 1000$ Hz is 710-1400 Hz using a 1/1 octave band filter, and 900-1120Hz in 1/3 octave band metrics. Table 2.5 presents the lower, centre, and upper frequencies for both 1/1 and 1/3 octave bands.

The standard 1/1, 1/3 octave-band analysers are known as constant-percentage bandwidth filters. As the centre frequency increases, so will the width of each frequency band. On the other hand, narrow-band analysers utilize a constant-bandwidth filter, selected by the user. Narrow-band analysis is applicable primarily to advanced noise control measurement or evaluation of specific sound sources such as emergency alarms.

2.4.7 Weighted Sound Levels

As discussed in the section on human hearing, the ear does not respond equally to all frequencies. Thus for measurements relating to human response it is necessary to include a filter in the measurement process that is similar to the frequency response of the human ear. The A weighting filter has been designed to have a similar frequency response to the ear and measurements made with this filter are expressed as dBA. Regulations for most occupational noise exposure are in terms of the A-weighted sound level,

The A-weighted level is most readily obtained by measuring it with a sound level meter set to the A-weighting frequency filter network. Essentially, A-weighting SPLs reduce the importance of lower frequencies at 500 Hz or less. The lower the frequency, the greater the A-weighted correction factor becomes (see Table 2.6 and Figure 2.9). Conversely, the mid to high frequencies from 2,000-4,000 Hz have a slight increase in overall magnitude, as 1.2 and 1.0 decibels are added to the linear SPLs at these frequencies

and the very high frequencies are again reduced as they extend beyond normal hearing.

Another weighting network used in workplace noise assessment, principally with respect to evaluation of impulse noise and for hearing protection, is the C-weighted level, expressed in dBC. As with the dBA, C-weighted correction values are applied to the linear SPLs per frequency, and then all data are added logarithmically to arrive at an overall dBC level. The C-weighted correction values per frequency are presented in Table 2.6, which shows significantly less low frequency roll-off relative to the A-weighted correction values. In fact, unless there is sound energy present below 25 Hz or above 10,000 Hz, the overall dBC result should equal or be very close to the linear SPL in dB.

The Z weighting has been introduced in recent times and is available on the modern sound level meters. It is essentially a linear response over the usual range of interest for noise assessments.

Table 2.6 - Octave band values for the A, C and Z frequency weightings

Frequency, Hz	A weighting	C weighting	Z weighting
16	-56.7	-8.5	
31.5	-39.4	-3.0	
63	-26.2	-0.8	
125	-16.1	-0.2	
250	- 8.6	-0.0	Flat
500	- 3.2	-0.0	from 10Hz
1000	0	0	to 20kHz
2000	+ 1.2	-0.2	
4000	+ 1.0	-0.8	
8000	- 1.1	-3.0	
16000	- 6.6	-8.5	

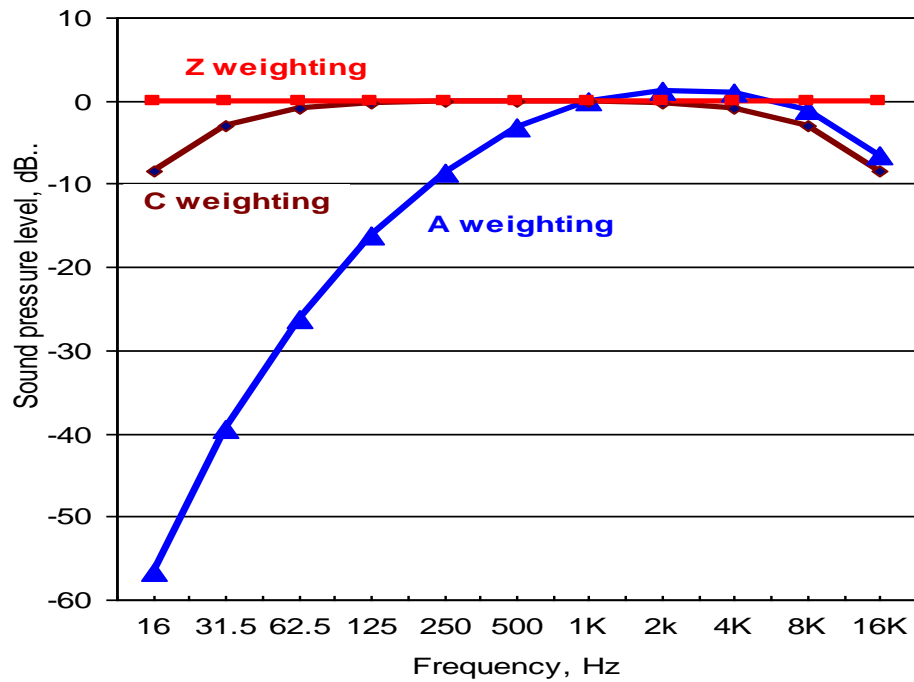
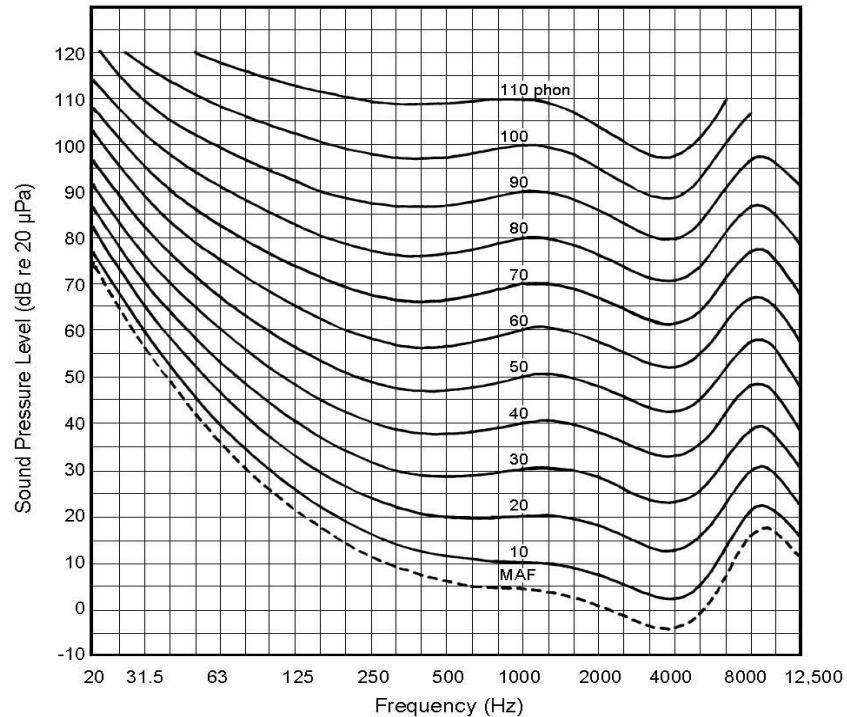


Figure 2.9 - Graphic representation of the A, C and Z weighting filters

2.4.8 The Human Audible Range of Hearing and Loudness

The accepted *range* in human hearing extends from 20 Hz up to 20,000 Hz. However, it is a relatively small percentage of the population that can truly detect sounds at the outer edges of this range. The *threshold* of hearing is that SPL that is just barely detected by a listener. Figure 2.10 depicts the equal-loudness contours for free-field conditions, with the minimum audible field (MAF), shown by the dashed line. Inspection of the curves in Figure 2.10 clearly shows human sensitivity is greatest from 2,000 to 5,000 Hz.



(Source: ISO 226:1987 - Reproduced with permission of the International Organization for Standardization)

Figure 2.10 - Equal-loudness contours of pure tones for field (open-ear, frontal incidence) listening conditions. The numbers indicate the loudness level, in phons, of the tones that fall on each contour

Figure 2.10 also shows how human hearing is a function of frequency and amplitude of the sound wave. A sound at one frequency may seem louder (or softer) than a sound of equal pressure amplitude at a different frequency. That variability also can be perceived differently between the right and left ear.

When sounds exist below and above the audible frequency range in human hearing, they are classified as *Infrasound* and *Ultrasound*, respectively. **Infrasound** is low frequency and so has long wavelength it can travel long distances and get around obstacles with little dissipation. Infrasonic sound waves exist naturally in the form of earth tremors, electrical storms, and volcanic activity. These low frequency sounds can also be generated by industrial equipment, such as transformers, some compressors, or within engine rooms. Infrasound is not harmful to human hearing; however,

excessive and prolonged exposure can lead to physical discomfort, headaches, and even nausea at times.

Ultrasound is short wavelength high frequency sound often used in industry for cleaning parts, welding plastic parts together, and sealing thermoplastic packaging. Ultrasonic devices operate at frequencies of 20,000 Hz and above, which are above the range in human hearing. However, sub-harmonics of the ultrasonic tone can exist and cause machine components to radiate audible airborne sound. Therefore, if you are measuring sound levels in an area with ultrasonic devices; keep in mind it may still be possible to measure audible sound levels due to this equipment.

2.4.9 Relationship between Sound Pressure Level and Sound Power Level

SPL and PWL are related by the equation:

$$L_p = L_w + k, \text{ dB}$$

Where,

L_p is the sound pressure level (SPL) in dB,

L_w is the sound power level (PWL) in dB, and

k is a constant factor, dependent upon the acoustics of the environment, directivity of the source, and distance from the source.

The easiest way to explain the differences between sound pressure and sound power is to consider the following analogy. Consider an example, where a 100-watt light bulb is placed in the centre of a room and completely painted with flat black paint, including the floor. The illumination in the room will seem rather dim or dull when compared to the identical set-up in a second room that is completely covered with glossy white paint. As you can imagine the white room will be significantly brighter. Nothing has changed as far as the power output of the light bulb. Only the environment (room) conditions have changed.

The same thing happens with sound. Recall that SPL is the *effect* (what we hear) of a pressure disturbance and PWL is the *cause* of the disturbance.

So following the concept described in the light bulb analogy, assume you have a machine with a rated PWL of 90 dB and place it in a small room where the floor and ceiling are both concrete, and the walls are brick; the resultant SPL we hear could be as much as 110 dB due to the reflection and build-up of sound energy inside the room. Conversely, if the same 90 dB PWL machine is placed on the ground outside, the SPL may only be on the order of 92 dB. Note the PWL is identical in both scenarios, but the effect is dramatically different. This is due to differences in the environment (k factor) that combines with the PWL to produce a specific SPL.

2.4.10 Time-Varying Noise Sources

Besides having frequency and amplitude characteristics, many-sounds also vary with time, i.e.: have temporal qualities. The acoustical instrumentation, meter settings, and measurement techniques for various sound characteristics are presented in Chapter 3; however, at this point it is important to understand the definition and concept of these temporal qualities.

Equipment such as compressors, fans, and electric motors, generally produce sounds that are continuous or steady state. By definition *steady state* sounds remain relatively constant in time, varying by no more than plus or minus (+/-) 3 dB. When machines operate through a range of tasks or functions, they often generate *intermittent* sounds. So if equipment generates sound levels that fluctuate more than 3 dB, then it is generally classified as an intermittent noise source.

Another temporal characteristic of sound is the instantaneous event, such as an impact or impulse. An *impact sound* can be generated by the solid collision between two objects, such as hammering, dropped objects, a door slamming shut, metal-to-metal impacts, etc., whereas impulse sound often refers to the rapid expansion of gas such as those generated by gunfire or explosions. *Impulse sound* is defined as an event having an exponential rise time constant of 35 milliseconds, and

an asymmetric decay time constant of 1.5 seconds (Earshen, 2000). It is important to note the terms impulse and impact sound are commonly used interchangeably, despite the fact they have distinctly different characteristics.

Peak noise on the other hand is instantaneous and records the highest level measured. With occupational noise the Peak noise should be measured not the Impulse noise. Impulse noise is more suited for environmental noise.

2.5 HUMAN RESPONSE TO SOUND

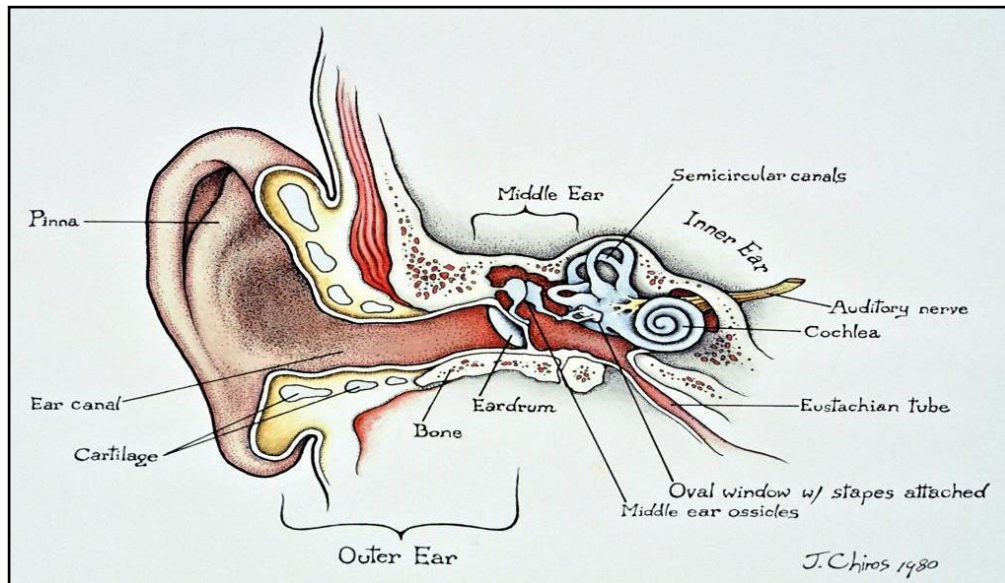
2.5.1 The Ear and its Response to Sound

Hearing is a critical human sense. Hearing facilitates communication with each other and our environment. Sound adds richness to life, be it the subtleties of language and humour, the emotions instilled by music, or the connection felt to our surroundings.

The unique and intricate anatomical and physiological design of the ear allows for the presence, clarity, and quality of sound to be experienced. Incredibly complex, the peripheral auditory system is delicate, yet rugged; vulnerable yet remarkably resilient. The following brief overview of ear anatomy and physiology gives an appreciation for our ears and how they respond to sound.

a) Anatomy and Physiology: The Structure and Function of the Ear

The hearing mechanism is traditionally divided into three major parts: the outer, middle, and inner ear. Refer to Figure 2.11 for these demarcations as well as for labelled anatomical references. The ear spans from the visible cartilaginous part on the outside of the head to deep within the bony part of the skull. For the scope of this manual, only the major anatomical sites and functions of the auditory system are introduced.



(Source: Image used with permission from Elliott H. Berger, Aearo Technologies)

Figure 2.11 – Illustration of the major anatomical references of the ear including the three divisions: external (outer), middle, and inner. The outer and middle ear consist of cartilage, the inner ear is encased in bone.

b) Outer (External) Ear

The outer ear, as shown in Figure 2.12, consists of the pinna, ear canal and the eardrum or tympanic membrane. The outer ear functions to direct and enhance sound waves into the ear and provides some protection to the middle ear.

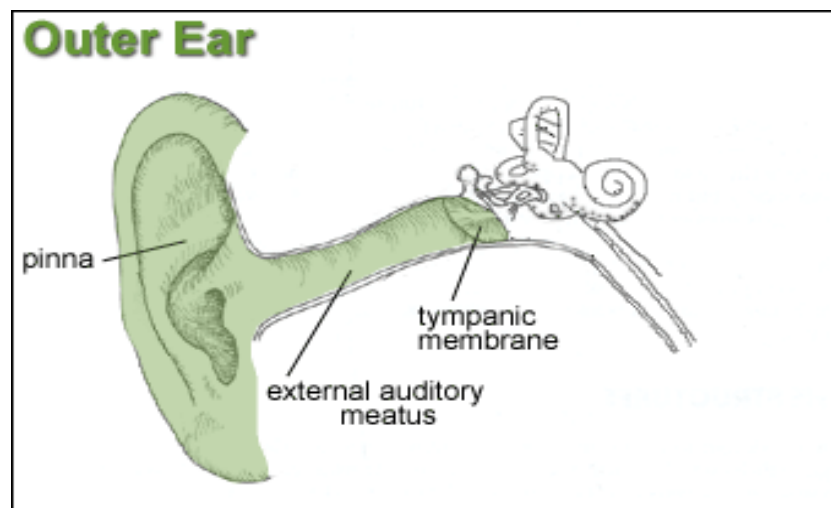


Figure 2.12 - The outer ear contains the pinna, ear canal, and tympanic membrane.

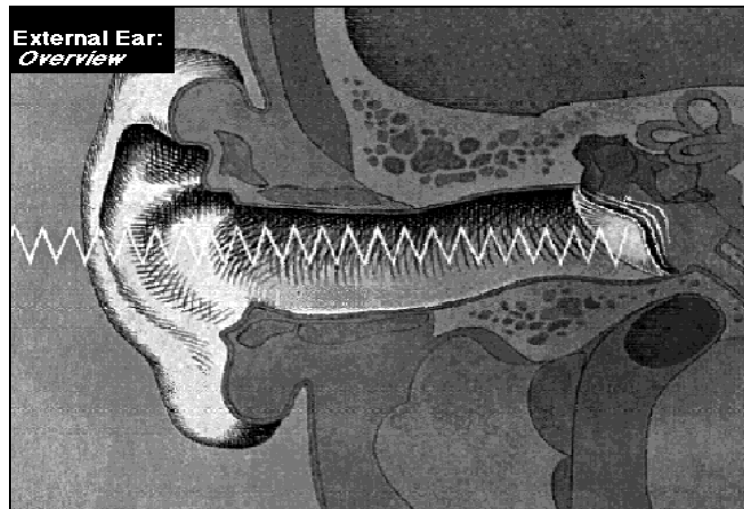


Figure 2.13 - Sound waves are channeled into the ear and enhanced by the shape and resonance characteristics of the ear canal. The eardrum transfers the acoustic vibrations to the middle ear.

Pinna:

The visible, cartilaginous portion of the ear helps to collect sound waves, as illustrated in Figure 2.13. The bowl of the pinna, the concha, is at the outside of the ear canal and aids in directing sound waves to the ear canal. Having two ears allows sound localization because the sound waves arrive at each ear at slightly different times. In addition to auditory benefits, the pinna is naturally unique to each individual.

Auditory meatus or Ear canal:

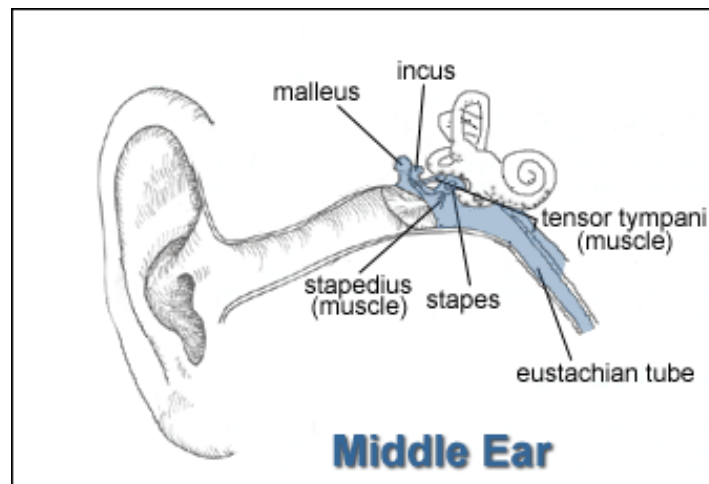
The passage leading from the pinna to the eardrum funnels the sound waves to the middle ear. Although most illustrations depict the ear canal as being straight, it actually has an “S” shaped curve. The shape of the canal acts as a closed end tube and has resonance properties which amplify sounds between 2000 – 5000 Hz, an important feature for allowing soft sounds to be audible. The ear canal is approximately 24 mm (1 inch) in length. The outer half of the canal wall is made of cartilage and the inner half of bone. The canal is lined by skin containing modified sweat glands which produce cerumen, or earwax, and fine hairs; both features serve a protective purpose to the eardrum.

Tympanic Membrane or Eardrum:

The eardrum is the terminal point of the outer ear and the originating point of the middle ear. It seals the ear canal, captures the sound vibrations in air and converts the acoustical energy into mechanical energy. The mechanical energy drives the ossicular chain (middle ear bones) by a connection at the umbo of the tympanic membrane. It is comprised of three layers of semi-transparent tissue, similar to skin, which grow continuously. The tympanic membrane must be intact for normal transduction of sound to occur.

c) Middle Ear

The middle ear (tympanic cavity) is an air-filled cavity between the tympanic membrane and bony capsule of the inner ear, and is illustrated in Figures 2.14 and 2.15. It contains the ossicular chain and muscles as well as the opening of the Eustachian tube. The middle ear transmits and enhances mechanical vibration from outer to inner ear.



(Image source: U.S. Dept. of Labor, OSHA)

Figure 2.14 - The middle ear is the air-filled space between the eardrum and the bony inner ear. It contains the middle ear bones and muscles and the Eustachian tube

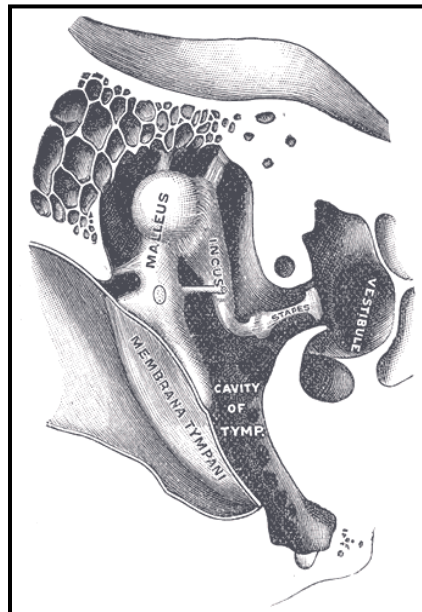


Figure 2.15: Close-up drawing of the middle ear showing the malleus, incus and stapes connecting the tympanic membrane to the inner ear

Ossicles:

The three smallest bones in the human body, the malleus (hammer), incus (anvil), and stapes (stirrup), are joined together to form the ossicular chain which is suspended in the middle ear space, secured by ligaments and muscles. The head of the malleus is attached to the tympanic membrane at the umbo at one end of the ossicular chain. The stapes footplate rests in the oval window of the cochlea in the inner ear at the other end. This delicate system has a unique purpose in overcoming the impedance mismatch between the air in the middle ear space and the fluid in the inner ear. The orientation of the ossicular chain in combination with the surface area differential between the tympanic membrane and the stapes footplate, creates a natural amplification; a ratio of 15:1 in which the sound vibration is amplified by passing from the outer ear through the middle ear to the inner ear. This is specifically relevant to our ability to hear extremely soft sounds.

Muscles:

Also located in the middle ear cavity are two tiny muscles: the tensor tympani and the stapedius. The tendon of the tensor tympani muscle attaches to the handle of the malleus and the stapedius muscle attaches to the neck of the stapes. Contraction of these muscles cause the malleus to be pulled inward and the stapes to be pulled away from the oval window, temporarily changing the vibratory characteristics of the ossicular chain, and potentially providing a protective mechanism against loud sound. The *acoustic* or *aural reflex* refers to the immediate contraction of these muscles in response to a loud sound. The reflex does not happen quickly enough to add significant protection from sudden burst of sound, such as a gunshot, however it can reduce vibratory stimulation for sustained sound. It is more apt to be present and effective in younger ears than in older ears.

Eustachian tube:

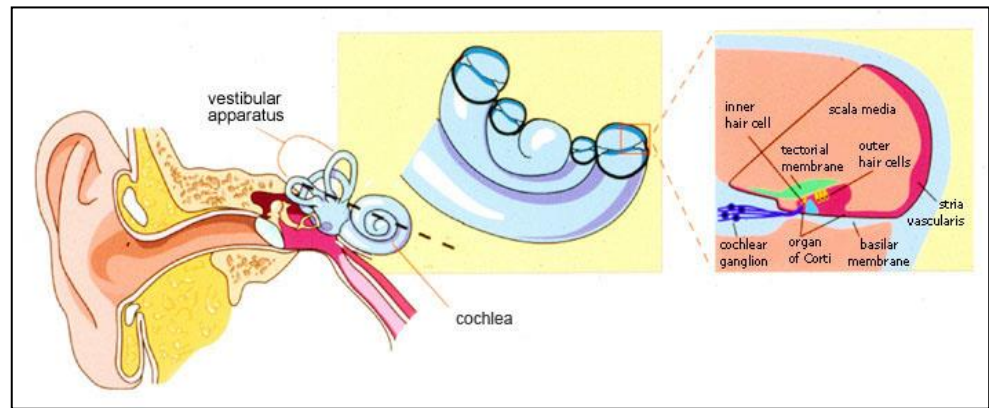
The *Eustachian tube* is an open tube passing downward and inward from the middle ear space to the nasopharynx. The Eustachian tube is about 45 mm (1.75 inches) in length. Its primary function is to equalize pressure differences between the outer and middle ear spaces for example when ascending or descending in an airplane.

d) Inner Ear

The inner ear is a fluid filled labyrinth within the temporal bone. It contains the sensory mechanism of both auditory and vestibular systems. It in the inner ear that mechanical vibration is converted to neural stimulation for hearing and balance.

Cochlea:

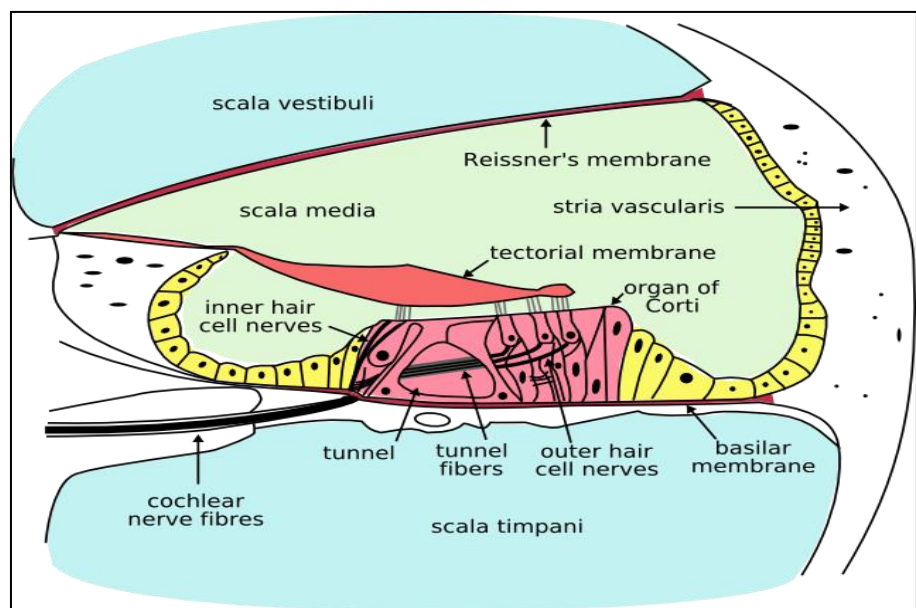
Often visualized as a snail shell, the cochlea is actually a fluid filled tube, which spirals 2.5 times on itself within the temporal bone, as shown in Figure 2.x. The tube is divided into three different parts by membranes.



(Source: Griffith and Friedman, NIDCD)

Figure 2.16 - Illustration of a section through the cochlea

The upper and lower parts, called the *scala vestibule* and the *scala tympani* respectively, both contain perilymph, a fluid rich in sodium. These two compartments are joined by a small passage way, the *helicotrema*, at the extreme end of the cochlea. The centre partition, called the *scala media*, is filled with endolymph, a fluid high in potassium.

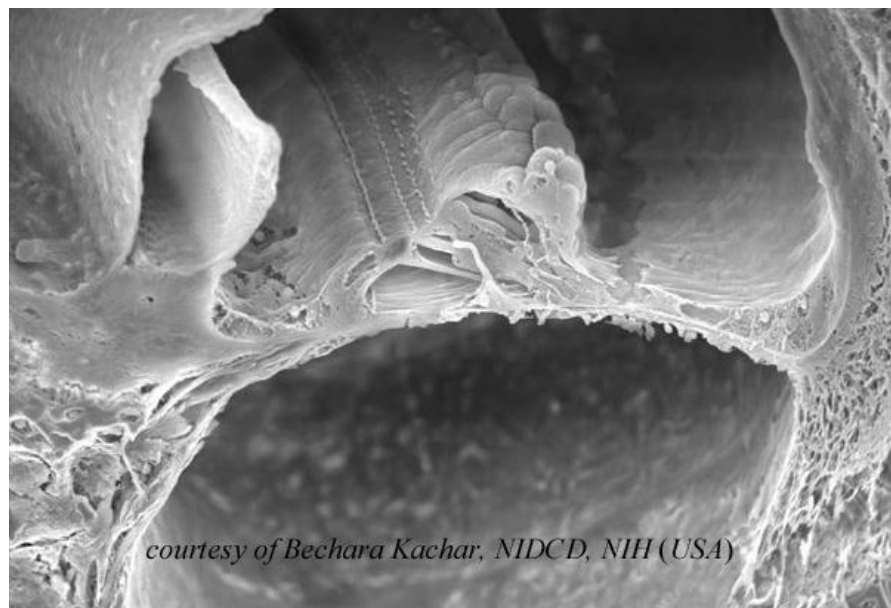


(Source: Image with permission from:

<http://upload.wikimedia.org/wikipedia/en/0/0c/Cochlea-crosssection.png>)

Figure 2.17 – A cross section of one turn of the cochlea illustrates the three fluid filled chambers: *scala vestibuli*, *scala media* and *scala tympani*. The organ of Corti, containing the inner and outer hair cells, sits on the basilar membrane within the *scala media*. This entire structure moves in response to sound.

Figure 2.17 illustrates a cross-section of the cochlea and Figure 2.18 presents an electron micrograph of the organ of Corti within the cochlear duct. The length of the cochlea is approximately 35 mm and the beginning of the cochlea is referred to as the “base” and the other extreme is called the “apex.” There are two openings, or windows at the base. The stapes footplate rests in the *oval window*, which is the entrance to the scala vestibuli. The *round window* is at the end of the scala tympani. As the stapes vibrates, the pressure disturbance, contained within the cochlea, causes the round window to move out as the oval window is pushed inward, in synchrony with the mechanical vibration of the stapes. As the fluids inside the chambers move, the membranes separating the chambers also move.

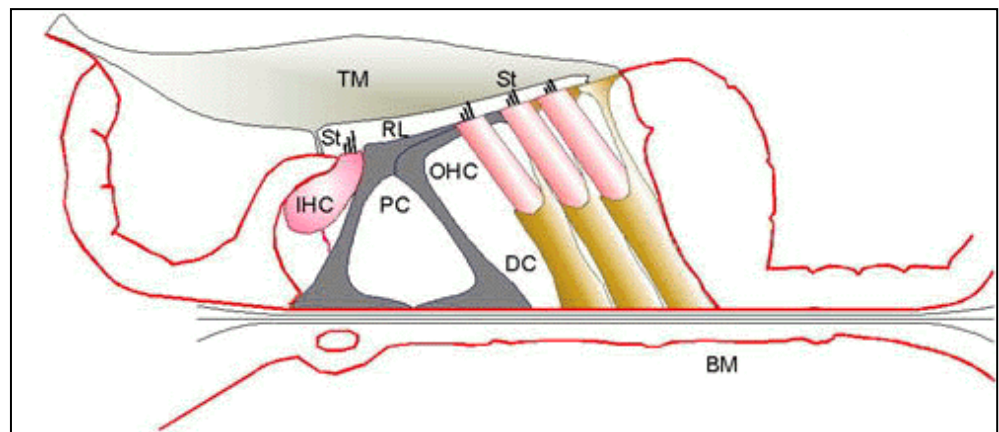


(Source: Image retrieved with permission Mammano & Nobili:
<http://147.162.36.50/cochlea/index.htm>)

Figure 2.18 – This electron micrograph shows the organ of Corti within the inner ear

Of particular importance is the movement of the *basilar membrane*, which separates the scala tympani from the scala media. The basilar membrane is comprised of several cellular structures; noteworthy is the *stria vascularis*, important because it is the blood supply to the cochlea. Within the scala media, located roughly in the centre of the basilar

membrane is the most studied element, the *organ of Corti*, as illustrated in Figure 2.19. The organ of Corti is supported by inner and outer pillar cells. Adjacent to these cells are the *inner and outer hair cells*. Another important structure is the *tectorial membrane*, consisting of a strong, gelatinous substance, which is significant, because it is in direct contact with stereocilia of the outer hair cell and must stand up to excessive movement within the organ of Corti. The boundary between the scala media and the scala vestibuli is *Reisner's membrane*.



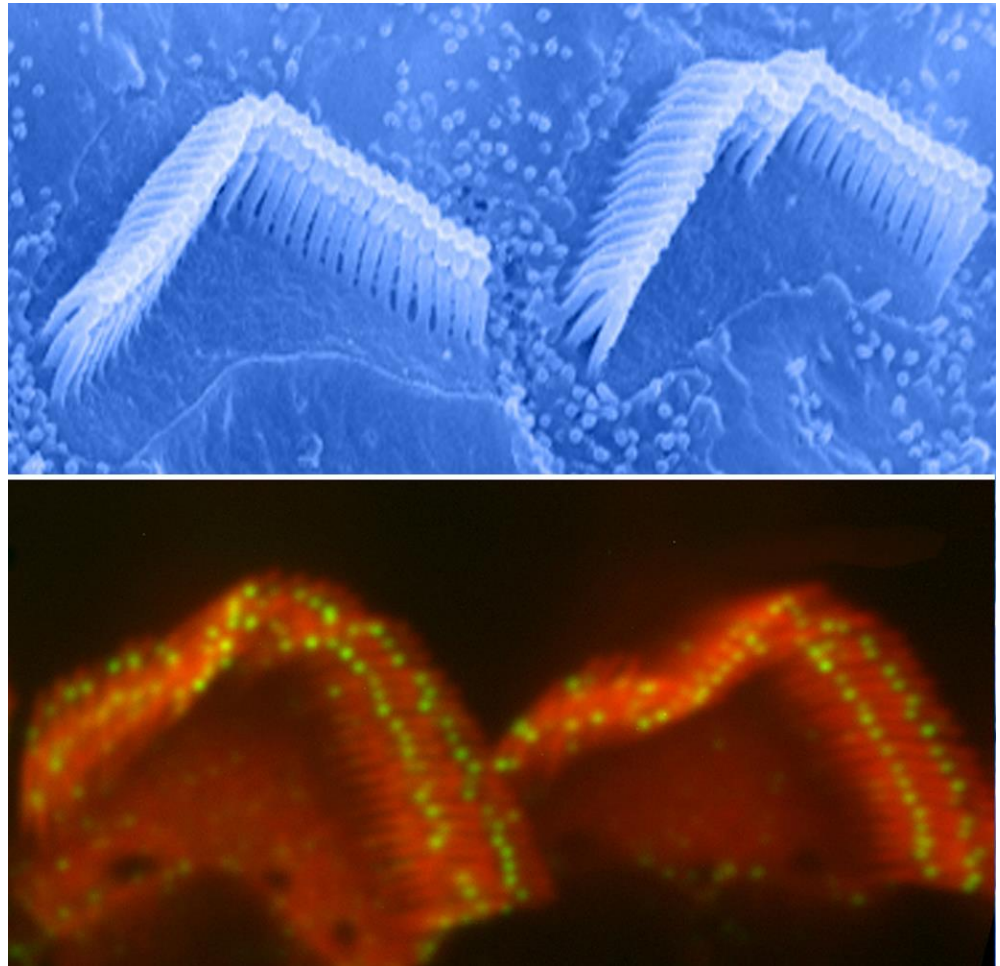
(Source: Image with permission (Mammano and Nobili) retrieved from: <http://147.162.36.50/cochlea/cochleapages/theory/index.htm>)

Figure 2.19 - The organ of Corti rests on the basilar membrane (BM). It consists of supporting structures (PC = pillar cells, DC = Dieter's cells, and RL = reticular lamina.) and sensory cells (pink). The sensory cells are one row of inner hair cells (IHC) and three rows of outer hair cells (OHC), each topped with stereocilia (St) which contact the tectorial membrane (TM)

Outer hair cell:

The supporting cells of the organ of Corti hold outer and inner hair cells in position. There are approximately 12,000 to 20,000 outer hair cells organized in three rows. On top of each outer hair cell are more than 100 stereocilia, arranged in a "W" shaped pattern, as shown in the electron micrograph in Figure 2.20. The stereocilia are aligned from tallest to shortest: the shorter stereocilia are connected to the taller ones by tip-lengths, made up of protein substances. Tip-lengths also connect across bundles of stereocilia. The direction of stereocilia deflection, from the shortest to the tallest, or from the tallest to the shortest, is

caused by either an excitatory or inhibitory response respectively. The shearing of the stereocilia corresponds with the lengthening and shortening of the outer hair cells, an ability unique to these cells.



(Source: B Kachar, NIDCD)

Figure 2.20 - The stereocilia of the outer hair cells are arranged in a “W” like pattern and are aligned from tallest to shortest, connected together by tiny tip-length protein based filaments. Top: Scanning electron microscopy shows the stair-step pattern of stereocilia. Bottom: Fluorescence microscopy image.

Inner hair cell:

Inner hair cells are arranged in one row on the spiral lamina. There are approximately 3500 inner hair cells in each ear. They also have

stereocilia, which are arranged in a “U” shaped pattern from short to tall. The primary difference between inner and outer hair cells is the motor function. Unlike outer hair cells, inner hair cells are purely sensory and are not capable of movement.

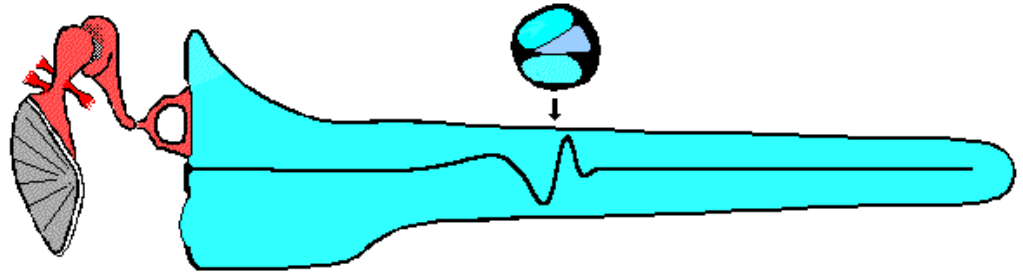
e) Central Auditory Pathway

Once sound passes through the peripheral auditory structures it has changed from vibratory energy to electrical stimulation and moves through the brainstem to the primary auditory cortex located on the temporal lobe of the brain. Referred to as the central auditory pathway, the complex system of nerve fibres and synapses must be in tact to make sound meaningful. The central auditory pathway enables fine distinctions in timing which aid in sound localization and sophisticated perceptions of sound quality.

f) Normal Hearing: Propagation of Sound through the Ear

For sound to travel through the ear, four different types of energy are required. First, *acoustical* energy or sound waves set the tympanic membrane into vibration synchronous to the sound pressure compression and rarefaction cycles. The eardrum responds and the acoustic energy is transduced to *mechanical* energy as the vibration is transmitted by the movement of the eardrum and the ossicular chain. At the stapes footplate, the medium through which the energy is propagated changes from the air in the middle ear to the fluid contained in the chambers of the inner ear. In the cochlear chambers, as the oval window is pushed in, by the piston-like motion of the stapes footplate, the perilymph in the scala vestibuli is displaced inward, perpetuating the wave of energy, called a *travelling wave*, through the helicotrema into the scala tympani. The vibration continues, causing the round window, at the opposite end of the cochlea, to protrude outward. The movement of the fluid causes the membranous walls of the scala media, which houses the organ of Corti, to move as well. Figure 2.21 shows a schematic drawing of the middle ear connected to the cochlea. The

cochlea has been unrolled to visualize more easily its function as a closed-end tube: the wave transmitted on the basilar membrane is shown.



(Source: Image used with permission Mammano and Nobili.
<http://147.162.36.50/cochlea/cochleapages/overview/index.htm>)

Figure 2.21 - A schematic representation of the propagation of sound waves: The middle ear is connected to an unrolled cochlea by the stapes. As the stapes footplate moves inward, the fluid in the inner ear is displaced creating the basilar membrane to move in a wave-like motion

At the level of the organ of Corti, the energy is both mechanical and *electrochemical*. The mechanical motion of the fluid and membrane movement causes the stereocilia on top of the outer hair cells (OHCs) to deflect. This deflection opens a “trap door” and allows a chemical exchange inside the hair cells. The stereocilia are organized from shorter to taller lengths. When the deflection is towards the tallest stereocilia, the cell is hyperpolarized, causing the cell to lengthen and become thinner. When the tip lengths bend towards the shortest stereocilia, the cell becomes depolarized, causing the cell to shorten and fatten. If the vibration detected by the outer hair cell is at its natural resonant frequency, the vibration will be enhanced. This repetitive shortening and lengthening of the outer hair cells pulls on the connected membranes, increases the movement the system to the degree that the inner hair cell stereocilia are deflected in like manner. In summary, at this stage of propagation, there is mechanical energy from the shearing of the stereocilia and electrochemical energy from the chemical exchanges in the fluids of the outer and inner hair cells.

The depolarization of the hair cells causes the release of neurotransmitters at the base of the hair cells. This chemical change creates an electrical signal that is sent to the auditory cortex, thus the energy is now *biochemical*. The chemical exchange thought to trigger the electrical stimulus involves the endocochlear potential. There is an electrical potential difference between the endolymph and the perilymph and it is hypothesized that the potassium flow between the cochlear fluids allows the cells to be more sensitive to minute pressure changes. The active process of the outer hair cells, called the “silent cochlear amplifier” or “cochlear amplifier” in effect pumps additional energy into the system by its ability to move. This enables us to make fine distinctions between frequencies and process them separately, known as *frequency selectivity*, and allows very soft sounds to become audible. It also creates an energy flow from the cochlea outwards to the outer ear which is known as an otoacoustic emission.

g) Pitch and Loudness Perception

Within the cochlea, sound is analysed for pitch and loudness characteristics by way of mechanical properties of the basilar membrane. The pitch of a sound is the human perception of the physical characteristic of frequency, or the number of cycles per second. Frequency is measured in Hertz (Hz), and is used interchangeably to refer to the pitch of a sound. Pitch is determined by the *position* on the basilar membrane of its maximum deflection in response to sound. The basilar membrane, (and in fact the auditory pathway) is “tonotopically” organized.

Like the keys on a piano, there is a progression from low pitch to high pitch from the apical end to the basal end of the basilar membrane . So, if the maximum deflection of the basilar membrane occurs in basal end, a high pitch tone is perceived. Refer to Figure 2.22 for a diagram of the tonotopic organization and of a travelling wave.

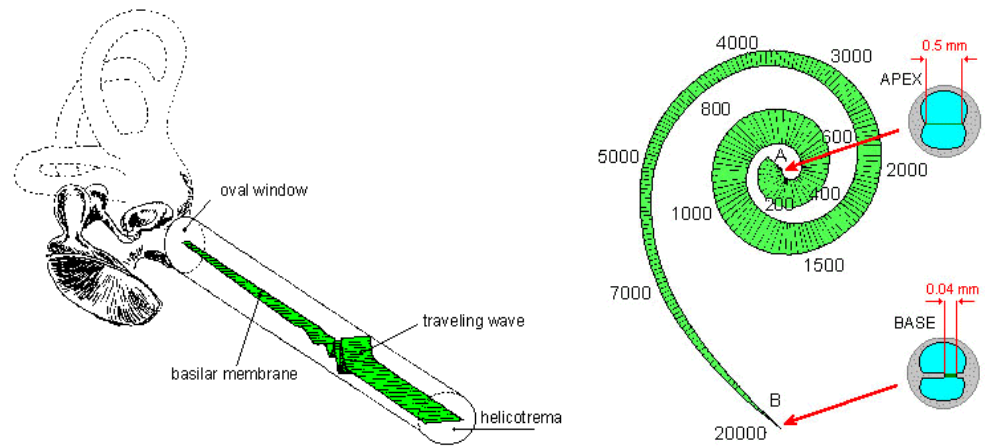


Figure 2.22 – The basilar membrane is tonotopically organized: it is responsive to high frequencies at its basal end and to progressively lower frequencies at the apical end. Properties of the organ of Corti affect the transmission of the vibration creating a traveling wave illustrated in an uncoiled cochlea. The point at which the traveling wave peaks corresponds to the frequency or pitch perception of the sound.

The loudness of the sound is determined by the amplitude, or *height* of the wave-like motion of the basilar membrane. The louder the sound, the greater is the mechanical vibration and movement of the basilar membrane, which increases both the number of hair cells that fire and the rate at which they fire. The brain recognizes the pitch and the loudness of the sound by the place and the rate of the hair cell stimulation. By measuring hearing sensitivity of various frequencies, the function of the ear can be assessed. The configuration of the hearing loss, as revealed in audiometry findings, is valuable for diagnosing ear pathologies, because pathologies affect the cochlea in different ways, often in unique and identifiable patterns.

h) Audible Range

Pitch/Frequency

Human hearing ranges in frequency from approximately 20 Hz (low pitch) to 20,000 Hz (high pitch). Hearing is most sensitive to the frequencies present in human speech, approximately 400 Hz – 5000 Hz. Vowel sounds tend to be lower in pitch while most consonant sounds tend to be higher in pitch. The ability to understand speech

requires the ability to discriminate between subtle differences in frequency.

Loudness/Intensity

The ear is very sensitive to changes in pressure, meaning it responds to an incredible range of intensities. The threshold of human hearing, defined as 0 dB at 1000 Hz, is equivalent to an intensity of 10^{-12} watts/m². This means the ear can detect a pressure change of less than one ten billionth of standard atmospheric pressure. On the other extreme, the threshold of pain is 10^{13} watts/m² which is equivalent to 130 dB. The dynamic range of hearing, from barely perceptible to painful is so large due to the unique anatomical and physiological properties of the ear, which amplify extremely soft sounds as well as provides some inherent protective mechanisms against extremely loud sounds.

The term “loudness” refers to the subjective perception of the strength of a sound. Loudness is related to, but not identical to the physical intensity of a sound because the ear is not equally sensitive to all sounds. Two different sounds may seem to be the same loudness yet have different intensities because hearing sensitivity varies by frequency. Variability in perceived loudness depends on many factors including genetics, age, work history, and other variables including differences between hearing capacity of each ear. This concept is best illustrated by plotting *equal loudness curves* (see Figure 2.10).

3. RISK ASSESSMENT AND NOISE SURVEYS

3.1 OCCUPATIONAL NOISE MANAGEMENT

Noise is often used to describe unwanted sound, but it is also often used interchangeably with sound as in “sound source” or “noise source”. The impacts it can have on an individual in an occupational environment depends on many factors, some which can be controlled while others cannot. However, the risk of exposure to these and the resultant risk of adverse outcomes to the individual need to be controlled or managed to an acceptable level.

The mantra for the control of any occupational hazard is

- Identify the Hazard
- Assess the Risk
- Control the Hazard or Exposure

Each jurisdiction has its own slightly different approach but they all have the same goal, that is to minimise the incidence of hearing loss or other problems caused by excessive noise exposures.

Identify the Hazard

This can be done by observation, discussion and measurement; it should be done in consultation with employees. It will require an audit and ranking of noisy processes and equipment.

Assess the Risk

To carry out a comprehensive noise management programme it is first necessary to determine the level of risk. This can only be done by observation and measurement and then comparison to acceptable standards or regulation. The measurements obtained in the identification stage may need to be supplemented to make a proper assessment of risk for the employees.

Control the Hazard or Exposure

The classic application of the hierarchy of controls can be used to reduce or remove unwanted noise exposures (Ref: <https://www.cdc.gov/niosh/topics/noise/reducenoiseexposure/noisecontrols.html>). This includes consideration of the following in the order listed: substitution options, engineering controls, administration controls and lastly personal protective equipment in conjunction with audiometric testing of the workers.

The elements of a noise management programme are included in the regulations or standards and in essence include:

- Assess the risks to your employees from noise at work;
- Take action to reduce the noise exposure that produces those risks using the hierarchy of controls approach;
- Provide your employees with hearing protection if you cannot reduce the noise exposure enough by using other methods;
- Make sure the legal limits on noise exposure are not exceeded;
- Provide your employees with information, instruction and training;
- Carry out health surveillance where there is a risk to health.

In each case noise measurements will have to be carried out to determine the level of risk or to assist in methods of control. This is achieved by noise surveys and will be covered in the later part of this chapter.

3.2 ACOUSTIC PARAMETERS AND MEASUREMENT

Noise Measures

Rarely is workplace noise static or steady, and even if it was, a moving person would receive a variable exposure. Noise levels will generally fluctuate to some degree as a function of variables such as the production rate or speed of equipment, product being manufactured, cyclical nature of machines, rotating equipment, process flow, etc. A sound level meter can measure

sound in different ways, so the number on the meter face is not meaningful unless it is understood what it represents.

There are two main types of weighting applied to the signal before a figure is displayed. They are frequency weighting and time weighting.

Frequency Weighting

For occupational assessments the most commonly used frequency-weighting networks are A, C & Z as discussed in Section 2. The A-weighting response is the most common and has a similar frequency response to that of the human ear at low level sounds over the 20Hz-20kHz frequency range. A-weighting is mandated by occupational and environmental guidelines to assess potential hearing damage and other health effects from exposure to noise. C-weighting reflects the human ear response at higher sound levels and is often used to measure peak sound levels and evaluate hearing protection. Z-weighting, or linear or flat, provides no adjustment to the sound pressure levels over the 20 Hz – 20 kHz frequency range and is often used to measure very high-level impulses and low-frequency noise

Time Weighting

Typically sound level meters will have selectable time responses, these are Slow, Fast, and Impulse. The Impulse response is a holdout from older needle-based instruments and is no longer used widely. The Slow and Fast time-weightings have been internationally standardized: 'S' (1 second) and, 'F' (125 milliseconds). Most occupational guidelines specify SLOW time-weighting for measurements.

The “fast” response is used to obtain the limits of a sound, such as the maximum or minimum, and is preferred when using the integration function on the instrument. Some references and standards use subscripts “S” and “F” for “slow” and “fast” response, respectively, with the reported level shown as LS and LF. When no subscript is described, then it is assumed the fast response was utilized.

A maximum or max hold is also available to allow for the determination of the loudest excursion of the meter over the averaging time. Should the Max be required it is important to ensure that the time constant specified in the regulation or code of practice is used.

The peak SPL, L_{pk} or L_{peak} , is defined as the greatest value of the absolute instantaneous sound pressure

Exchange Rate

Regulations governing noise exposure specify that unprotected exposure should be limited to a prescribed maximum noise level averaged over a nominal work shift. This defines a limit, but does not describe how time-varying noise levels should be handled when determining the noise exposure. Although the time/intensity relationship is most commonly referred to as the exchange rate, it is also referred to as the “doubling rate,” “trading ratio,” and “time-intensity trade-off.” The 3-dB exchange rate is also known as the equal-energy rule or hypothesis, because a 3-dB increase/decrease represents a doubling or halving of the sound energy.

The 3 dB trade-off relationship is called the exchange rate, which is commonly used to describe the metric employed for worker noise exposure determinations. Note: the exchange rate is also referred to as the doubling rate, trading ratio, or time-intensity trade-off. The concept here is that a person can accumulate the same noise exposure during a nominal workday by exchanging lower noise levels for more exposure time, or conversely, exchanging higher noise levels for less exposure time.

Not all jurisdictions have accepted the 3-dB exchange rate and there have been and still are some other exchange rates such as 6-dB and 5-dB in use. In the US, for example, federal OSHA uses a 5-dB exchange rate for regulatory compliance whereas the military and other organizations use a 3-dB exchange rate. Meters, in particular the older dosimeters can have the other exchange rates set as ‘factory defaults’ so beware and always check the settings before commencing measurements.

Equivalent Continuous Sound Level:

For the measurement of varying sound fields, it is necessary to average the sound energy over the duration of the measurement such as a cycle of operation or the whole work shift. *Equivalent continuous sound level*, expressed as $L_{eq,T}$, is used to quantify the average SPL for a given measurement period. It is worth noting the term *average sound level* is sometimes used when the exchange rate is different than 3-dB for all practical purposes, it is functionally identical. To obtain an $L_{eq,T}$ measure, an integrating SLM is used. The following equation may also be used to approximate the average sound level from a series of individual SPLs:

$$L_{eq,T} \cong 10 \log \left[\frac{1}{T} \sum_{i=1}^n t_i 10^{L_{pi}/10} \right] \text{ dB}$$

Where,

i is the i^{th} increment,

n is the total number of increments,

t_i is the duration of i^{th} increment,

L_{pi} is the SPL for each increment, and

T is the sum of all individual time increments.

Next, for averaging A-weighted sound levels, the expression is:

$$L_{Aeq,T} \cong 10 \log \left[\frac{1}{T} \sum_{i=1}^n t_i 10^{L_{Ai}/10} \right] \text{ dBA}$$

Where, the L_{Ai} is now the A-weighted sound level for the increment.

The $L_{Aeq,T}$ has many potential applications in standards and regulations governing noise exposure, evaluating hearing protection effectiveness, measuring the average level of equipment, and community noise assessment. Each of these applications is described further in the respective sections of this manual.

Although defined with the equations above, Figure 3.1 is useful to review for clearly explaining and understanding the terminology and symbol notation.

As shown in the figure, the capital letter “L” indicates “level,” the integration period or duration of the measurement is symbolized by “T,” the “A” represents the A-weighted filter is used, and “eq” indicates it is an average or equivalent-continuous level.

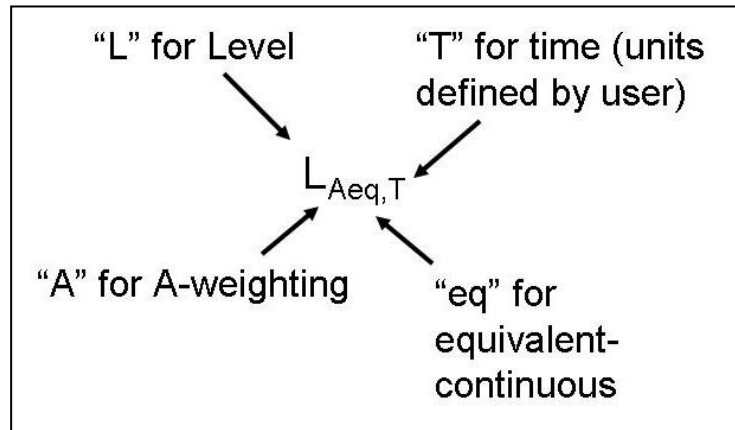


Figure 3.1 - Description of the symbol notation

It is important to note the term $L_{eq,T}$ may also appear in standards (especially ISO standards published in late 2007 to the present) as $L_{peq,T}$, where the subscript “p” indicates “pressure” as in SPL. For the A-weighted equivalent continuous sound level, $L_{Aeq,T}$ may appear as $L_{pAeq,T}$. For purposes of this manual the metrics $L_{eq,T}$ and $L_{Aeq,T}$ are used.

Noise Exposure:

To quantify the risk to workers it is necessary to determine their time-weighted average *noise exposure*. Most regulations consider eight (8) hours to be a nominal workday. Therefore, the term “noise exposure normalized to a nominal 8-hour working day,” and commonly expressed as $L_{EX,8h}$, is calculated as follows:

$$L_{EX,8h} = L_{Aeq,Te} + 10 \log \left[\frac{T_e}{T_o} \right] \text{ dBA}$$

Where,

$L_{Aeq,Te}$ is equivalent continuous A-weighted SPL,

T_e is the effective duration of the working day,

T_o is the reference duration, $T_o = 8$ hours.

Note: the term above is also called the “daily noise exposure level” or simply “noise exposure” in some references and standards. For this manual the expression “noise exposure” is used.

In those instances where the effective duration of the workday is equal to 8 hours, then $L_{EX,8h}$ equals $L_{Aeq,8h}$. For longer or shorter workdays normalizing all noise exposure results or data to an 8-hour day allows for easy and direct comparison to internationally recognized noise standards and regulations, whose noise criteria or exposure limits are typically based on an 8-hour day.

Noise Dose:

In addition to setting a limit for noise exposure, some regulations use the concept of *noise dose*, as in *Noise Dose*, *Dose*, or simply *D*. The use of this term has been largely superseded by the use of the $L_{Aeq,8hr}$ though it is widely used in the United States and few other jurisdictions. The use of the word ‘dose’ helps to explain how the individual noise exposures for the various tasks contribute to their overall daily noise exposure. The method below describes the mathematical basis but it was more common to use a chart for the determination of the partial and full noise doses.

The Daily Noise Dose is given as a percentage and shall not equal or exceed 100 and it is calculated according to the following formula:

$$D = [C_1/T_1 + C_2/T_2 + \dots C_n/T_n] \times 100$$

Where

C_n = Total time of exposure at a specified noise level, and

T_n = Exposure duration for which noise at this level becomes hazardous.

The daily noise dose can be converted to an 8-hr TWA according to the following formulas:

$$TWA = 10.0 \times \text{LOG}_{10} (D/100) + 85$$

Or (if using U.S. OSHA Standard based on 5-dB exchange rate and 90 dBA PEL)

$$TWA = 16.61 \times \text{LOG}_{10} (D/100) + 90$$

Determination of Daily Noise Exposure:

It is unusual for a person to be exposed the same noise level for the entire day. It is common for a determination of daily noise exposure for the noise level of individual tasks, or particular work areas, and the time the person spends at those tasks or in those areas to be determined. With this information the partial noise exposures for each of these tasks and then the overall noise exposure, $L_{Aeq,8h}$ determined using the following equation.

$$L_{Aeq,8hr} = 10 \log \left(\frac{1}{8} \int_8 \frac{p_i^2(t)}{p_0^2} dt \right)$$

Alternatively, the data in Table 3.1 can be used to assist with this determination. This table gives the value of p^2 for the different values of sound pressure level. So for each sound source or task the table is used to determine the value of p^2 in Pa^2 . which is then multiplied by the exposure time for that noise or task to give the partial noise exposure in Pa^2hr . All these partial exposures are added to give the total exposure for the day.

This is divided by 8 to normalize to the standard 8 hour day and the resultant value in Pa^2 is used to find from the chart the corresponding value for the sound pressure level. The outcome of this is the $L_{Aeq,8hr}$ which can be compared with the regulatory limit value.

Table 3.1 – Values of Pa² for a range of sound pressure levels

DECIBEL TO PASCAL-SQUARED CONVERSION									
dB	Pa²	dB	Pa²	dB	Pa²	dB	Pa²	dB	Pa²
75	0.013	85	0.13	95	1.3	105	13	115	130
75.5	0.014	85.5	0.14	95.5	1.4	105.5	14	115.5	140
76	0.016	86	0.16	96	1.6	106	16	116	160
76.5	0.018	86.5	0.18	96.5	1.8	106.5	18	116.5	180
77	0.020	87	0.20	97	2.0	107	20	117	200
77.5	0.022	87.5	0.22	97.5	2.2	107.5	22	117.5	220
78	0.025	88	0.25	98	2.5	108	25	118	250
78.5	0.028	88.5	0.28	98.5	2.8	108.5	28	118.5	280
79	0.032	89	0.32	99	3.2	109	32	119	320
79.5	0.036	89.5	0.36	99.5	3.6	109.5	36	119.5	360
80	0.040	90	0.40	100	4.0	110	40	120	400
80.5	0.045	90.5	0.45	100.5	4.5	110.5	45	120.5	450
81	0.050	91	0.50	101	5.0	111	50	121	500
81.5	0.057	91.5	0.57	101.5	5.7	111.5	57	121.5	570
82	0.063	92	0.63	102	6.3	112	63	122	630
82.5	0.071	92.5	0.71	102.5	7.1	112.5	71	122.5	710
83	0.080	93	0.80	103	8.0	113	80	123	800
83.5	0.090	93.5	0.90	103.5	9.0	113.5	90	123.5	900
84	0.10	94	1.0	104	10	114	100	124	1000
84.5	0.11	94.5	1.1	104.5	11	114.5	110	124.5	1100

Example

Consider an employee who undertakes the following tasks:

Use of planar with noise level at the ear of 102 dBA for 0.5 hours

Use of saw with noise level at the ear of 98 dBA for 4 hours

Use of drill with noise level at the ear of 89 dBA for 2.5 hours

Hammering with noise level at the ear of 92 dBA for 2 hours

Source	Sound pressure level, dBA	Sound pressure squared, Pa ²	Exposure time, hr	Sound exposure, Pa ² hr
Planar	102	6.3	0.5	3.2
Saw	98	2.5	4	10
Drill	89	0.32	2.5	0.8
Hammering	92	0.63	2	1.3
			Total Pa ² hr	15.3

To normalise to 8 hour day divide 15.3 by 8 to give 1.9 Pa²

Then find the value of sound pressure level corresponding to this value for Pa² is 97 dBA

So the $L_{Aeq,8hr}$ for the person exposed to these noises during the day is 97 dBA .

Determination for long days and for weeks

The criteria for noise exposure have been based on the typical work day being around 8 hours and that the remaining 16 hours are spent in considerably lower noise environments so that the hearing mechanism has an opportunity to recover before the exposure the next day. For those working long shifts or forced to rest in areas where the noise levels are not low, this 'recovery time' is considerably shortened. In some standards (AS1269 for example) there is a method for allowing for long shifts by adding a number to the calculated noise exposure. Table 3.2 gives the additional value from AS/NZS 1269.

Table 3.2 - Amount to be added to the $L_{Aeq,8}$ to allow for long shifts

Shift length	Adjustment to $L_{Aeq,8}$
up to 10 hr	0
10 to 14 hr	+1
14 to 20 hr	+2
20 to 24 hr	+3

So if the noise exposure, $L_{Aeq,8}$ is determined to be 89 dBA from a study of the noise levels and the time at each activity, if the actual time exposed to the noise is between 14 and 20 hours then the noise management plan should be developed on the basis that the noise exposure is $89+2$, i.e.:91dBA.

If a worker has very different noise exposure from one day to another then noise exposures determined from the averaged exposure over the entire week can be determined. This is based on the assumption that the ear has a longer recovery time during the days when the noise exposure is lower. For the determination of the noise exposure using the data over the week, the determination is made for each day in the usual manner. For each day the Pa^2 values are added and the total divided by 5, i.e. always normalized to a 5 day week, and the resultant $L_{Aeq,8}$ determined.

Example

For a worker with very different tasks on Monday, Wednesday and Friday to Tuesday and Thursday, the determinations of Pa^2 for each day have been found to be

Monday	0.06
Tuesday	0.63
Wednesday	0.06
Thursday	0.63
Friday	0.06
Total Pa^2 for the 5 days	1.44 Pa^2
divide by 5	0.29 Pa^2 and from Table 3.1
$L_{Aeq,8h}$	88.5 dBA

Thus the noise management plan can be developed on the basis of noise exposure of 89 dBA.

If the worker regularly works for 6 or 7 days the total exposure over all the work days should then be normalised to 5 days and the noise management plan developed on the basis of that exposure level. So for each day the Pa^2 values are added and the total divided by 5, i.e. always normalized to a 5 day week. The resultant $L_{\text{Aeq},8\text{h}}$ is then determined from the table of Pa^2 vs dB and the noise management plan developed on the basis of that level.

Example

For a worker on a 6 day schedule the determinations of Pa^2 for each day have been found to be

Monday	0.25
Tuesday	0.25
Wednesday	0.25
Thursday	0.25
Friday	0.25
Saturday	0.25
Total Pa^2 for the 6 days	1.50 Pa^2
divide by 5	0.3 Pa^2 and from Table 3.1
$L_{\text{Aeq},8\text{h}}$	89 dBA

Thus the noise management plan will need to be developed on the basis of noise exposure of 89 dBA.

Non-auditory risk factors

There is increasing evidence that non-auditory factors can have an effect so that a greater hearing loss is experienced than would be expected from the noise levels alone. At this stage there is insufficient evidence to quantify exactly the effect and the allowance that should be made to the noise exposure criteria. However, it is considered wise that noise management should be implemented at lower noise levels should employees be exposed to chemicals that are known to be ototoxic i.e. lead to hearing damage even without exposure to noise. Some examples of industrial ototoxic agents are solvents including toluene, styrene, trichloroethylene, carbon disulphide, xylenes, hexane and butanol, and toxic metals including lead, mercury and carbon monoxide. Also mixtures of solvents that include xylene, heptane and

ethyl benzene have been implicated in some ototoxic studies. In 2018, in the US, OSHA and NIOSH published an [informational bulletin](https://www.osha.gov/dts/shib/shib030818.html) to raise awareness of this issue, provide examples of ototoxic chemicals, list industries and occupations at risk and provide prevention information (<https://www.osha.gov/dts/shib/shib030818.html>). Also in 2018 in the US, the American Conference of Governmental Industrial Hygienists published a Notice of Intended Change to its TLV® recommendation proposing the adoption of an OTO designation in the “Notations” column to highlight the potential for a chemical to cause hearing impairment alone or in combination with noise, even below 85dBA. It stated that “the OTO notation is intended to focus attention, not only on engineering controls, administrative controls and personal protective equipment needed to reduce airborne concentrations, but also on other means of preventing excessive combined exposures with noise to prevent hearing disorders. Specifically, affected employees may need to be enrolled in hearing conservation and medical surveillance programmes to more closely monitor auditory capacity.” (2018 TLVs® and BEI® Notice of Intended Change. American Conference of Governmental Industrial Hygienists, Cincinnati, OH. p 74).

Other factors that have been considered to cause greater hearing loss when there is a combined exposure with noise include smoking, vibration, dust and stress.

3.3 EXPOSURE LEVELS AND LEGISLATION FOR NOISE

The general knowledge on the hazardous effects of noise exposure and means to protect workers continues to evolve. Even today there is no simple answer as to what constitutes a “safe” noise exposure limit. The answer is concealed in the intricate and diverse variables associated with an individual’s susceptibility to noise and with the characteristics and magnitude of the noise exposure.

It is important to keep in mind that, by definition, exposure accounts for both the magnitude of sound and duration a worker is exposed to various sound

levels. The A-weighted sound level is used in standards and regulations since it provides a single-number value (broadband sound level) to assess how humans perceive the loudness of sounds, and it correlates well with hearing-damage risk due to long-term noise exposure. In contrast the hearing damage risk from short impulsive noise like explosives is assessed in terms of the peak noise level in dBC.

Noise Exposure Criteria:

The principal challenge with setting an exposure limit is trying to balance worker protection versus economic feasibility. Both technical and policy considerations which affect the development of exposure criteria and their application to standards and regulations. These considerations include a) What proportion of the noise-exposed population should be protected?; b) How much hearing loss constitutes an acceptable risk?; and c) Should we protect even the most sensitive members of the exposed population against any loss of hearing, should we protect against only a compensable hearing handicap, or should we protect people against some amount of hearing impairment that lies between these two extremes? Presenting a detailed discussion on damage-risk criteria is beyond the scope of this manual.

In the late 1960s to early 1970s, both ISO and the U.S. based National Institute for Occupational Safety and Health (NIOSH) researched studies for selecting an appropriate noise exposure limit. In 1971, ISO formalized the standard *“Assessment of Occupation Noise Exposure for Hearing Conservation Purposes”*. Similarly, in 1972 NIOSH published their *“Criteria for a Recommended Standard: Occupational Exposure to Noise”* (NIOSH, 1998). Both scientific bodies recommended that an 8-hour noise exposure of 85 dBA be the limit where hearing conservation measures need to be implemented.

As a result of the ISO and NIOSH research, as well as most professional association recommendations when hearing conservation measures need to be implemented are:

a noise exposure criteria of 85 dBA for the 8-hour workday noise exposure

AND

at no time during the day should the peak level exceed 140 dBC.

These are the criteria in national legislation or guidelines in the majority of non EU countries. In 2003 the European Union passed the directive 2003/10/EC of the European parliament and of the council on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise), available in all European languages. [<https://osha.europa.eu/en/legislation/directives/82>]. This directive included a staged approach with a lower and an upper action level and an exposure limit. The UK Noise regulations have adopted this and the criteria summarised in the Noise at work Guidance for employers on the Control of Noise at Work Regulations 2005

[<http://www.hse.gov.uk/noise/regulations.htm> which states:

- The levels of exposure to noise of employees averaged over a working day or week; and
- The maximum noise (peak sound pressure) to which employees are exposed in a working day.

The values are:

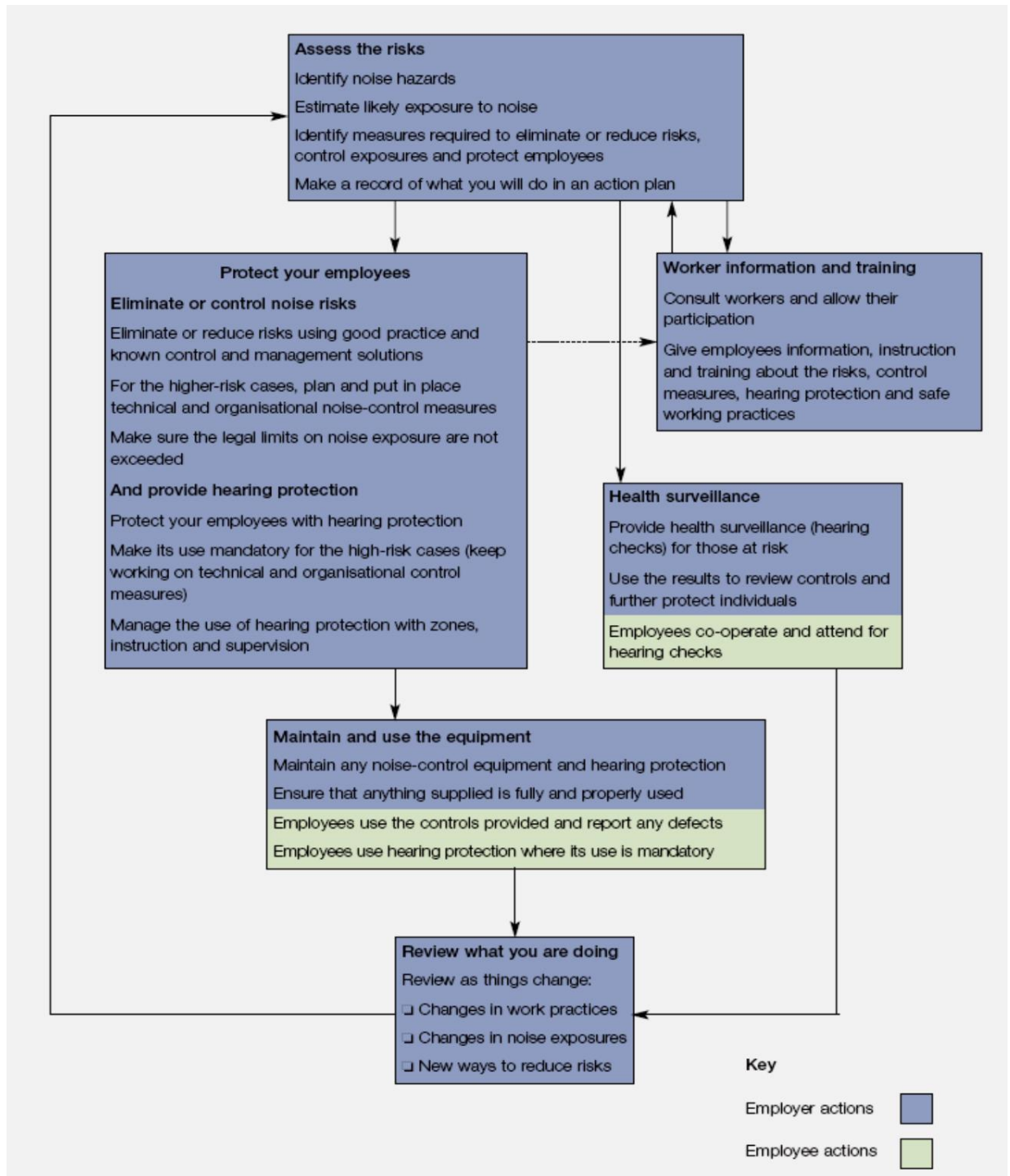
- Lower exposure action values:
 - Daily or weekly exposure of 80 dB;
 - Peak sound pressure of 135 dB;
- Upper exposure action values:
 - Daily or weekly exposure of 85 dB;
 - Peak sound pressure of 137 dB.

There are also levels of noise exposure which must not be exceeded:

- Exposure limit values:
 - Daily or weekly exposure of 87 dB;
 - Peak sound pressure of 140 dB.

These exposure limit values take account of any reduction in exposure provided by hearing protection.

The actions necessary at the lower and upper values are described in the HSE documentation and shown in Figure 3.2.



(Source: HSE "Noise at Work" – reproduced with permission)

Figure 3.2 – Recommendations for managing the risks once a noise hazard has been identified

3.4 ACOUSTICAL INSTRUMENTATION

3.4.1 Sound Level Meters

The *sound level meter* (SLM) is a device designed to measure sound pressure levels. Figure 3.3 illustrates the basic components of an SLM. The basic function starts with the microphone, which senses pressure fluctuations in atmospheric pressure and generates a relatively small electrical signal. Manufacturers provide information regarding the frequency of factory calibrations. Factory calibrations are performed using a specific guidance to ensure the electrical components are within specifications determined by the reference standards. Factory calibrations are done independent of field calibrations, which are performed before and after use in the field applications. Certifications are provided to the owners on the performance characteristics of SLM, octave band analyzer, or other noise measuring device.

The electrical signal is amplified by a preamplifier, and then is regulated to an applicable level by the range control on the meter. The signal may or may not pass through a filter weighting network (e.g., A- or C-weighting). Prior to taking an actual sound level measurement, the surveyor has the option of engaging the weighting network. If the network is bypassed, then the measured result is termed *linear* or *flat*.

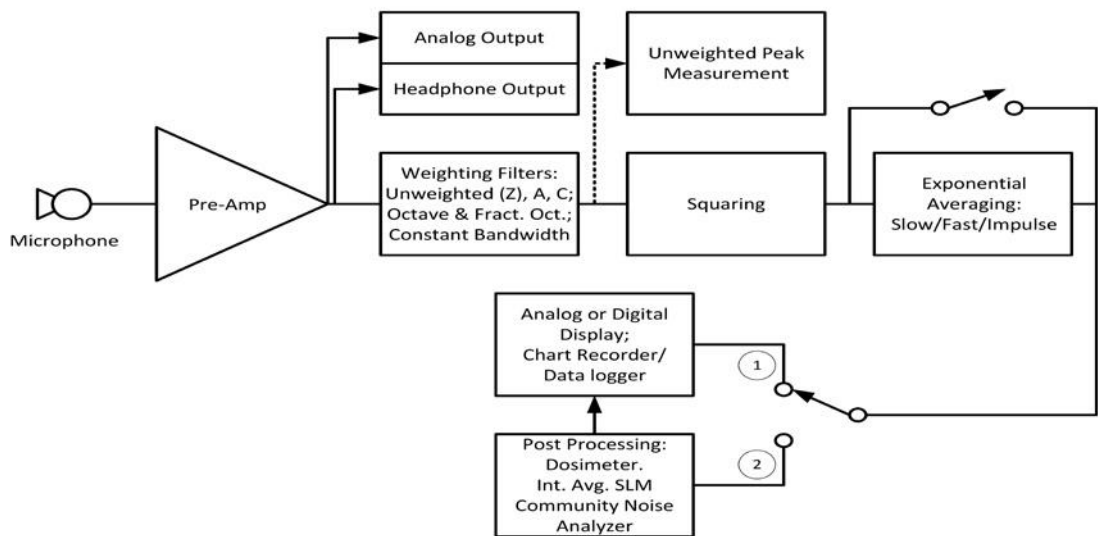


Figure 3.3 – Simplified block diagram of the components for a typical sound level meter (used with permission of William J Murphy and Chucri Kardous, CDC-NIOSH)

Some SLMs have internal frequency filters, or may allow for an external filter set to be attached. The frequency filters may be full octave-band, 1/3 octave-band, narrow-band, or any combination of the three options. The next step in the basic function includes a response circuit, which controls the damping of the readout on the display. For example, the dynamic response may be set to measure options such as fast, slow, impulse, or peak hold. The last step in the process is the display of the result.

The typical display with today's SLMs is digital (showing a number), but there are also older SLMs in use that employ an analog display. Some additional features may include functions such the capability to average or integrate sound pressure levels (SPLs), automatic hold of the maximum and minimum level, logging function (time-history of SPLs), data storage capabilities, Bluetooth® connectivity, FFT (Fast Fourier Transform) Waveform Analysis, and input/output connectors for sending data to a printer and computer.

a) Types of SLMS

There are two types or classes of SLMs established by International Standards (IEC 61672). Type 1/Class 1 is a precision meter, and Type/Class 2 is a general purpose instrument with lower performance specifications than Type 1/Class 1. Legislation should be consulted to ensure that the measurements are undertaken with the appropriate class of SLM. Typically, Class 2 SLMs should not be used for regulatory compliance enforcement but rather as a screening tool because of an inherent 2 dB error factor.

b) Types of Microphones and Their Use

Microphones are transducers that detect sound pressure and convert it into an electrical signal for subsequent processing.

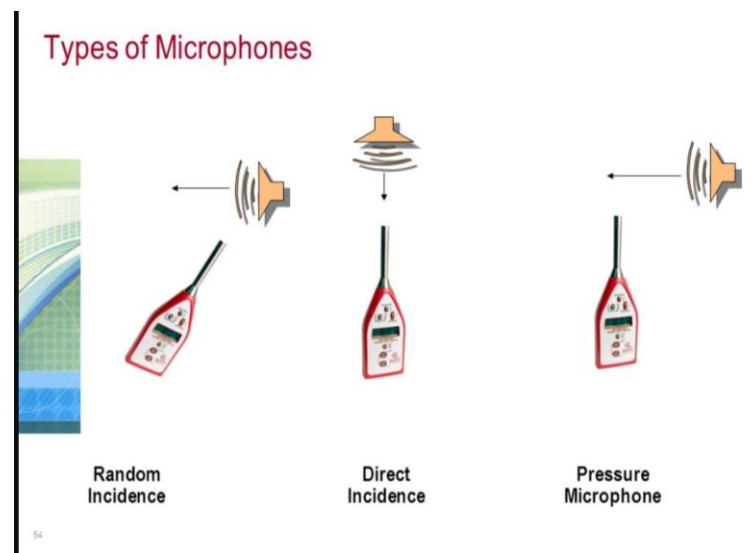
For occupational noise measurement there exist primarily three microphone types, as depicted in Figure 3.4, which are random incidence, direct incidence, and pressure microphones. Random incidence microphones, also called omni-directional, measure sound pressure levels more or less evenly from any direction and are designed for measurement in a diffuse field. It is common to use a random incidence microphone by holding it at a 70-degree angle to the noise source, which also facilitates reading the display. However, for occupational noise measurements it is more important to ensure that the microphone is measuring the sound reaching the ear.

Direct incidence microphones, also known as free-field or perpendicular-incidence, measure sound propagating toward the microphone at a 0-degree angle (held perpendicular to source), and are designed for measurement in free-field, i.e. non reverberant conditions.

Pressure microphones (pressure-response) are designed to measure sound level accurately at a 90-degree angle to the source (held parallel to source). They are often used to measure the high sound levels associated with explosions or blasting.

The most common microphone supplied by SLM manufacturers for occupational noise measurement is the random incidence or omnidirectional microphone. It is critical; however, that the user confirms the microphone type by reviewing its specification or checking with the manufacturer to ensure they are using the device properly.

It is also important to note that for all practical purposes most microphones used for workplace noise measurement are one-half inch (1.27 cm) or less in diameter. This means they are essentially independent of the angle of sound incidence at frequencies below approximately 6,000 Hz (Earshen, 2000).



(Source: Courtesy TSI/Quest Technologies, Inc.)

Figure 3.4 - Types of microphones and their use relative to the direction of sound propagation from the source

3.4.2 Sound Measurement Mobile Applications (Apps)

The ubiquity of smartphones and the sophistication of current sound measurement applications present a great opportunity to revolutionize current data collection and surveillance practices for noise. Through the use of crowdsourcing techniques, workers around the world may be

able to collect and share workplace (or task-based) noise exposure data using their smartphones. Scientists and occupational safety and health professionals can rely on such shared data to build job exposure databases and promote better hearing health and prevention efforts. In addition, the ability to acquire and display real-time noise exposure data raises workers' awareness about their work (and off-work) environment and allows them to make informed decisions about hazards to their hearing.

In 2014, researchers at the U.S. National Institute for Occupational Safety and Health (NIOSH) conducted an evaluation of applications that run on the Android and iOS mobile operating systems (Kardous and Shaw, JASA 2014). Applications were selected based upon whether they had different weighting functions (A/C/Z), selectable exchange rates (3-dB / 5-dB), adjustable time constants (Fast/Slow), equivalent continuous sound level (Leq) or time-weighted average (TWA). Other features that could be desirable were calibration adjustments, recording of samples, reporting and sharing of recordings and measurement findings. These selection criteria led to ten iOS apps and four Android apps and none for Windows operating systems. The results were reported for the iOS devices as the apps were consistent across the devices tested. Inaccuracies were noted for many of the applications across the different iOS devices with which the apps were tested. No effort was made to calibrate the products because most users do not have the ability to calibrate their mobile devices and will install the software and proceed to taking measurements. A similar study with iOS devices (Nast et al, 2014 Noise & Health) reported similar results. Their study reported accuracy with level and frequency for levels of 50 to about 95 dB SPL. Several of the apps exhibited a nonlinear response function as the amplitude of the input signal increased. In addition, the response of the app across frequency when presented the same level exhibited significant variations and nonlinearity. Nast et al (2014) recommended against using even the best application without a thorough calibration. Their recommendation highlights the problem with

using a mobile device with an integral microphone. The calibration of these devices can only be completed within a known sound field – something that professional users may be able to create but which is inaccessible to the general user.

Kardous and Shaw (2016) conducted a follow-on study using two external microphones with the four iOS applications and one Apple device. They found that when the microphones are calibrated, the accuracy of the measurements had confidence intervals less than ± 2 dB. For some of the apps and one of the microphones, the confidence intervals were less than 1 dB over a range of levels from 65 to 95 dB SPL. The NIOSH studies revealed that most commercially available sound measurement apps lacked the accuracy and functionality necessary to conduct occupational and general-purpose noise measurements. As a result, NIOSH researchers developed a sound measurement app for iOS devices that can be freely distributed to the occupational safety and health community as well as the general public.

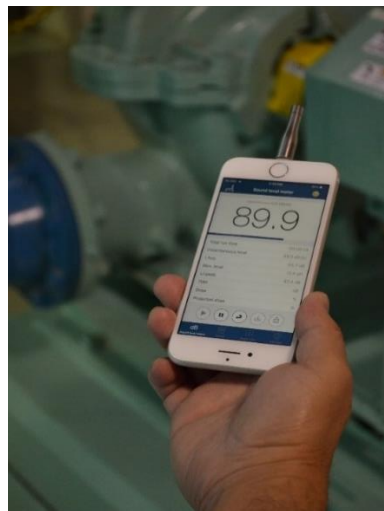


Figure 3.5 NIOSH Sound Level Meter app

(Courtesy of Chucri Kardous, CDC/NIOSH)

Professional sound level meters must comply with national and international standards such as IEC 61672 (ANSI S1.4) Specification for Sound Level Meters. IEC/ANSI standards specify acoustical, electrical,

and environmental tests with indicated tolerance limits and measurement uncertainties that are specified in decibels over a wide frequency range (typically from 10 Hz – 20 kHz). Such tests must account for level linearity, directionality, time and frequency-weighting responses, tone bursts, radio frequency interference, and atmospheric and environmental conditions. The standards also specify that these tests shall be made on the complete instrument, including the microphone and pre-amplifier. Celestina et al (2018) evaluated the performance of the NIOSH Sound Level Meter app as part of a system (iPhone + external microphone) for compliance with type 2 requirements of IEC 61672/ANSI S1.4 standard: Sound Level Meters – Part 3: Periodic Tests.

3.4.3 Acoustical Calibrators

An *acoustical calibrator* is a device that produces a fixed SPL at a fixed frequency, and it is used to check the meter function before and after carrying out a survey. This is known as a “field check” Performed in order to validate the manufacturer’s electronic factory calibration is within the inherent error factors of the instrumentation design. For example, most Type 2/Class 2 SLMs should be within 2 dB of the last electronic calibration at a single frequency of 1,000 Hz.

The calibrator is used by inserting the survey instrument’s microphone into an appropriately sized adaptor, which in turn is tightly inserted into the loudspeaker cavity on the calibrator. Next, following the SLM or dosimeter directions for calibration, the oscillator internal to the calibrator produces a fixed-reference frequency and output signal, which is boosted by an amplifier, and then transmitted by a loudspeaker to the microphone. Typically, the frequency is 1,000 Hz and the nominal output level may be selectable. Figure 3.6 shows a typical acoustical calibrator used for field calibration.

Typical Calibrator

- 1) Loudspeaker
- 2) ON/OFF switch
- 3) Battery indicator
- 4) Microphone adapter



(Source: Courtesy Quest Technologies Inc.)

Figure 3.6 – Typical acoustical calibrator used for field calibration

3.4.4 Frequency Analysis

Frequency analysis is a vital tool used extensively for noise control, evaluation of hearing protectors, and environmental or community noise assessment. Frequency analysis is conducted using an SLM with an octave-band or 1/3 octave band filter. The characteristics of these filters were discussed in section 2 of this manual.

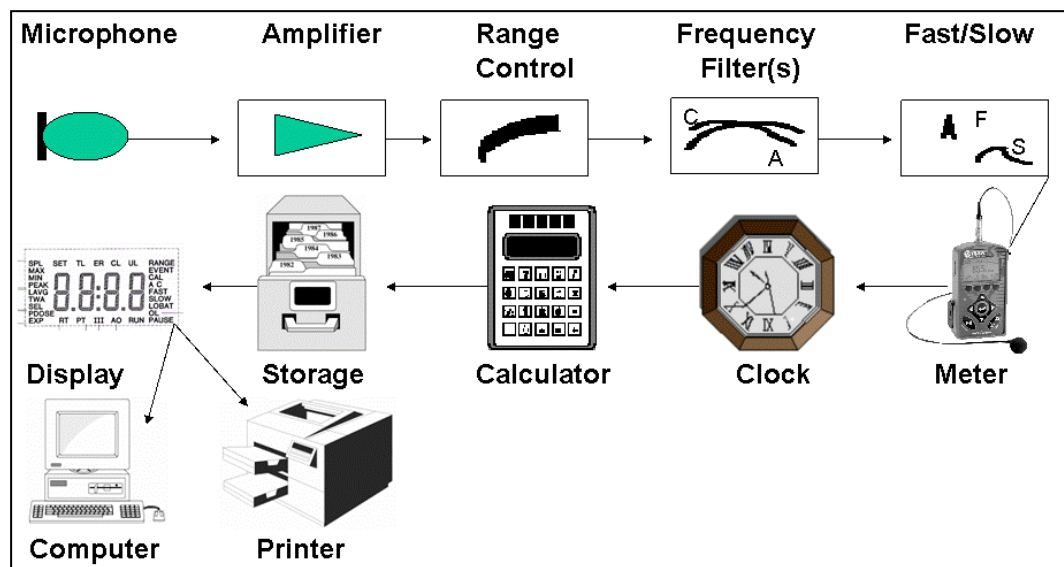
Besides octave-band analyzers, high-resolution frequency filtering, known as narrow-band analyzers are also available with more sophisticated SLMs. These filters transform a signal from the time-domain representation into a frequency-domain representation, while measuring all frequencies at once. This method is known as Fast Fourier Transform (FFT) analysis.

Narrow-band analyzers are used for advanced noise control efforts, such as tracing a distinct tone to a specific piece of equipment.

3.4.5 Personal Noise Dosimeter

The *noise dosimeter* is basically an SLM designed to measure a worker's noise exposure integrated over a period of time. The dosimeter is also referred to as a *noise dose meter* or a *personal sound exposure meter*; however, for purposes of this manual the term noise dosimeter is used.

Figure 3.7 depicts a simplified block diagram of a typical noise dosimeter. Essentially, the microphone, preamplifier, weighting network, and dynamic response are the same as for the SLM. The internal clock keeps track of sampling time as well as the period the dosimeter may have been paused (not sampling). The calculator computes the noise exposure, based on the criterion level, exchange rate, and threshold level set up internally on the instrument. Some dosimeters can measure using multiple criteria settings, which may be for regulatory compliance and any other internal purpose for the user. Next, the memory stores all times, calculations, and data. A digital display may be used to read the survey results, and/or the data may be downloaded to a computer or printer for post-survey analysis.



(Source: Courtesy Quest Technologies Inc.)

Figure 3.7 - Simplified block diagram for the components of a typical noise dosimeter

The dosimeter output will typically be available as both noise dose and noise exposure. Noise exposure may be shown in terms of a number of descriptors such as $L_{eq,8h}$, $L_{EX,8H}$, or time-weighted average (TWA). Note: the TWA is used predominately in the USA, and implies an eight-hour average.

3.5 ASSESSMENT SURVEYS

3.5.1 Instrumentation Requirements for Surveys

Personal noise dosimeters should at least conform to the requirements for Type 2/Class 2 instruments. Typically, Type 2/Class 2 SLMs should be sufficient for industrial environment surveys. Acoustical calibrators should also comply with appropriate standards, or their latest revision.

If SLMs and/or dosimeters are used in hazardous atmospheres or within areas where flammable/combustible gases, vapors, liquids, and dusts may be present; the SLM should meet the National Fire Protection Association (NFPA) or other country intrinsically safety requirements whereby the instrumentation can be used in and around Class I or Class II hazardous locations. Labeling information should appear on the SLM exterior for the user to understand.

Other instrumentation such as frequency analyzers, sound sources, statistical analyzer's computer software and hardware should all be calibrated to the manufacturer's recommendations and used in accordance with the manufacturer's handbooks.

The procedures described in the manufacturer's owner's manual must be followed to ensure proper use of each acoustical calibrator, sound level meters and noise dosimeter. Manufacturers provide information regarding the frequency of factory calibrations. Factory calibrations are performed using a specific guidance to ensure the electrical components are within specifications determined by the reference standards. Factory calibrations are done independent of field calibrations, which are performed before and after use in the field applications. Certifications are provided to the owners' on the performance characteristics of SLM, octave band analyzer, or other noise measuring device. All acoustical calibrators, sound level meters and noise dosimeters should be periodically calibrated against certified standards, as required by the manufacturer's instructions.

In addition, the SLM and/or noise dosimeter should be field checked before and after each measurement session. The pre-survey check includes verifying the instrument's accuracy, as well as performing any adjustments needed to match the output signal of the calibrator. The post-survey check is conducted without adjustment to verify that the instrument is still within the tolerance limits of the calibrator output. If the post-survey check indicates the reading is outside the limits (± 1 dB for Type 1/Class 1 and ± 2 dB for Type 2/Class 2 SLMs), then all survey data collected since the preceding check are considered invalid or suspect and the measurements need to be repeated until a valid post-survey check is achieved.

It is recommended practice to always use the microphone's wind screen provided by the manufacturer. Even though there may not be any concern for excess wind noise inside a facility the use of the windshield may reduce erroneous results caused by the microphone touching clothing and giving a false peak. The wind screen also helps protect the microphone from potential contamination due airborne particulate, moisture or dripping liquid, and physical damage due to accidentally bumping into machines or other solid objects.

Additional instrumentation information to document and maintain with the survey records includes the following:

- Name of area or department,
- Date,
- Name of surveyor,
- Manufacturer, model, and serial number for each instrument,
- Reason for survey (e.g. initial, change, periodic update, etc.).

3.5.2 Preliminary Survey

a) Purpose

The preliminary survey is a needs assessment. This survey identifies those areas, equipment items, and/or job classifications needing a more

detailed sound survey as the noise levels may represent a hazard for the workers in the area.

b) When to Conduct

A preliminary survey should be conducted after new equipment is installed, process changes occur, the size of the workforce changes, or in those areas where no previous sound level survey has been conducted.

c) Method for Conducting a Preliminary Survey

If a sound level meter is not available then a preliminary indication of the areas of concern can be obtained subjectively through multiple means. If one has to talk in a raised voice at an arm's length from a listener to be understood above the background noise, then this is an indication the sound level is likely greater than 80 dBA. Alternatively, consider the use of one of many publicly available mobile phone applications for an initial subjective assessment. If a Type 2/Class 2 sound level meter is used and the resultant sound level is 80 dBA or above, then a more detailed sound survey in those areas should be performed to fully assess the environment. Prior to conducting the preliminary survey, the sound level meter should be calibrated and be set to measure the A-weighted sound level, in SLOW response.

The person undertaking the preliminary survey should conduct a walk-through of the entire work area. Observations should be made at each piece of equipment, work station, or any desired location for the task duration, typical work cycle and/or change to a different task to make a clear determination as to whether or not the sound level equals or exceeds 80 dBA. All portable and/or intermittent sources, such as pneumatic hand-held tools, air compressors, saws, etc., need to be measured as part of this survey.

The presence of any sounds that could have excessive "peak" noise levels should be noted.

d) Reporting and Documentation

All areas less than 80 dBA should be documented as such. Documentation may take the form of a memo to the file indicating the date of the survey, the name of the surveyor, name of the area or department inspected, , instrument (make/model/type) used, calibration check, and the fact it has been identified as a low noise risk area.

For those areas with sound levels at 80 dBA or above, a detailed sound survey (e.g. sound contour mapping) should be scheduled and conducted as soon as possible. Sound surveys may be necessary for many other purposes, such as evaluating communications interference, evaluating rest areas, etc., but these are beyond the scope of this manual.

For some work environments lower exposure limits may exist such as for maritime and offshore personnel; and in these cases it is recommended the preliminary survey be bypassed for these work environments and comprehensive sound level and noise exposure surveys be conducted.

3.5.3 Detailed Sound Level Survey

Once there are areas where potentially hazardous noise levels have been identified, there are two general approaches to the detailed survey.

- One method involves determining the noise levels over a work area or around each particular machine. This method is referred to as an area or machinery noise survey.
- The other method focuses on determining the noise exposure for a person from data on the noise exposure for each of the tasks carried out during the day. This is referred to as a personal noise assessment/dosimetry- but it can relate to the noise exposure of other personnel undertaking that particular work pattern.

A detailed sound level survey needs to be repeated whenever there are changes to equipment, increase in workforce, change in work patterns or at maximum intervals of 5 years, but in the normal work environment it would be unlikely that process materials and operations remain constant for 5 years and more often would be expected.

The findings are used to check that the noise management programme is appropriate and is being implemented correctly. It is important to check the actual worker noise exposures as changes in work patterns can result in changes to exposures, even when area and equipment sound level surveys do not indicate a change in the sources.

Before commencing the detailed survey it is important to have a good understanding of the workplace practices, work schedules and the operation of the machinery. This involves talking with management, with supervisors and with employees. It is only once you have a good understanding of the factors that may be important for assessing the noise exposure of the workers that you can implement the appropriate sound level survey procedure.

When undertaking the noise survey it is important to not just focus on the measurements necessary for the determination of $L_{Aeq,8h}$ as there is also a need to determine if the peak noise level, L_{Cpeak} , exceeds the limiting level. Every report should have some reference to the potential for excessive impact noise. If it is clear from subjective assessment that there are no very loud impulsive sounds in the work area then this should be documented in the report. If there are noticeable then they should be measured at each location along with the L_{Aeq} .

A modern Type 1/Class 1 or Type 2/Class 2 SLM will permit you to measure sound levels and peak levels, within the upper limitation of the instrument, while most personal dosimeters can only measure sound levels up to 140 dB SPL (Kardous and Wilson, 2004).

For any noise hazard risk assessment there are three crucial noise measurements which must be reported. These are:

- Operational L_{Aeq} for each noise source and for each worker in the area
- Peak L_{Cpeak} for each worker in the area
- Estimation of $L_{Aeq,8h}$ based on the typical work pattern for the worker

For an individual noise assessment the noise level for each activity and the time spent doing that activity should be clearly listed along with the method of estimating the individual noise exposure, $L_{Aeq,8h}$. For an area survey the data or the map should be clearly presented and the areas where the noise levels are at a hazardous level should be identified to prioritize noise control efforts. For a machinery noise survey any work areas where the noise levels are likely to be hazardous should be clearly identified and priority given to reducing these high levels. For a noise control survey the detailed noise level data on the sources should be provided and used in the justification for the proposed noise control measures.

3.5.4 Area and/or Equipment Sound Level Survey

a) Purpose

The purpose of the area and equipment sound level survey is to document all machines and components operating at 80 dBA or above, identify required hearing protection areas, and create a priority list of noise sources suitable for noise control treatment.

The detailed survey should be repeated on a regular schedule, such as every five years, to validate or update existing data or sooner as indicated in the section above. Production records and other data should be reviewed to determine if the noise level is indicative of a regular work schedule. The noise in some sites vary depending on the work schedule and demand for production. This volatility makes it difficult in determining a regular schedule. Repeated efforts may be

needed to determine if the noise levels could increase above recommended levels of exposure.

b) Method for Conducting the Survey

Prior to the survey, the sound level meter should be calibrated and be set to measure the A-weighted sound level, "SLOW" response, and at least for 1,000 Hz. Multiple octave band frequency centers are recommended for precision instruments. Calibration should be done in a relatively quiet location such as an office setting to prevent any outside or environmental interference with the noise calibration.

For an area survey the measurement locations can be made in a systematic manner using a predetermined grid superimposed on the entire work area. Alternatively the measurements can be restricted to those regions used by the workers in the area.

For a machinery noise survey where there are only a specified number of worker locations, the measurements can be made at those worker locations. Alternatively the measurement locations can be distributed around the machine at an appropriate distance, which is typically 1m.

At each location the measurement microphone should be positioned so that it has the best opportunity to obtain data on the noise level at the ear of the person working in that area. The procedures in relevant standards and codes of practice for workplace noise measurement should be followed. Most recommend that the microphone should be at:

- 0.1 to 0.2 m from operator ear when the operator is present.
- if no person is present then 1.5 m above ground for a standing person or 0.8m above seat for a normally seated person

It is important to beware of the effect of the presence of reflecting surfaces and to note these down if they could be adding to the noise at the worker ear. As a worker rarely keeps their head in the one fixed

location during their working activity it is also good practice to move the microphone slowly around the general area of the selected measurement location. Also if the measurements are made with the worker present, repeat measurements should be made at the left and the right ear as the noise exposure may be different.

As discussed previously, although a windscreen is rarely needed to protect the microphone from wind it can be used to provide some protection for the microphone.

The time, T , for each measurement location should be long enough to ensure that the value of $L_{Aeq,T}$ is truly representative of the entire task or if it is a complex task then it needs to be long enough to include each component of that task. For instance if the source is essentially constant, a time of 30 sec to 1 minute may be sufficient. However if the noise level varies as the product is processed, the time T needs to be long enough to be representative of the entire task, tasks or worker exposure.

Using a Band Saw as an example the time period may need to be long enough to include set up, idling between cuts, cutting and staking of the cut product. To be representative the measurement time period needs to be long enough to include three, four or more cycles of such a process to allow for variance within the cycles.

It is critical to document the conditions at the time of survey, including information such as production rate, any nearby equipment either in operation or shut down, and any other operational variables. Preferably, measurements should be collected during typical operating conditions to record sound levels representative of normal daily operation. If the sound environment is unusual or abnormal (i.e., due to a temporary steam leak, equipment needing repair, etc.), then document these sound levels and conditions separately in the tabulated results and narrative report.

c) Sound Contour Map

Sound contour maps are an effective means to document the sound levels in an area. These maps can provide a simple representation of the sound field over a large area and identify those areas where the noise exposure could be excessive.

Various drawing software packages can be used to produce contour maps and the technique can be used also to demonstrate the noise levels around just one source. Alternatively, having a good floor plan of the facility while making measurements works as well.

Some detailed sound contour maps may colorize the relative risk of noise exposure so that workers better understand those areas where hearing protection is required. If the sound contour maps are done correctly, they can show the relative pattern of noise propagation in various work areas. In some working environments, the sound contour maps are posted along with signage for using hearing protection in the various work areas.

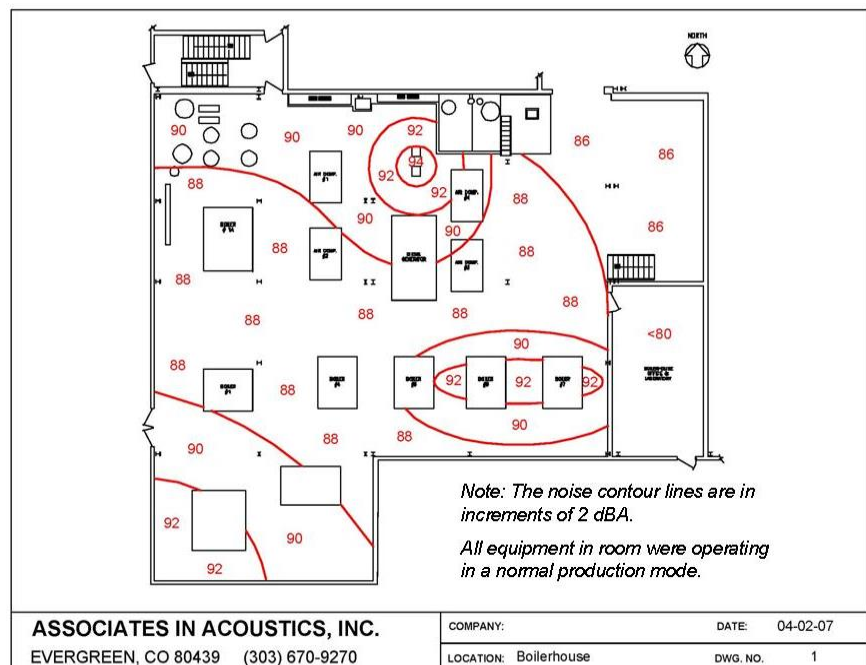


Figure 3.9 - Example of a sound contour map showing sound level contours in 2-dBA increments. This map was generated using AutoCAD 2004 and by manually drawing each contour line within the application programme.

Caution: it is important to keep in mind that sound contour maps are simply a snapshot in time of the sound levels on the day of the survey. The actual levels will vary from day-to-day, depending upon the product, production rate, and equipment actually operating in the area. Therefore, these maps should not be used to delineate fine lines on the production floor as to where hearing protection is and is not mandatory. Toward this latter item professional judgment needs to be exercised. It is common practice; however, that companies will designate the entire noise area, room, or department as a hearing protection area if it contains any sound levels above a specific threshold level, such as 85 dBA.

d) Reporting and Documentation

Notifications can be accomplished by posting the report and results in the workplace, or through individual notification, such as email or a written letter. Workers should be provided an explanation of the noise results in comparison to regulatory requirements and need to participate in a hearing conservation programme. Name of surveyor, survey date(s), measuring equipment, measurement location, details of the operating equipment production rate, any abnormal or unusual conditions, and measurement positions should be noted on the data table and/or described in the narrative report.

For an area survey the data or the noise contour map should be clearly presented and the areas where the noise levels are at a hazardous level should be identified to prioritize noise control efforts. For a machinery noise survey any work areas where the noise levels are likely to be hazardous should be clearly identified and priority given to reducing these high levels. The noise survey also should focus on identifying the contributing noise source.

3.5.5 Noise Exposure Survey

a) Purpose

The purpose of the noise exposure survey is to collect sufficient sound level and/or noise exposure data for personnel in the area to enable the hearing conservation programme administrator to make informed decisions regarding management of the programme.

b) Methods for Conducting the Survey

Individual Noise Assessment: This involves shadowing workers while they are carrying out their work or examples of their work. This is normally done by holding an integrating SLM at arm's length in proximity of the workers ear and taking a sample for the duration of the task while observing the process and noise sources during the task. The L_{Aeq} and the peak measurements are recorded and the next task is then undertaken. The data can be used in two main ways. One is to gain an indication of the likelihood of each task to contribute to the person's daily exposure. This method has the advantage of being relatively quick and allowing noise exposure modelling or profiling. The noise levels for each task are listed and those in excess of 85 dBA or 140 dBC are identified for further investigation

Table 3.3 - Example of results in a Noise Survey Result Table. This tabulates the Equivalent Continuous Sound Level in (A) weighted, Peak noise level and the exposure time required to exceed regulatory requirements.

No.	Work Process or Operation	L_{AeqT}	L_{Cpeak}	Complies with Regulatory Requirements
1	Cushman Truckster	75	103	YES
2	Cushman Spray Unit	76	102	YES
3	Quad Runner	72	101	YES
4	Honda Bike	67	-	YES
5	Mower Reelmaster 6700-D	83	102	YES
6	Mower Ransomes 213-D	83	102	YES
7	Mower John Deere 2653A	86	105	NO, if exposure exceeds 6 hrs 36 min
8	Mower John Deere F1145	90	115	NO, if exposure exceeds 2 hrs 32 min
9	Whipper Snipper Kawasaki	98	113	NO, if exposure exceeds 25 min
10	Blower Echo	94	108	NO, if exposure exceeds 1 hr 4 min

Predictive Noise Exposure Modeling

This method uses the data on the time or duration a worker is exposed to sound from each source, activity, or task throughout the workday to estimate the daily noise exposure. This process has been described in Section 3.4 of this manual. Start by conducting interviews with the supervisor and workers to clearly define the various work routines. Personal observations of the workers are also recommended to help understand the job functions. The $L_{Aeq,T}$ is measured for a representative time near to the operator's ear for each activity. An example noise exposure estimate is shown in Figure 3.10. In this example the job title is Carpenter and the department is the Wood Shop.

NOISE EXPOSURE ESTIMATION					
<p>This spreadsheet may be used to calculate the accumulated dose and $L_{Aeq,8}$ or $L_{EX,8h}$ based on area/equipment noise level data. Simply fill in the yellow shaded cells for the sound level in dBA and estimated exposure time (duration) in minutes for each job activity.</p> <p><i>Note: This spreadsheet will normalize all data for non-eight hour workshifts to an 8-hr day.</i></p>					
<p>JOB TITLE: Carpenter DEPARTMENT: Wood Shop SHIFT LENGTH: 8 hours</p> <p>ESTIMATED TOTAL DAILY NOISE DOSE AND $L_{Aeq,8}$ FROM EXPOSURE TO DIFFERENT SOUND LEVELS FOR DIFFERENT DURATIONS (3-dBA EXCHANGE RATE, 85-dBA CRITERION, NO THRESHOLD)</p>					
SOURCE NUMBER	JOB ACTIVITY/LOCATION	SOUND LEVEL, dBA	REFERENCE DURATION, MINUTES	EXPOSURE TIME IN MINUTES	% DOSE PER SOURCE
1	Hammering	89.0	190	30	15.75
2	Band Saw	95.0	48	30	63.00
3	Planer	88.0	240	60	25.00
4	Jointer	93.0	76	60	79.37
5	Router	96.0	38	120	317.48
6	Lathe	89.0	190	90	47.25
7	Clean-up	82.0	960	30	3.13
8	Lunch/Breaks	65.0	48765	60	0.12
<p>NOISE DOSE (%) AND $L_{Aeq,8}$ (dBA):</p> <p style="text-align: right;">TOTAL ACCUMULATED DOSE: 551.1 %</p> <p style="text-align: right;">CALCULATED $L_{Aeq,8}$: 92 dBA</p>					
<p>Calculations are based on a 85-dBA Criterion, No Threshold Level, with a 3-dBA Exchange Rate</p> <p>Reference Duration is the amount of time it takes to reach a 100% dose at a certain sound level.</p> <p>$L_{Aeq,8}$ is the average daily noise exposure in dBA, which is normalized to an 8-hour workday.</p>					

Figure 3.10 - Example application of spreadsheet to estimate the noise exposure for a Carpenter.

This assessment method is more applicable for those job activities or classifications that have well-defined work routines or patterns, and are exposed to continuous or consistently cyclic sound levels. It can also be used as a screening tool applying worst-case assumptions. That is, one can assume the worst case for the amount of time workers spend in the highest noise locations. If this worst-case estimate indicates that exposures would be well below an average of 85 dBA, then a more detailed risk assessment is not necessary.

Personal Noise Dosimetry: One method for determining worker noise exposure is through use of personal noise dosimeters. These are designed to be worn by the worker for part or all the workday. The microphone should be positioned, as per the manufacturer's instructions. However, typically the microphone is located at the top mid-section of the employee's shoulder or shirt collar. If the dosimeter control unit is connected via a cable then the control unit must be clipped to the wearer's belt or placed in a pocket. As dosimeter technology continues to evolve, there are more models that have the control unit and microphone in a self-contained device, which is attached to the shoulder and a master control unit for downloading at the end of the time period. Irrespective of the dosimeter configuration, the microphone should not be covered by any clothing. Care should be taken to ensure the dosimeter continues to be properly positioned should the employee remove or put on a jacket or personal protective clothing during the workday. Noise dosimeters continuously measure and process A-weighted sound levels obtained then produce an average level of noise exposure that occurred throughout the sample period.

The dosimeter should be set to measure the A-weighted equivalent-continuous sound level, $L_{Aeq,T}$, during the time period T, using a 3-dB exchange rate (check country specific regulations) and no threshold level. The peak detector weighting should also be set.

Caution: some jurisdictions require monitoring using different thresholds and/or exchange rates. For example, in some countries dual threshold levels of 80 dB and 90 dB, and/or a 5 dB exchange rate, may be required under the regulation. So it is essential that the appropriate legislation be consulted and the measuring equipment be set up in accordance with those requirements.

For a noise dosimetry survey the following procedures are recommended:

- Perform a battery check, as per the manufacturer's instruction, to ensure sufficient battery life exists for the intended sample duration. If necessary, start with a new battery.
- Calibrate the dosimeter just prior to starting the survey.
- Explain to the person being monitored the purpose of the survey, and address any questions or concerns they may have about wearing the dosimeter. Workers should be instructed not to scream or talk loudly into the microphone or allow their co-workers to speak loudly into the microphone. Some dosimeters may also record sounds, and when that is the case, the worker should be informed. Tampering with the measurement may adversely impact the outcome of the noise survey.
- Follow the dosimeter manufacturer's instructions for placement of the microphone and, if applicable, place the main body of the dosimeter on the person's belt where it will not interfere with their work or be uncomfortable. If corded, the microphone cord should be fastened to the garment worn by the worker to prevent entanglement with equipment and machinery. If a belt is unavailable, then it is acceptable to clip the dosimeter to the top of the pants or secure it in a pocket. Typically the microphone is to be placed on center of the shoulder with the cord behind the worker. Note: if the source of sound is directional, then it is best to locate the microphone on the side of the head closest to the source. Also, it is best to place the microphone on the worker first before starting the actual sample measurement to avoid extraneous noise from bumps and taps on the microphone during the set up.
- Explain to the wearer there is nothing they need to do other than perform their normal duties and they are not to remove the dosimeter or relocate the microphone once positioned by the surveyor.
- Explain to the person that if they are to wear additional clothing, such as a jacket or fire-retardant clothes, it is critical the microphone not be

covered. It is critical to ask the worker about this issue before mounting the microphone and, if necessary, take appropriate steps to avoid this potential problem.

- Obtain from the worker a brief description of their assignment or “normal” duties they expect to perform throughout the day.
- Once the dosimeter is placed on the worker find out when they are scheduled to finish work, then tell them what time and exactly where you will meet them to collect the dosimeter. From the author’s experience, if you do not tell the person when and where you will retrieve the dosimeter, they will often remove the dosimeter themselves and bring it to you or give it to a supervisor well before the actual end of the workday.
- During the sample period, check with the person several times throughout the day to ensure the microphone is still in its correct position, and see if they have any questions you may be able to address. Note: it is always a good practice to do an initial check with the person within the first 15-30 minutes of the sample period, as this will let the worker know you are observing them and especially to ensure the dosimeter and/or microphone cable are not interfering with their work. During that timeframe and intervals throughout the workday, periodically take noise measurements with a SLM to corroborate the noise dosimeter data. It may not always be similar if there is variability in the sound intensity.
- When possible, stay in the vicinity of the person or workers being monitored during the first 30-60 minutes of the sample period. Stay visually engaged with the workers by doing area sound level measurements, or any other industrial hygiene survey work. Observe the production or process equipment to obtain an understanding of its function and characteristics of its sound output. This procedure will be useful later when reviewing the dosimetry results and comparing them to the area and/or equipment sound level data.

- Meet the person at the pre-scheduled time and place, and only the surveyor is to remove the dosimeter. Stop or pause the dosimeter prior to removal, to reduce measurement artifacts.
- Briefly interview the worker and determine if their workday was normal, and if not, then find out what abnormal or unusual conditions or events occurred that could adversely affect the results.
- If time and circumstances allow, permit the workers to observe the preliminary results as they are readout and documented, and then briefly discuss the results with the workers.
- Verify the post-survey calibration.
- Record all final results as soon as possible.
- Post-survey, compare the dosimetry results to the area sound level data. Judgment needs to be used to assess whether or not the dosimetry results are reasonable, based on the magnitude of sound levels measured in the area where each person wearing a dosimeter worked. A word of caution: it is not unusual for the dosimetry results to be as much as 5 dBA higher than some of the equipment sound levels, due primarily to the on-the-body versus off-the-body effects on the microphone (Earshen, 2000). Note: these effects are minimized by proper dosimeter microphone placement. When using area sound level data to support the dosimetry results, the key is to look for consistency between the results.

In addition to the check list above, there are a number of things that can go wrong with a noise dosimetry survey, such as:

- Failure to follow the manufacturer's instructions for placement of the microphone.
- Failure to START THE DOSIMETER. Note: it is best to position the microphone on the worker first, then press the start or run key on the dosimeter. This step prevents any measurement artifacts that may result as the microphone is handled and secured to the worker.

However, it can also result in failure to start the dosimeter, especially if the surveyor is distracted or besieged by a group of workers all waiting for their turn to be set up with a dosimeter

- The microphone was accidentally pulled off, lost its wind screen, covered up by clothing, or was rubbing on the person's clothing or hair.
- The person being surveyed tampered with the instrument or microphone, either intentionally or inadvertently out of curiosity about the meter. Common attempts to tamper with the instrument include items such as shouting several times into the microphone, scratching or thumping the microphone, removing the battery for a brief moment, or removing the dosimeter and laying it next to a loud machine or in a quiet area for an extended period. Note: research has shown that attempts to intentionally manipulate the results by shouting, thumping, or blowing into the microphone may only add 1-2 decibels to the $L_{Aeq,8}$ or $L_{EX,8h}$ results when the noise environment is in the mid-80 dBA range (Royster, 1997). These effects are even smaller in environments with higher sound levels (greater than 90 dBA). Frequent observations of the worker will help prevent or minimize these issues.
- The person did not have a normal workday, or their workday was not representative of the job title of activity you intended to sample. For example, the person may be reassigned to another activity after the sample is started, or has to attend a training class or other meeting away from their normal work environment.
- The person was working in a windy area. The manufacturer's instruction manual should contain the maximum acceptable limit for wind speed, both with and without using a microphone windscreen.
- Battery, instrument failure, and/or post-calibration out of acceptable range.

Representative Worst-Case Monitoring: Representative monitoring may be used to streamline the number of dosimetry samples needed. When using this strategy observations and interviews are used to identify similar exposure groups that have the same job function or activity, and are exposed to similar sound sources. From groups containing four or more employees, it is recommended at least three individuals (or at a minimum of 20% of the total at-risk population) should be selected for monitoring with personal noise dosimeters.

Three-to-five dosimetry samples are suggested to clearly establish the highest or worst-case representative noise exposure that could typically be encountered by any employee within a similar exposure group. Professional judgment needs to be used when selecting those individuals for monitoring. Toward the selection process, those employees anticipated to be the highest exposed should be designated for monitoring. When only one to three employees comprise a job activity or classification, then each individual should be sampled.

Because of mobility and the variation in sound levels often experienced within a job function, it is best to monitor each employee as close to an entire work shift as practical. Assuming the workers who are monitored experience routine or normal work days, the noise exposure results should then be presumed to be applicable to all remaining employees within the particular job function. When more than one valid dosimetry result exists for the same job activity, the accepted procedure is to assign the highest noise exposure to all personnel within the group.

Note that representative monitoring strategy is meant to be used to establish the maximum exposure for a similar exposure group rather than to determine the true average and range of exposures. This is a precautionary approach that is protective of health while reducing the amount of time needed for surveys.

This strategy is usually the most suitable method to use when the objective is ensuring regulatory compliance. Should a more exact

exposure be desired, then the statistical monitoring approach described next is recommended.

Statistical Monitoring: When having difficulty clearly defining a representative noise exposure statistical monitoring may be used. In fact, statistical monitoring is preferred for individuals having job activities or classifications with highly variable work schedules, exposure to highly variable noise sources, and/or random mobility throughout the workday. An appropriate application of statistical monitoring could be when the work tasks for workers vary throughout the workday such as job shop. Other applications may be due variability in production output, alternating workforce, or changes in equipment and machinery use.

The objective of statistical sampling is to collect sufficient noise exposure data to make informed decisions regarding risk assessment. It is recommended that the sampling should include employees having daily noise exposures of 85 dBA (TWA, $L_{EX,8h}$, or $L_{Aeq,8}$ ≥ 85 dBA) on more than 5% of their workdays (roughly 13 days per year).

Caution: it is important when using statistical sampling to maintain randomness in the approach to selecting employees to be sampled. For example, it is not appropriate to exclude workers on days when you know their exposure will likely be “less than normal,” due to a scheduled training class, personnel meeting, or other activity carried out in a quiet setting.

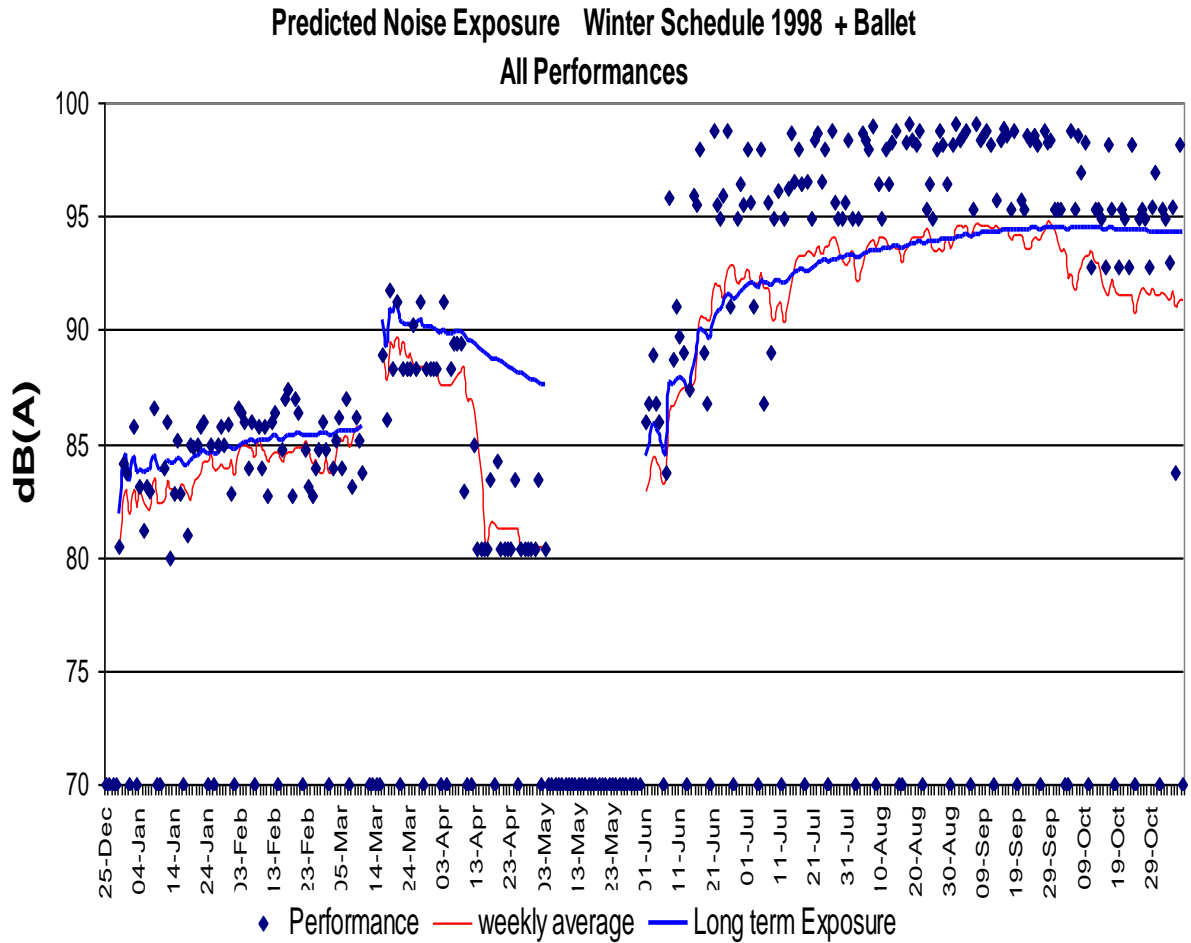
Monitoring should be sufficient to be confident that the upper 5% of exposures can be estimated with reasonable confidence. To establish the number of dosimetry samples required to identify the top 20 percent noise exposed to within a 95 percent confidence level, Table 3.4 should be used (Leidel, 1977).

Table 3.4 - Sample Size for Top 20% and Confidence 0.95

Total Number in Job (N):	7-8	9-11	12-14	15-18	19-26	27-43	44-50	51-∞
Required Number of Samples (n):	6	7	8	9	10	11	12	14

Note: Use $n=N$ if $N \leq 6$

Figure 3.11 is an example of statistical monitoring applied to the members of an orchestra in order to develop a noise management plan. The data for a position in the brass section was obtained for all performances over a year. The large difference in individual performance noise level related to the different performance programmes. This data was used to determine a long term noise exposure for a person who played every performance – a very worst case that would not be achieved as it was not possible for the one person to perform every performance. The data was also used to develop a roster as part of the noise management plan for the brass section.



(Source: K Mikl)

Figure 3.11 Example of statistical monitoring data used to determine long term noise exposure.

c) Data Analysis and Interpretation of Results

All noise exposure data should be normalized to an 8-hour average for purposes of comparison with criteria. The 8-hour average noise exposure should be referred to as the $L_{Aeq,8}$, but may be termed the time-weighted average (TWA), especially in the United States. However, $L_{Aeq,8h}$ is preferred as it implies the equal-energy principle (3 dB exchange rate) is used; whereas, TWA can be confused with the same term which has been used by the Occupational Safety and Health Administration in the U.S., which uses a 5 dB exchange rate in the TWA calculation. Also, for purposes of this manual the phrase “noise exposure” refers to the $L_{Aeq,8hr}$.

d) Reporting and Documentation

For each sound survey a written record should be prepared. NIOSH researchers (Babik et al., 2017) published standardized industrial hygiene data collection forms for many agents, including noise (<https://www.tandfonline.com/doi/full/10.1080/15459624.2018.1490022>).

The report should contain at least the following information:

- Purpose of the survey,
- Who conducted the survey,
- Date(s) of the survey,
- Survey procedure(s),
- Instrumentation, including model, type, and serial number,
- Instrument settings and record of calibration check,
- Department, areas, process units, and/or job activities surveyed,
- Any unusual conditions which would impact results,
- All sound level data tables and/or maps,
- Measurement data for each employee sampled,
- Noise exposure assignments per job activity or classification,
- A picture or general diagram of the work area and the approximate location of the worker in relation to the noise source.
- Names and identification numbers of all employees per affected job activity or classification,
- Recommendations, and
- Conclusions

The sound survey report and all data should be maintained for the time period defined in the applicable legislation, which could be 40 years or even longer.

e) Employee Notification

All employees assigned a noise exposure, whether determined from an actual or representative sample should be notified and provided an explanation of the results. Results should be conveyed to safety representative, department leads, and managers as well.

The notifications can be accomplished by posting the report and results in the workplace, or through individual notification, such as email or a written letter. Interpretation of the results should also be discussed at a future safety meeting. The worker should be provided an explanation of the noise results in comparison to regulatory requirements and whether there is a need to participate in a hearing conservation programme.

4. NOISE CONTROL ENGINEERING

The most effective way to prevent noise-induced hearing loss (NIHL) is through effective implementation of engineering noise controls at the source, between the source and receiver or at the receiver. Removing or reducing the cause of noise exposure is always the primary goal of any hearing conservation programme. Practical examples can be seen online at https://www.osha.gov/dts/osta/otm/new_noise/#engineering and <http://www.safeinsound.us/winners.html>.

Since control of all excessive noise sources can take an extended time the use of hearing protection is an immediate but interim defence. Conversely, there are situations where no feasible engineering controls exist, or they are cost prohibitive; and therefore, reliance on hearing protection becomes the principal means for preventing the effects of over exposure to noise.

In all workplaces a “*buy quiet*” approach should be adopted when purchasing new or when upgrading items of plant or equipment (see 4.10). A “buy quiet” policy is implemented by including noise limits in the purchase specifications or preferentially purchasing the lower noise plant or equipment. There are a number of resources available including <http://buyquietroadmap.com/> <https://www.cdc.gov/niosh/topics/buyquiet/default.html> and <https://www.hse.gov.uk/noise/choosequieter.htm>

Your local Government health and safety department may also have resources.

In determining the relative priority for implementing noise control measures, the employee exposures, the occupancy of the space and the overall area sound levels should be considered. Obviously, the desired result is to obtain the maximum employee noise exposure reduction for the monetary funds invested. Keep in mind noise exposures are a function of both the source magnitude and duration of exposure by workers. It is important to keep in

mind a 3 dBA reduction in noise is significant; as it represents a 50% reduction in sound intensity. Unfortunately, noise control engineering is not as easy as we may desire. Quite often it requires multiple steps to reach sound level goal of 85 dBA to 80 dBA throughout the workplace. Therefore, when the objective of the noise control effort is to eliminate all hearing-loss risk, it will require both patience and persistence; however, over time the success of these efforts will result in a safer environment for employees and long-term cost savings to the employer.

There are many options available to control noise and with increasing international efforts there are new and innovative solutions being developed. An effective noise control programme requires an understanding of:

- How sound is generated, including inherent design, as well as lack of maintenance and repair,
- How to identify the source(s) of noise,
- What the options are for treating the source, path, and/or receiver,
- How to determine the benefits and costs of noise control,
- What appropriate noise control products, and resources are available for selection and procurement, and
- What other methods are available to reduce worker noise exposure.

The information listed above is critical for addressing existing noise problems, as well as controlling noise during the procurement and design phases for new equipment and facilities.

Some noise control challenges lend themselves to straight-forward solutions. With an understanding of the principles of noise control and proper use of acoustical materials, both occupational health professionals and plant engineers can make significant progress in reducing equipment noise levels and employee noise exposures. However, there are situations where the acoustical environment is too complex, or the professional overseeing the

noise control programme simply does not have sufficient time, so outsourcing the project often occurs. As a result, a noise control engineer may be retained to conduct the detailed survey, identify the sources, design the engineering controls, and develop a plan of action for a client company.

In this situation, the programme administrator needs to have a good working knowledge of acoustics and noise control to effectively manage and/or assist the consultant, plus direct the implementation of various recommendations. To assist the reader in developing an understanding of acoustics, as applied in real-world occupational environments, this chapter focuses on the practical aspects of noise control engineering.

4.1 SOURCES OF MACHINE NOISE

Machinery noise is created for the most part by mechanical impacts, high-velocity air, high-velocity fluid flow, vibrating surface areas of a machine, and quite often by vibrations of the product being manufactured. It is important to understand how noise is created before any attempts to minimize it through good acoustical design are implemented. Similarly, understanding the noise generating mechanisms is useful toward the overall noise control programme, especially when it comes to facility design and/or equipment selection. The earlier in the design stage that consideration is given to the noise related aspects of a project, including equipment selection and layout, the greater the probability of success will be in preventing noise problems. Machinery noise control is a system challenge. Each component in the system needs to be considered individually as a potential noise source as well as the records for maintenance and repair. This chapter discusses many common noise sources, their acoustical characteristics, and presents design and/or selection considerations for noise control. Above all, maintaining and monitoring equipment are low cost measures that will avoid unnecessary and sudden noise issues. Later in this chapter more in-depth noise control measures are discussed, especially as they relate toward the retrofit of existing noise problems.

4.2 ELECTRIC MOTORS

The principal power source driving industrial equipment, such as fans or blowers, pumps, generators, etc., is the electric motor. Essentially, an electric motor converts electrical power into mechanical power, which motivates the component machinery attached via a coupling or belt drive mechanism.

Sources of Aerodynamic Noise and Considerations for Control:

Aerodynamic noise is generated by the fan used to move cooling air over the body of the motor. Here there are two sources of fan noise. The first being high velocity air striking the motor casing or body, and the second being turbulent air created by rotation of the fan within the fan housing. The first item will exist regardless of the fan type, as it is an essential component regulating motor temperature. The latter item can be addressed during the procurement stage. Unless a direction of fan rotation is specified by the buyer, electric motors are commonly supplied with a non-directional cooling fan. This fan type is designed to provide the requisite cooling service, regardless of its direction of rotation, i.e., clockwise versus counter-clockwise.

Sources of Mechanical Noise and Considerations for Control:

Mechanical noise is due to the rotational forces exerted on the rotor or shaft, which in turn passes vibratory energy into the attached components and support structure. Other mechanical sources include friction, impact, and unbalanced components. Selection of proper vibration isolation is imperative with all motors to minimize the transfer of vibration. The latter mechanical sources are controlled primarily during motor design and fabrication, and by ensuring proper installation and maintenance.

Source of Magnetic Noise and Consideration for Control:

Magnetic noise is due to the air gap between the rotor and stator that results in excess eccentricity. This results in harmonics that occur at each multiple

of the motor rotational speed. The only control measure here is to maintain the correct air gap, which typically occurs with machining or adjustment.

Selection of Low-noise Motors:

Since motor noise is related to the size and speed of the motor, motors should be appropriately selected for the task at hand. Therefore, it is important to keep in mind that most motor manufacturers have available low-noise units, built to tighter tolerances and higher-end components, and buyers need to decide if these motors are warranted for their application. Usually, these low-noise motors are desirable for locations where workers will be directly and routinely exposed to their noise output.

For electric motors already in production, there are a number of retrofit considerations, such as fan silencers, motor mounts, and acoustical enclosures. This is often a more expensive option than buying quiet at the start of a project or upgrade, but it could still represent saving when compared the many other requirement that excessive noise levels can trigger.

4.3 INDUSTRIAL FANS

Industrial fans or blowers utilize a power-driven rotating impeller to move high volumes of air for a variety of manufacturing and production reasons. All fans have at least one source of intake or inlet air, and another discharge or outlet air path. Fans are usually driven by electric motors, via direct drive or belts, but they may also be motivated by an internal combustion engine, or a steam or gas turbine. There are two common fan types in industry: axial and centrifugal. Axial fans have a set of blades attached to a hub, which in turn is mounted to a rotating shaft, as shown in Figure 4.1. Axial fans move air by creating a vortex type flow. A centrifugal fan, Figure 4.2, has a number of fan blades mounted around a hub, which moves air by centrifugal force. In general centrifugal fans are typically much lower in sound level than axial fans.

All fans will contribute noise based on the size and operating speed. Fans may also have different blade shapes and configurations which can affect

sound levels. Centrifugal fans, for example, can come with a variety of blade configurations, as shown in Figure 4.3. Fan options should be investigated to select the appropriately quiet fan for the application at the design stage.

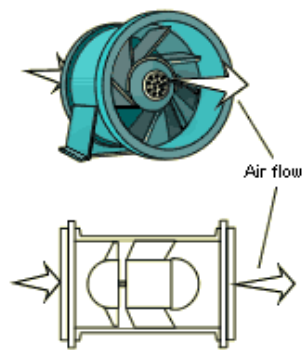


Figure 4.1 – Axial Fan

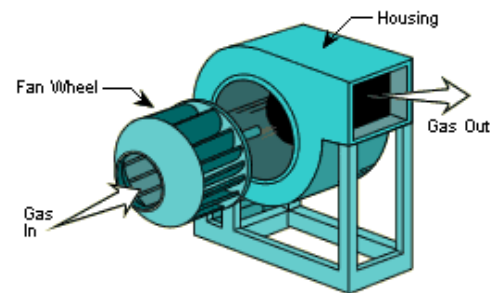


Figure 4.2 – Centrifugal Fan

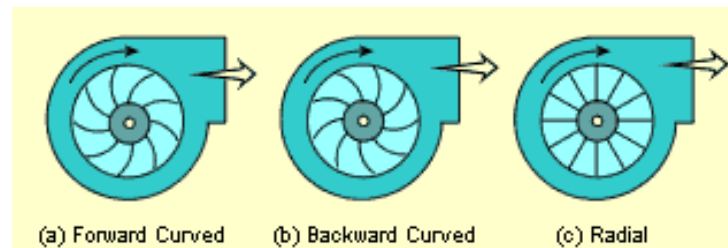


Figure 4.3 - Various fan blade configurations for centrifugal fans

There are a number of general guidelines that should be followed to prevent unnecessary noise from fans. One of the most comprehensive guidelines is published by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (Schaffer, 1991), which is presented herein with some adaptation:

Guideline for Controlling Fan Noise in the Design Stage:

1. Efficient fan selection and design will minimize the noise output. Carefully select the most efficient type and size of fan for the application. When possible, a low discharge velocity is also preferred.

2. When practical, to move a fixed volume of air, it is best to use large and slow moving fans instead of smaller, faster units.
3. Select the fan to operate on the right side of the fan curve, safely away from the stall region.
4. Allow a clearance of at least 1 fan wheel diameter at all unducted inlets and 1.5 wheel diameters at all unducted outlets.
5. Use vibration isolation mounts or hangers, with auxiliary bases, if required, for all fans over 1 hp located near noise-sensitive areas (such as offices, conference rooms, etc.).
6. Attach ductwork to fans with an elastomeric flexible connector to prevent transmitting fan vibration through ductwork.
7. Inlet and discharge transitions should be gradual. The total included angle within the transition should be no more than 15 degrees (1:7 slope).
8. In ducted installations, the nearest upstream and downstream silencer, sound trap, elbow, offset, transition, or take-off should be at least 3 equivalent duct diameters from the fan.
9. All duct fittings should be designed for low pressure drop, e.g., long radius elbows with full radius turning vanes.
10. Because noise travels upstream and downstream from a fan, silencers and/or duct liners are sometimes required in both the inlet and discharge air paths. However, before adding a silencer to a fan system, check to ensure all principles of good fan design are followed as best as possible, which may eliminate the need for a silencer.

Additional noise controls for retrofit to fan systems include vibration isolation, acoustical lagging of piping or ducts, and silencers.

4.4 COMPRESSORS

Compressors are mechanical devices that increase the pressure of gas by reducing its volume. In the workplace they are often used to power pneumatic equipment.

Types of Compressors:

Compressors can be sources of high-velocity fluid or gas flow noise. Centrifugal compressors are primarily used for continuous, stationary service industries such as chemical and petrochemical plants, oil refineries, and natural gas processing plants. It is not uncommon for compressor noise to be mistaken for pipe generated noise. Noise within a pipe can be effectively handled with in-line silencers and/or acoustical lagging.

4.5 PUMPS

Pumps are very similar to compressors in that they pressurize and move liquids or gases. The purpose of the pump is to convert this energy into pressure energy of the fluid to be pushed through the associated piping system. It is not too common for a pump itself to be noisy.

Sources of Pump Noise and Considerations for Control:

When pumps do generate high noise levels, the sources are usually the power (electric motor or internal combustion engine) used to drive it, the shaft or coupling, and the associated piping system. For example, it is possible for a long length of pipe to resonate at the pump running speed, resulting in pipe vibration and airborne noise. This issue is eliminated by changing the length of pipe by perhaps adding a longer loop in the line, which will prevent any resonance. As far as other noise controls for pumps, typically retrofit applications such as acoustical lagging (also called insulation or cladding), vibration isolation, and/or enclosures are the primary options. In addition, pump noise is also minimized by operating it as close as possible to the design point, which is its maximum efficiency. Cavitation is avoided by keeping adequate head on the pump suction.

4.6 HYDRAULIC NOISE

Hydraulic systems use pressurized hydraulic fluid to drive machinery and/or its components. Noise due to hydraulics is usually associated with the pump drive motor, actuators, fluid flow, including pulsations and cavitation.

4.7 MECHANICAL IMPACTS

Mechanical impact noise is common in equipment utilizing air valves or solenoids, punch press devices, riveting operations, application of impact and percussive pneumatic hand tools on metal structures, etc. Controlling impact noise requires proper set up and maintenance of equipment and effective damping to reduce radiated noise from the surrounding surfaces. Also keeping equipment operation within the initial design parameters will help minimize impact forces on the system.

4.8 PANEL OR STRUCTURE RADIATED NOISE

Manufacturing and process equipment can generate vibratory energy, which is transferred to a surface that may be an efficient radiator of sound. An example would be an electric motor directly mounted to the metal casing of a machine. Although the casing is not the origin of the acoustical energy, it becomes a sounding board, typically radiating noise that exhibits a resonant tone based on the vibrational characteristics of the panel or surface area. Controlling panel radiated noise is best accomplished by dividing large sections of a machine casing into smaller sub-sections, adding mass, damping and stiffness where practical, or similar means available to minimize the sound radiation efficiency of a panel. Although in the motor example described above, the best control is to add vibration isolation at the motor footings or attachment points.

4.9 ENGINEERING CONTROLS

Reducing excessive equipment noise may be accomplished by treating the source, sound transmission path, receiver, or any combination of these

options. A description of these control measures is contained herein. Online resources where some examples of control measures are discussed include:

- <http://www.hse.gov.uk/noise/reducenoise.htm>
- https://www.osha.gov/dts/osta/otm/new_noise/
- <http://www.safeinsound.us/winners.html>
- <https://www.nap.edu/catalog/12928/technology-for-a-quieter-america>.

4.9.1 Some Approaches to Control at Source

The best long-term solution to noise control is to treat the root cause of the noise problem. However, for source treatment to be effective it almost always requires a comprehensive noise control survey be conducted to clearly identify the source and determine its relative contribution to the area's noise level and worker's noise exposure. Noise is caused for the most part by mechanical impacts, high-velocity fluid flow, high-velocity air flow, and vibrating surface areas of a machine.

a) Avoiding or Minimizing Impacts

Impacts due to the force of one object hitting another are a primary noise generating mechanism. These collisions are often the result of metal-to-metal impacts, parts hitting each other, or parts hitting hard surfaces such as hopper bins, conveyor chutes, indexing of machines, etc. When impact noise is identified as a cause of high noise, the control options to investigate are reduction of the driving force, reduction of the distance between impacting parts, dynamically balancing rotating equipment, and maintaining equipment in good working order.

b) Pneumatic or Compressed Air Systems

High-velocity air from compressed air and pneumatic devices such as air valves, solenoids, or air cylinders is one of the most common noise sources within manufacturing equipment. However, in many air valve set ups it is the direct exhausting of compressed air to atmosphere that generates excessive noise. Additional compressed air applications

involve the use of air guns or nozzles, which are used to clean parts, blow off debris, and/or eject product from a conveyor line.

c) High Velocity Fluid or Gas Flow

High-velocity fluid flow in pipe lines can often create excessive noise as the transported medium passes through control valves or simply passes through the piping. Frequently, noise is carried downstream by the fluid, and/or vibratory energy is transferred to the pipe wall. A comprehensive acoustical survey can separate out the actual source, which will help identify the appropriate noise control measures.

d) Surface or Panel Radiated Noise

Machine casings or panels can be a source of noise when sufficient vibratory energy is transferred into the metal structure and the panel is an efficient radiator of sound. Typically, machine casings or large metal surface areas have the potential to radiate sound when at least one dimension of the panel is longer than $1/4$ wavelength of the sound. A thorough noise control survey will assist with identification of the source of vibration and the existence of any surface radiated sound. When a machine casing or panel is a primary noise source, the most effective modification is to reduce its radiation efficiency.

e) Vibration Damping

Vibration damping involves application of a material to the surface of a structure to reduce its ability to vibrate and efficiently radiate airborne noise. The primary use of vibration damping is to treat structural resonances, which are inherent in systems comprised of stiffness and mass.

The noise reduction of all damping materials are in general frequency and temperature dependent. Some common applications for vibration damping include:

- Hopper bins and product chutes,
- Thin metal machine casings or panels that radiate resonant tones, such as pellet transfer lines, machine casings or panels, compressor intake and exhaust ducts, etc.,
- Metal enclosure walls,
- Fan housings, and
- Gearbox casings

f) Vibration Isolation

Most industrial equipment vibrates to some extent. Whether or not the vibrating forces are severe enough to cause a problem needs to be determined by comprehensive noise survey. As machines operate, they produce either harmonic forces associated with unbalanced rotating components, or impulsive forces attributed to impacts such as punch presses, forging hammers, shearing actions, etc. Excessive noise can be one result; however, more common is the potential damage vibratory energy can cause to the equipment itself, the building, and/or the product being manufactured.

Quite often vibration problems are clearly identified by predictive-maintenance programmes that exist within most industrial plants.

Assuming the root cause or source cannot be effectively modified, the next option for controlling undesirable vibration is to install vibration isolation. Isolators come in the form of metal springs, elastomeric mounts, and resilient pads. These devices serve to decouple the relatively “solid” connection between the source and recipient of the vibration. As a result, instead of the vibratory forces being transmitted to other machine components or the building, they are readily absorbed and dissipated by the isolators.

For selection of the appropriate isolation device(s), it is recommended the expertise of trained professionals be used. It is critical to note that

improper selection and installation of isolators can actually make a noise and vibration problem worse. Many manufacturers of vibration isolation equipment have useful websites where existing problems can be defined and solutions recommended.

Some common applications for vibration isolation are:

- Pipe hangers,
- HVAC equipment,
- Flex connectors for piping systems,
- Rotating machinery mounts and bases for electric motors, compressors, turbines, fans, pumps, etc., and
- Enclosure isolation.

g) Silencers

Silencers are devices inserted in the path of a flowing medium, such as a pipeline or duct, to reduce the downstream sound level. Typically, for industrial applications the medium is typically air.

There are basically three types of silencers: dissipative (absorptive), reactive (reflective), and combination of dissipative and reactive elements. The type of silencer required will be dependent upon the spectral content of the noise source and operational conditions of the source itself.

To decide what type of silencer is best for a particular application, it is recommended a trained professional be used. The manufacturer or their designated representative will need to work closely with the facility engineering representative(s) to clearly identify all operational and physical constraints.

Typical applications for silencers are:

- High-pressure gas pressure regulators, air vents, and blow downs,
- Internal combustion engines,
- Reciprocating compressors,
- Centrifugal compressors,
- Screw compressors,
- Turbines,
- Rotary positive displacement blowers,
- Rotary vacuum pumps and separators, and
- Industrial fans or blowers.

4.9.2 Replacement with Low Noise Alternative

Another source treatment is to use alternative equipment or materials that are inherently quieter, yet still meet the production needs. This option is called substitution for the source.

Often equipment manufacturers have alternative devices that perform the same function at lower noise levels. However, these quieter devices typically cost more, as they require tighter tolerances and more precision as they are manufactured, for example low noise blades for saws.

The supplier's or the manufacturer's website should be consulted to learn if quieter equipment is available and at what additional cost.

Particular focus on quieter alternatives should be sought for:

- Gears,
- Bearings,
- Fans or Blowers,
- Control valves,
- Trim valves,
- Air compressors,
- Pneumatic hand tools,

- Air guns and nozzles,
- Furnace burner nozzles,
- Electric motors,
- Pumps, and
- Impact tools.

There may also be opportunities for alternative and quieter ways to accomplish the task or intended service. Just some examples of source substitution include using belt drives in place of gears, using an electric motor to remove bolts, etc., in place of impacting and replacing omni-directional fans on electric motors with unidirectional aerodynamic fans.

4.9.3 Treatment of the Sound Transmission Path

Assuming all available options for controlling noise at the source have been exhausted, deemed infeasible, or simply do not provide sufficient noise reduction, the next step in the noise control process is to determine ways to treat the sound transmission path. Typical path treatments include adding sound absorption materials to the room or equipment surfaces, sound transmission loss materials between rooms, acoustical enclosures, barriers, or any combination of these path treatments.

a) Sound Absorption Materials

Sound absorption materials can be used to reduce the build-up of sound in the reverberant field. Any benefit from additional sound absorption in the room will only be in the far field and not close to the machinery (where the operator is often located).

From a conceptual viewpoint, adding sound absorption to the surfaces of a room has both advantages and disadvantages as outlined below:

Advantages:

- Can provide a reduction in the reverberant sound build-up, especially in pre-existing hard spaces,

- Works best in relatively small volume rooms or spaces (less than 300 m³),
- Can be purchased and installed at a reasonable cost, and
- Works best on mid-to-high frequency noise.

Disadvantages:

- Room treatment does nothing to address the root cause of the noise problem,
- Can interfere with facility lighting, ventilation, and/or sprinkler patterns,
- Does not reduce any noise due to direct sound propagation,
- Will have no measurable benefit to employees working primarily in the direct field,
- Cleaning and maintenance of porous sound absorbing materials can be problematic,
- The materials can deteriorate over several years, and may need periodic replacement (perhaps every 7-10 years), and
- Rarely does this form of treatment alone eliminate the need for hearing protection.

b) Sound Transmission Loss Materials

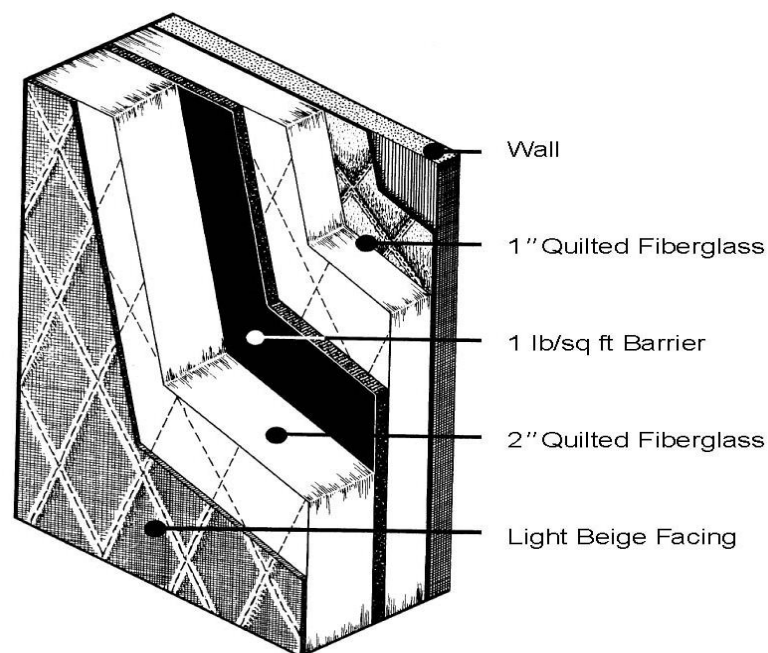
Sound transmission loss (TL) materials are used to block or attenuate noise propagating through a structure, such as walls of an enclosure or room. These materials are typically heavy and dense, with an increased ability to reduce sound being transmitted through the material. Common applications include enclosure panels, windows, doors, and building materials for room construction.

c) Multilayer Panels

Quite often the manufacturers of acoustic enclosures will combine a sound absorption material (often light and soft) with a high transmission

loss material (usually solid, heavy and dense) to form a composite system (see Figure 4.4).

The enclosure panels should have the sound absorbing material facing the noise source supported by the solid exterior panel. Sound absorption and dissipation by the light material reduces the build-up of sound energy (reverberation) within the enclosure. The solid material helps block the sound from penetrating outside the enclosure.



(Source: Courtesy McGill AirPressure LLC)

Figure 4.4 - Illustration of a panel comprising sound absorbing material on the side facing the sound and a solid outer shell providing good sound transmission loss.

d) Acoustical Enclosures

The acoustical enclosure is probably the most common path treatment. Quite often enclosures are used to address multiple noise sources all at once, or when there are no feasible control measures for addressing the source.

However, there are a number of pros and cons associated with this form of noise control that should be considered by the user.

The pros of enclosures are as follows:

- Does not require definitive identification of the source or root cause of the noise problem,
- A well-constructed enclosure (no acoustical leaks) can provide 20-40 dB of noise reduction,
- Can be installed in a relatively short time frame,
- Can be purchased and installed at a reasonable cost, and
- Provides significant noise reduction across a wide range of frequencies.

The cons are:

- Worker visual and physical access to equipment are restricted,
- Can be difficult to provide acoustic seal around opening for product or connections for services,
- Repeated disassembly and reassembly of the enclosure often results in the introduction of significant sound flanking paths via small gaps and openings along the panel joints,
- Heat build-up inside the enclosure can be problematic,
- Internal lighting, gas detection, and/or fire suppression may need to be incorporated into the design,
- Can create a confined space and related entry concerns for workers,
- The long-term potential for internal surface contamination from oil mist or other airborne particulate is an issue and must be dealt with through periodic cleaning or replacement of the sound absorption material,
- The panels become damaged or the internal absorption material simply deteriorates over time,

- Enclosures require periodic maintenance, such as replacement of seals and gasket material, to keep the acoustical integrity at a high attenuation value, and
- Employee acceptance, especially in a retrofit situation, can be difficult to achieve.

Machine enclosures normally exhibit significant gaps around pipe penetrations, small cracks due to wear and tear, and openings for operator access and product flow. As a result, the actual noise reduction achieved will be less than that estimated from the TL of the components alone. Similar principles apply to the construction of an enclosure around the operator when it is not cost effective to install enclosures around the noise sources. This enclosure then becomes a quiet space for the operator who is required to wear hearing protection when it is necessary to go into the main work area to attend to the equipment.

Ten Critical Elements for Building Acoustical Enclosures:

1. *Enclosure Dimensions*
2. *Enclosure Panels*
3. *Seals*
4. *Internal Absorption*
5. *Protection of Absorption Material*
6. *Enclosure Isolation*
7. *Product Flow*
8. *Worker Access*
9. *Ventilation of Enclosure*
10. *Fire Prevention*

Quite often for physical safety reasons, machines or components of a machine are guarded with partial enclosures made from Lexan[®], Plexiglass[®],

or some other comparable polycarbonate material. However, these guards often contain significant gaps or openings along the panel edges that allow significant acoustical energy to escape the enclosure. Although the intended purpose may be to guard against personal injury, or some other function, it is entirely possible to improve upon these partial enclosures to provide a substantial noise reduction benefit.

g) Screens and Barriers

An acoustical barrier is a partial height partition inserted between the noise source and receiver, as depicted in Figure 4.5, which helps block or shield the receiver from the direct sound transmission path.

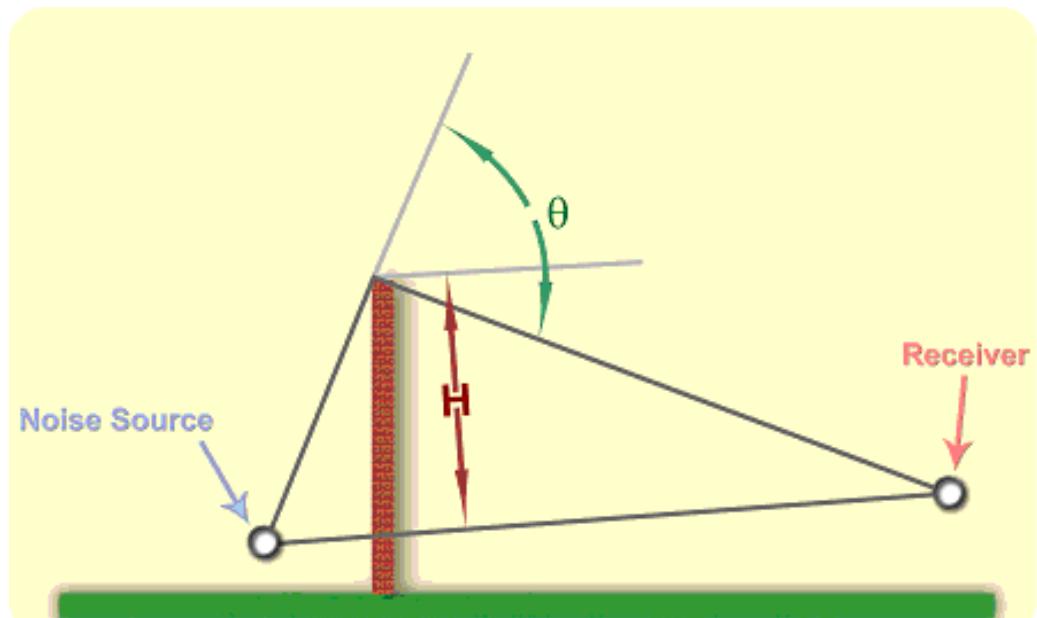


Figure 4.5 - Illustration of a barrier wall inserted between the source and receiver

The noise reduction provided by a barrier is a direct function of its relative location to the source and receiver, its effective dimensions, and the frequency spectrum of the noise source.

The practical limits of barrier attenuation will range between 10-20 dB. As a guide to maximizing the noise reduction capabilities of acoustical barriers, the following recommendations are offered:

- Locate the barrier as close as practical to either or both the source and receiver,
- The width of the barrier on either side of the noise source should be at least twice its height (the wider the better to avoid flanking),
- The height should be as tall as practical above a notional line between the source and receiver. This is the 'effective height' of the screen and indicated by the H on Figure 4.5.
- The barrier should be solid and not contain any gaps or openings, and
- If it is necessary to include a window for visual access to equipment, then it is important for it to have similar noise reduction properties to the main part of the partition.
- Keep in mind that barriers can be less effective because of nearby reflective surfaces, including ceilings.

e) Acoustical Insulation or Lagging

Airborne noise generated by piping systems is typically the result of one or more of the following factors:

- Noise in the liquid or gaseous medium being transported, which radiates excessive acoustical energy through the pipe wall.
- Vibratory energy transferred to the pipe wall, which may be an efficient radiator of noise, and/or transfer of the vibratory energy to other surface areas capable of radiating airborne noise.

Both forms of noise can result from: (1) the operation of rotating equipment, such as compressors, pumps, etc., (2) control valves, (3) excess velocity or turbulent flow within the medium being transported, and (4) the movement of solid particles (i.e., resin pellets), all of which transfer vibratory energy into the medium and/or the pipe wall.

Acoustical insulation, also known as lagging, is the most effective noise control option whenever the pipe wall itself radiates a dominant portion

of the acoustical energy being transmitted, and an in-line silencer is deemed to be infeasible. Note: the application of acoustical insulation is not limited to pipes. For example, the same treatment may be applied to fan housing, metal conveyor chutes, hopper bins, and the like, as a means to absorb and attenuate sound transmission. However, for purposes of discussion, the pipe application is used primarily herein.

4.10. BUY QUIET

Buy Quiet is an occupational health and safety prevention initiative which encourages companies to purchase or rent quieter machinery when new businesses start or when a plan is created to consider noise levels when older machinery is replaced, in order to reduce worker exposure to noise. Such programmes could start with an inventory of a company's existing machinery and equipment with respective noise levels. The company's purchaser can use the inventory to compare the noise emission levels of differing models of replacement equipment prior to their purchase. The inventory is then updated as equipment inventories are expanded or newer quieter equipment is purchased to replace retiring worn out louder equipment. The inventory can also be used for facilitating, documenting, tracking, and promoting a company's Buy Quiet purchase. NIOSH (<https://www.cdc.gov/niosh/topics/buyquiet/component.html>) suggested levels of commitment may include:

- Buy Quiet Beginners: Commit to purchase replacement machinery that produces less noise than the original machinery.
- Mid-Range Level: Commit to purchase the most cost-beneficial piece of machinery available that produces less noise than the original machinery.
- Highest Level: Commit to purchase the quietest piece of machinery available regardless of price.

Buy Quiet is also a specific application of a broader NIOSH initiative – Prevention through Design (PtD). The PtD initiative seeks to prevent or reduce occupational injuries, illnesses, and fatalities through the inclusion of prevention considerations in all designs that impact workers. Buy Quiet addresses this vision by eliminating noise hazards early in the life cycle of

equipment and machinery, thus reducing the risk of occupational hearing loss among workers who use these tools.

Many materials are available in the NIOSH BUY QUIET website to guide the development of such strategies

(<https://www.cdc.gov/niosh/topics/buyquiet/background.html>).

4.11 ADMINISTRATIVE NOISE CONTROLS

Administrative noise controls involve management decisions that affect worker noise exposure in a positive manner. These decisions may involve one or more of the following actions:

- Scheduling of shifts and tasks to minimise exposure times
- Reallocation of noisy tasks to more controllable areas
- Analysis of work flows to minimise interaction between quiet and noisy tasks
- Proper use of noise refuge areas or control rooms
- Equipment automation, remote control, and/or remote monitoring
- Maintenance and servicing schedules which ensure the acoustic performance of equipment is maintained
- Purchase and/or design specifications for limiting noise levels
- Keep workers away from noisy areas whenever possible

For example, rotating two or more employees through a job activity with high noise levels actually distributes the daily exposure among the participants, thus lowering the overall exposure that would have been received by a single worker. Another method of reducing exposure is to isolate the worker in an acoustical booth or control room, assuming the job activities require the worker to be stationary for extended periods of time. These actions, as well as other ideas, are described below in more detail.

The principal difficulty with implementation of administrative controls is they often require significant training and cooperation of both workers and

management to insure work schedules are followed, equipment is maintained in good working order, purchase specifications are enforced, etc. To overcome this difficulty or challenge, all employees, including management, need to receive formal instruction. This needs to include a discussion about the facility's noise control programme, specific information on each administrative control, and a candid explanation as to why employee cooperation is needed to maintain the success of all engineering and administrative controls over time.

The most important factor when evaluating the practicality of administrative noise controls is to assess the amount of potential reduction in worker exposure that can be effectively achieved. In other words, do the benefits justify the costs, or would it be better to invest the funds in engineering controls, or other actions? Therefore, all constraints will need to be examined to determine whether or not administrative noise control measures are feasible.

4.11.1 Changes to Employee Work Routine

Changing employee work routines is one way to affect noise exposure. Rotating two or more employees through a job activity with high-noise levels actually distributes the daily exposure among the participants. However, rotating employees in this manner will at least double the number of employees exposed to the source(s) of concern, and this procedure should only be implemented if the resultant noise exposures for the affected workers are still at safe or acceptable levels.

4.11.2 Planning the layout of the work area

Noise control by location of the source should be considered for the design and equipment layout of new plant areas and for reconfiguration of existing production areas. A simple rule to follow is to keep machines, processes, and work areas of approximately equal noise level together; and separate

particularly noisy and particularly quiet areas by buffer zones having intermediate noise levels. In addition, a single noisy machine should not be placed in a relatively quiet, populated area. Reasonable attention to equipment layout from an acoustical point of view will not eliminate all noise problems, but it will help minimize the overall background noise level and provide more favourable working conditions.

Besides grouping equipment by like noise levels, the space density of machines is also an important factor to consider. As sound waves spread outward from a noise source, the sound level decreases with increasing distance from the source, unless the room is total diffuse or reverberant. Therefore, the closer machines are placed together, the greater the opportunity for the build-up of sound energy due to multiple sources.

Similarly, the closer employees are to noisy equipment, the higher their noise exposure. To effectively have a positive impact on worker noise exposure, it is important to evaluate the interrelationship between the location of the noise source(s) and worker(s). One key fact to keep in mind is high noise levels may exist and are acceptable, provided these levels do not contribute significantly to worker noise exposure. This fact is often exhibited in factories where large compressors are grouped together in a room by themselves, isolated from any workers. Noise levels in these unmanned compressor rooms can range from 95-105 dBA. However, the only people exposed to compressor noise are properly protected maintenance or operating personnel that conduct short excursions in the room to check gauges, inspect the equipment, briefly clean up, etc., and then exit the space.

As an example, when workers service or operate production equipment in manufacturing plants, perhaps tending to a number of stations up and down a manufacturing line, they will often walk or move along the line approximately one meter away from the equipment. When checking details the person may be very close to the machine and hence exposed to much higher noise levels. By careful planning of the work area, the machinery location and the controls this high noise exposure can be minimised.

4.11.3 Use of Noise Refuge Areas, Control Rooms, Automation, and Remote Monitoring

The use of noise refuge areas is another method for reducing daily noise exposure. The concept here is to provide relief from sound levels at or above 80 dBA through the use of “quiet” areas for employees to take breaks, eat meals, complete their paperwork, etc.

Control rooms or noise isolation booths, as shown in Figure 4.6, are another means to provide relief from noise, as well as hot or cold thermal environments. However, the job needs to be one that will permit, or can be restructured to allow, the worker to spend a significant portion their workday inside a control room. It is common for the ambient sound level inside acoustical control rooms to range from 50-75 dBA, which is low enough to provide sufficient relief from factory noise. There are various options available to employers for increasing the time a worker can spend in a control room. For example, putting equipment controls and gauges inside the room, using automation or computer-based systems, providing remote monitoring via video cameras, etc., can easily increase the time workers can effectively spend inside the control room.



Figure 4.6 - Acoustical control room and noise refuge in a paper manufacturing facility

Control rooms or noise isolation booths are commercially available from the majority of noise control product manufacturers that make acoustical enclosures. Alternatively, the room or booth may be custom-designed and fabricated in-house. For this latter item, the “Guidelines for Building Enclosures” should be followed to ensure a high degree of attenuation is achieved (<http://associatesinacoustics.com/wp-content/uploads/2014/11/Enclosure-Guidelines.pdf>). To gain employee acceptance, it is always a good idea to include their input in the decision process. When employees feel their ideas were considered by management, they feel a sense of ownership and are enthusiastic, or at least receptive, about working with this form of noise control.

4.11.4 Regular Maintenance of Equipment

Equipment will often generate increased sound levels when it is in need of adjustment, alignment, repair, etc. Therefore, maintaining all equipment at its optimum performance condition should be the first step in any noise control programme. Hand-in-hand with general mechanical maintenance, which improves the performance and life-span of any piece of equipment, an acoustical maintenance programme will ensure the equipment remains within the noise limits specified by the company, or as the equipment should generate under optimum conditions.

The following are recommended elements of an effective acoustical maintenance programme:

- Conduct an initial baseline sound level survey for each machine in good working order while it operates under normal conditions. This should consist of documenting the A-weighted sound level at fixed locations for each machine or production line.
- Talk to the operator as they often note the change in sound from the machinery they work with

- Periodically conduct a general sound survey of each machine, and compare the operating sound level with the baseline sound level data.
- If noise generating elements are identified, or the sound levels indicate at least an increase over the baseline data of 2 dBA, then appropriate repair should be performed, and
- Maintenance and operating personnel should be trained to observe and listen for potential noise sources outside the norm for the equipment of concern. They should become familiar with the noise generating mechanisms of each machine and with the visual inspection procedures.

When a noise-producing problem is identified during a visual and auditory inspection, the problem should be corrected immediately if it involves only a minor malfunction or adjustment, and even if the equipment appears to be operating normally. If the problem requires more extensive attention, then it should be labelled or tagged at the problem location and be scheduled for service during the next maintenance round. Successful implementation of an acoustical maintenance programme will ensure the correction of simple and often overlooked noise problems. This process alone will yield significant benefits in both the long-term life of the equipment and minimizing the noise exposure risk to employees.

4.11.5 Noise Limits in Specifications

It is standard practice in today's business environment to use written specifications to define requirements, including noise criteria, for equipment procurement, installation, and acceptance. The most pro-active approach to control noise in the facility design and equipment procurement stage exists in Europe. In 1985, the twelve member states of the European Community (EC) adopted "New Approach" Directives designed to address a broad class of equipment or machinery, rather than individual standards for each type of equipment. By the end of 1994 there were three "New Approach" Directives issued that contained requirements on noise.

For companies outside the EC and United States attempting to implement a voluntary buy-quiet programme, the degree of success achieved is largely dependent upon the timing and commitment of the entire management. The first step in the programme is to establish acceptable noise criteria for construction of a new plant, expansion of an existing facility, and purchase of new equipment.

For the programme to be effective, the specified noise limits should be viewed by both the purchaser and vendor as an absolute requirement. When a product does not meet other equipment design parameters, such as size, flow rate, pressure, allowable temperature rise, etc., it will be deemed unacceptable by company management. Similarly, the decibel limit (noise criteria) should be included with the list of required design parameters; otherwise, the effectiveness of the buy-quiet programme will be tenuous at best.

The earlier in the design process that consideration is given to the noise-related aspects of a project or equipment purchase, the greater the probability of success. In many situations the factory designer or equipment buyer will have a choice of equipment types. Knowledge of the noise characteristics of the various equipment alternatives will allow the buyer to specify the quieter ones.

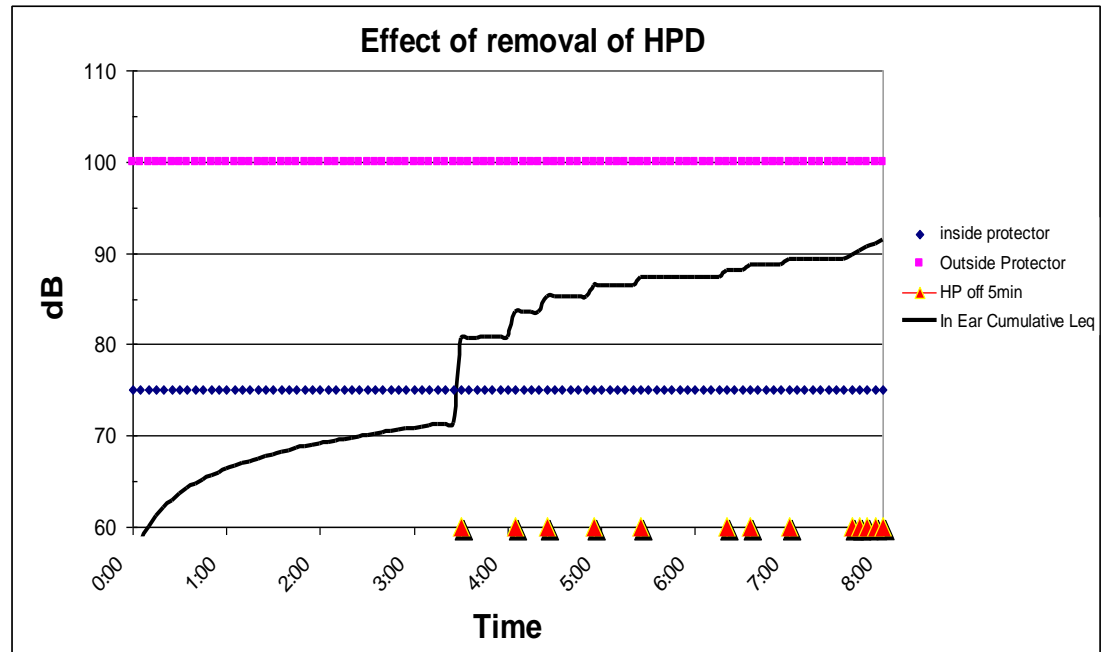
Even the most thorough and concise specification document is of little value unless the onus of compliance is placed on the supplier or manufacturer. Clear contract language should be used to define the means of determining compliance. Company procedures designed to enact guarantees should be consulted and followed. It may be desirable to include penalty clauses for noncompliance. Foremost in enforcement is the purchaser's commitment to seeing that the requirements are met. Compromise on the noise criteria in exchange for cost, delivery date, performance, or other factors should be the exception and not the rule.

5. HEARING PROTECTOR PROGRAMME

Hearing protection devices (HPDs) consist of earplugs, earmuffs or combinations of these and are used to reduce the level of sound reaching the inner ear. HPDs should be used in designated high-noise areas until feasible engineering and/or administrative noise control measures effectively reduce work place noise exposure levels to acceptable levels.

There are several broad types of hearing protectors and several methods of rating them for their comparative performance. The quoted performance can differ significantly from the real world performance and these differences must be given careful consideration when setting up a Risk Management Strategy based on Hearing Protectors.

HPDs are only effective when they are worn correctly and at all times when in a noisy environment. Due to the exponential increase in hazard from a small decibel increase in noise exposure, removal for only short periods will significantly degrade their effective performance as shown in Figure 5.1. The practical implication is to keep in mind that comfort is imperative for use throughout the exposure period. That can be achieved by offering individuals options that provide the needed attenuation, not less, not more.



(Source: K Mikl)

Figure 5.1 – Effect of Removal of Hearing Protection Devices

5.1 TYPES OF HPDs

HPDs come in a variety of sizes, shapes, and forms. Earplugs are designed to fit into or against the entrance to the ear canal and provide an air-tight seal. Earmuffs block sound by totally encompassing the outer ear (pinna) to form a tight seal against the sides of the head. There are variants and combinations of these as well as specialist Active and Passive nonlinear devices and helmets. The various types of HPDs are described below.

5.1.1 Foam Insert Plugs

Foam insert earplugs are both roll-down or push-in type, made from either polyvinyl chloride or polyurethane closed-cell material, and come in a variety of sizes and shapes.



Figure 5.2 – Foam Insert Plugs

Foam plugs are undoubtedly the most commonly used HPD, as they are considered to be the most comfortable plug for long-term use (throughout the workday) and offer a high degree of attenuation. Plus, one size fits most, but not all, individuals (see *Section 5.4 Fitting*). Achieving the quoted noise reduction performance of ear plugs depends on the quality of fit in the ear canal. Even when they are inserted correctly it is usually wise to assume that the protection achieved will be less than that quoted on the manufacturer's data sheet.

5.1.2 Pre-molded Plugs

Pre-molded plugs are fabricated from soft, flexible materials; and come in a variety of sizes. These plugs contain anywhere from zero to five flanges. Pre-molded plugs are good devices for continuous use, as well as for utilization by workers that move in and out of high-noise or hearing protection required areas, as they are relatively easy and quick to insert and remove. These HPDs are long lasting and easy to keep clean.



Figure 5.3 – Premolded Plugs

Pre-molded plugs are fabricated from soft, flexible materials; and come in a variety of sizes. These plugs contain anywhere from zero to five flanges. Pre-molded plugs are good devices for continuous use, as well as for utilization by workers that move in and out of high-noise or hearing protection required areas, as they are relatively easy and quick to insert and remove. These HPDs are long lasting and easy to keep clean. It is worth noting; however, when worn for extended periods pre-molded plugs can work loose during the day, and may need to be periodically repositioned or re-seated by the user. Pre-molded plugs often do not provide an effective seal in the ear canal and so have a low noise reduction performance. However if the required reduction is only a few dB then these plugs may be quite suitable.

5.1.3 Custom-molded Plugs

Custom-molded earplugs are formed to fit an individual's ear canal using a malleable silicone putty, or similar material. It is also possible to use laser scans to make custom plugs.

A word of caution, the fit and attenuation of custom-molded plugs are highly dependent upon the expertise of the individual making the device. For example, Figure 5.4 depicts custom-molded plugs made *on the same ear canal* by five different technicians. Clearly, this figure shows little consistency between each plug.

As with pre-molded plugs, custom devices will also need to be repositioned from time to time throughout the day. Because of the high cost associated with custom-molded devices, relative to foam or pre-molded plugs, the employer needs to understand these devices are not permanent. They will dry out, shrink, crack, become damaged, or even lost by the worker. So there will be an associated replacement cost. A properly fitting custom moulded plug can provide effective noise reduction and recent developments offer the opportunity for 'tuning' the performance of the plug to better cope with the noise and any special hearing requirements of the user.



(Source & Photo: Courtesy Aearo Technologies)

Figure 5.4 – Five Custom-molded Plugs made for the same ear canal by five different technicians

5.1.4 Semi-Insert or Canal Caps

Semi-insert type HPDs are essentially two soft earplugs or pods attached to a narrow spring-loaded band that presses them against the entrance to the ear canal.



Figure 5.5 – Semi-insert Device

Semi-insert plugs are also known as canal caps, semi-aural devices, and earplugs on-a-band.

Maintaining an airtight acoustic seal requires a fair amount of force against the ear canal entrance, which can make this device uncomfortable to properly wear for extended use (more than 30 minutes at a time). However, this type of HPD is ideal for short-term or intermittent use by maintenance, management, or any other personnel that visit high-noise areas for relatively short durations. Similar to the pre moulded plugs, these inserts and caps rarely provide an effective seal in the ear canal and so have a low noise reduction performance. However if the required reduction is only a few dB or the person is only in the noisy area for a short time, such as in a transit path, these may be quite suitable.

5.1.5 Ear Muffs



Figure 5.6 – Ear Muffs

Ear muffs are constructed of ridged plastic cups that completely cover a wearer's outer ear or pinna. The cups are mounted on a thermoplastic or metal spring-loaded headband, and the attenuation is dependent upon how well the cushions on the cups seal against the sides of the head and, to a lesser extent, the material of the cup. Generally, ear muffs fit a large percentage of people, but not all (*see Section 5.4 Fitting*).

It is important to ensure compatibility of ear muffs with other personal protective devices, such as face shields, safety glasses, hard hats, etc. Well-constructed and properly fitted ear muffs generally have a higher noise reduction performance than plugs. However if the seals around the outer ear is not good, the noise reduction provided by the muffs can be less than that provided by good quality ear plugs. Also it should be noted that the performance of cups mounted on hard hats do not usually provide as good a seal as the same cups mounted on a headband. Consequently, the attenuation of hat mounted hearing protectors can be lower than other models.

5.1.6 Combination of Ear Plugs and Ear Muffs

In very high noise areas it may be necessary to use both ear plugs and ear muffs. In a work environment where the general noise level and working environment is such that ear plugs are more suitable for the majority of the time, ear muffs can be worn over the plugs for the shorter time periods of higher noise level. It is important to realize that the performance of the combination of the ear plug and ear muff is not determined by simply adding the performance of each individually. Nor is it easy to calculate the estimated performance due to the differences in performance across the frequency spectrum of the different types of devices. The effectiveness of the combination should be measured in a similar manner to the measurement procedure for any HPD. Some manufacturers of a range of HPD will have the data for the performance of the combination.

5.1.7 Special Purpose Protectors

Special types of HPDs are used to accommodate workers in differing environments or special needs, such as;

- Radio communication
- Protection against extremely high noise environments
- Devices which turn off and on automatically

- Linear protection to provide good quality transmitted sound for musicians
- Devices with particular frequency response or
- Choice for persons with pre-existing hearing loss.

These devices may be an earmuff or earplug, and their real-world attenuation will follow the values cited above for the respective class of protectors. Workers having special needs due to hearing loss should work through the site audiologist or physician to ensure the device selected for use will be protective and appropriate for the individual's situation. A few special types are discussed below.

Linear ear protection

Most ear protection devices vary in performance across the frequency range. Thus they are unsuitable for use by musicians who need to hear the music in an undistorted manner. Linear ear protection (usually in the form of ear plugs) are sometimes called musicians ear plugs or HiFi plugs. They are designed specifically to have a flatter frequency response than normal ear plugs. The benefits of using this kind of device is to balance the need to hear the music with minimal distortion with the risk of excessive exposure. They are more relevant to classical or acoustic musicians as amplified musicians can utilise the signal from the mixing desk.

Level-dependant ear plugs

Military and enforcement agencies have a special need to be able to hear clearly but also have protection from impulse noise from firing. A 'level-dependant ear plug' or 'non-linear ear plug' has been developed which incorporates a specially designed 'filter' within an ear plug. Non impulsive sound passes through the hole in the plug with minimum reduction. An impulse sound with a sharp rise time is attenuated by the 'filter'.



Courtesy of William J. Murphy, NIOSH, 2019)

Figure 5.7 - Level-dependant ear plugs Constant sound can be transmitted down the tube to the ear but sharp rise time impulse noise is attenuated by an insert

Electronic active ear muffs

Electronic active ear muffs are designed for use in places like firing ranges where protection from impulse noise is important but also communication is necessary. The electronic active ear muffs have good passive reduction but to enable communication incorporate a microphone and small loudspeaker speaker inside the cup. When a sudden loud noise or a sharp rise time impulse sound is detected the amplification to the small loudspeaker is cut and the passive protection of the ear muff provides attenuation for the loud noise or the impulse sound.



(Source: <http://www.peltor.se/>)

Figure 5.8 – Ear Muff which allows for communication but protects from impulse noise

Active noise cancellation headsets and helmets

Active noise cancellation headsets and helmets use active noise reduction to cancel out the intruding noise. This technique involves analysing the existing noise signal then producing a signal which is 180 degrees out of phase and in principle this cancels the original noise signal. This technique involves sophisticated signal processing and is only really effective for low frequency sound. Active noise cancellation should only be considered for hearing protection when the sound is predominantly low frequency. A useful application is when low frequency noise causes disturbance to communication such as in aircraft cockpits. They can also be used by passengers to assist with clearer in flight audio entertainment.

A range of active headsets and earplugs is available for use with personal listening devices and such to screen out traffic noise, etc. while the wearer listens to music. These are not as yet certified for use in industrial environments.

Adaptive hearing protection

Adaptive hearing protection is a relatively new concept that balances speech enhancement with noise suppressions using sophisticated signal processing. Sensear (<https://www.sensear.com/>) has developed this technology which can also be used to enable use of mobile phones and other communication tools in a noisy environment.

5.2 SELECTING HEARING PROTECTION DEVICES

Keep in mind when selecting HPDs there is no such thing as a “best” hearing protector. The area noise levels, worker noise exposures, communication needs, comfort, hearing ability, personal preference, and interaction with other safety equipment all need to be considered when selecting HPDs. In reality, the “best” HPD is the one that will be properly used by workers at all times when working in high-noise areas.

As a minimum, the noise level under the protector should be reduced below 85 dBA. However, to avoid over protection it is recommended the level under the protector be between 70-80 dBA. Overprotection can lead to a feeling of isolation from the surroundings and be an obstacle to correct use. Also, unnecessarily high-performance HPDs may be a little more uncomfortable and so there is a tendency to remove them (<https://blogs.cdc.gov/niosh-science-blog/2018/10/24/hearing-protection/>).

To achieve worker acceptance a variety of HPDs should be made available to workers. At a minimum, it is recommended employees be allowed to choose from at least two different types of ear plugs and ear muffs. However, even though employees may select the type of earplug, they should not be allowed to choose the earplug size without assistance from a properly trained individual.

5.3 HPD RATING METHODS

There are a number of different methods used around the world to select appropriate hearing protection. It is best to choose one method, if appropriate or follow the local regulations. The methods each offer a standardised way of comparing characteristics of different HPD and they do not necessarily represent the “in-ear” noise level in your workplace.

The methods range from the octave band method to the single number simple methods. They all have varying complexities in measurement of the noise environment and calculating the appropriate HPD. The Octave band method

is the most complex and may be required for high noise level or significantly tonal environments. Many regulations recommend the use of the single number rating methods.

The attenuation ratings are obtained in laboratory conditions. Evidence indicates that these do not accurately predict how much attenuation an individual is actually getting (see 5.3.2). In 2019, NIOSH stated that the best way to know how much noise reduction you are getting from a hearing protector is by fit-testing (<https://blogs.cdc.gov/niosh-science-blog/2018/10/24/hearing-protection/> ; see 5.6.1) . The goal of fit testing is to provide an individual user with feedback on whether he/she is properly wearing a given hearing protector and that it offers sufficient protection for the condition in which it is to be used. With that information the user can better understand how to fit earplugs to attain the needed protection.

5.3.1 Octave-band Method

The most precise method for estimating the “protected” level under the HPD is to use the manufacturer’s octave-band mean attenuation and standard deviation data, along with the sound spectrum of the noise source(s), then calculate a broadband level under the device. This method is commonly known as the *Octave-band Method* or the *Long Method* and is considered the gold standard for estimating performance for groups of users (Berger, 2000). In view of the variability in the real world performance, it should be remembered that even though the calculation method may be precise, the resultant is only an estimated “in-ear” level.

There are some variations but the common version of the Octave-band Method de-rates the mean attenuation data of the HPDs at each frequency by one standard deviation to be conservative! The steps in the process are:

- the A weighting is applied to each frequency of the linear spectrum for the sound source to determine the A weighted level for each octave band
- one standard deviation is subtracted from each value across the frequency spectrum for the quoted performance of the hearing protector.

- the HPD performance minus one standard deviation is subtracted from the A weighted levels across the frequency spectrum to estimate the in-ear noise level
- the values for the in-ear noise level across the frequency spectrum are added using the usual dB addition rule and the overall A weighted estimated in ear noise level is determined.

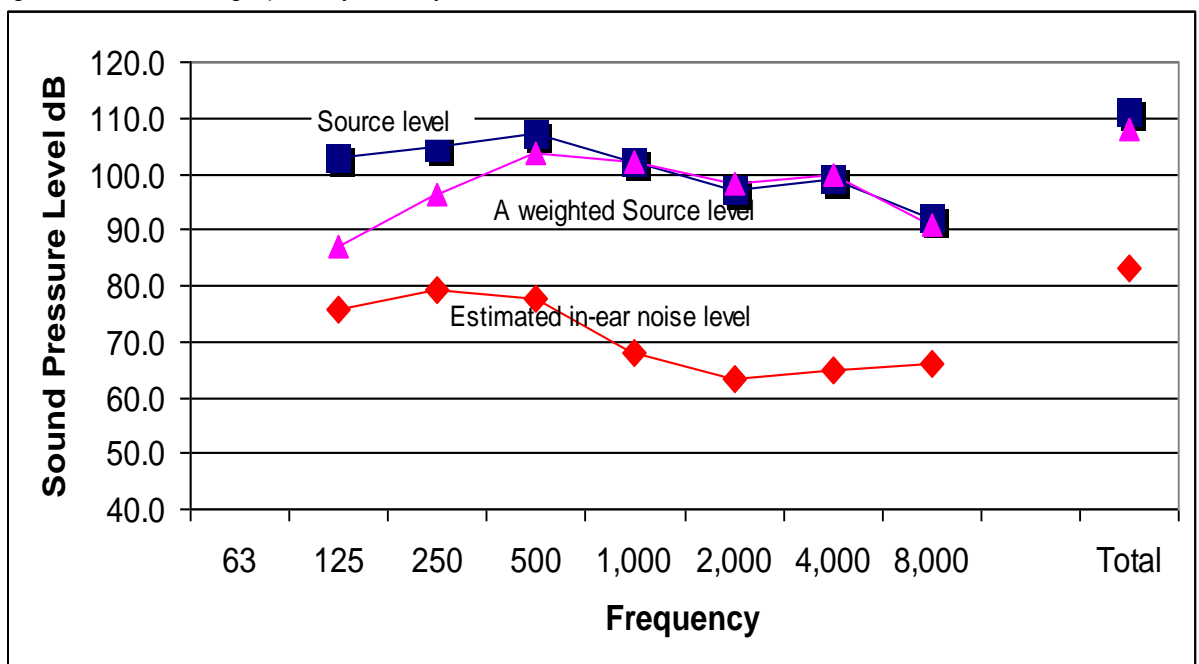
The following example demonstrates hearing protector evaluation using the Octave-band Method.

Example Calculation - Hearing Protector Evaluation Using Octave Band Method

- 1) In each octave band column sum the Noise level (*line 1*) and the A weighting (*line 2*) to calculate the A-weighted sound level of the source (*line 3*)
- 2) To determine the noise reduction of the protector, subtract one standard deviation (SD) from the mean attenuation specifications for the protector.
- 3) Subtract the mean minus one standard deviation (*line 6*) from the A-weighted sound level (*line 3*) to obtain the estimated in ear noise level (*line 7*)
- 4) Each of the octave band frequency values is added across the columns to determine the overall estimate of the in-ear noise level in dBA for comparison with the criterion. (*bottom RHS corner*)

<i>line</i>	Frequency (Hz):	125	250	500	1000	2000	4000	8000	Overall level
1	Linear Noise Level dB	103	105	107	102	97	99	92	111
2	A-weighted Correction dB	-16.1	-8.6	-3.2	0	+1.2	+1.0	-1.1	--
3	A-weighted Noise Level dBA	86.9	96.4	103.8	102	98.2	100.0	90.9	108
4	Mean Attenuation of HPD	12.8	19	28.5	36.1	38.1	38.3	26.7	--
5	Standard Deviation	1.8	2.0	2.5	2.1	3.1	3.3	1.7	--
6	Mean-1 SD	11	17	26	34	35	35	25	--
7	Estimated in-ear level, dBA	75.9	79	77.8	68	63.2	65	65.9	83

Based on this example, the overall protected level under the HPD is 83 dBA, and the sound level in each octave band is less than 80 dBA; consequently, the earmuff may be an acceptable device. The figure below shows graphically the key data from the table



5.3.2 Noise Reduction Rating

To simplify the estimation of attenuation for wearers, the U.S. Environmental Protection Agency (EPA) in 1979 required manufacturers to label their packaging with a single-number rating, which is termed the *Noise Reduction Rating (NRR)* (EPA, 1979). Essentially, the NRR was meant to represent the “effective” exposure under the HPD in dBA. In the US, the NRR gained wide acceptance in the early 1980s primarily due to its simplicity and the fact U.S. regulators allowed for its use in the Occupational Safety and Health Administration’s (OSHA’s) Occupational Noise Exposure: Hearing Conservation Amendment; Final Rule (OSHA, 1983). Under the OSHA regulation, the procedure allows for the user to subtract the manufacturer’s published NRR value from the C-weighted noise exposure to get the estimated A-weighted protected level under the device. Other rating and classification schemes have been proposed and are used outside the US (see next sections).

The NRR is obtained in laboratory conditions. Evidence indicates that the NRR does not accurately predict how much attenuation an individual is actually getting; it overestimates the protection many wearers will receive in the real world (CAOHC, Hearing Conservation Manual, 5th edition, <http://www.caohc.org/educational-resources/hearing-conservation-manual>). In 2019, NIOSH stated that the best way to know how much noise reduction you are getting from a hearing protector is by fit-testing (<https://blogs.cdc.gov/niosh-science-blog/2018/10/24/hearing-protection/> ; see 5.6.1. The goal of fit testing is to provide an individual user with feedback on whether he/she is properly wearing a given hearing protector and that it offers sufficient protection for the condition in which it is to be used. With that information the user can better understand how to fit earplugs to attain the needed protection.

If fit-testing is not available at the workplace, one can check earplug fit by counting out loud while slowly cupping and un-cupping his or her hands over your ears. If he or she has a good fit, his or her voice should sound about the

same as he or she cup and un-cup the ears. [NIOSH has a QuickFitWeb](#) which can be used to check if you are getting more or less than 15 dB of sound reduction (<https://blogs.cdc.gov/niosh-science-blog/2018/10/24/hearing-protection/>).

5.3.3 Noise Reduction Rating (Subject Fit)

In 1995 the National Hearing Conservation Association's (NHCA's) *Task Force on Hearing Protector Effectiveness* (Berger, 1996) proposed an alternative labelling requirement for HPDs computed from Method B data (subject-fit real-ear attenuation results) from ANSI S12.6-1997, *Method's for Measuring the Real-Ear Attenuation of Hearing Protectors* (ANSI, 1997). Under this standard Method B data are deemed the most practical estimates of field attenuation, primarily since the test subject fits the HPD, as compared to Method A where the experimenter fits the device prior to testing. The result is the new single-number descriptor termed *NRR (Subject Fit)*, or *NRR(SF)*. It is the consensus of the professional community, including NIOSH; the *NRR(SF)* better represents the real-world attenuation achieved by groups of workers relative to the original *NRR*, provided the workers are properly training in the use of their HPDs. To estimate attenuation simply subtract the *NRR(SF)* from the A-weighted noise exposure or worse-case sound level to find the "protected" level under the device. Note: The 7-dB correction factor to adjust for C-weighted versus A-weighted differences is not applied when using the *NRR(SF)*.

5.3.4 Noise Level Reduction Statistic

The most recent rating method to come out of the U.S., and the first one actually embodied in an American National Standard, is the Noise Level Reduction Statistic for use with A-weighting (NRS_A), as described in ANSI S12.68 (ANSI, 2007). This standard recognises the problem that no single-number rating can accurately predict the range of performance achievable from HPDs (Gauger and Berger, 2004). Therefore, it is recommended that the simplified ratings be presented as pairs of numbers.

One rating represents the level of protection for most users can achieve, called the 80 percent value (NRS_{A80}); and the other rating value representing what a few highly proficient and motivated wearers can obtain or exceed, called the 20 percent value (NRS_{A20}). The difference between the 80 percent and 20 percent value indicates the uncertainty factor and range of HPD performance that may be anticipated. Finally, the particular meaning of each value depends upon whether Method-A or Method-B data (ANSI, 1997) are used, as defined below (ANSI, 2007):

- Method A, NRS_{A80} (80th percentile value) – the protection that is possible for most individually trained under to achieve or exceed.
- Method B, NRS_{A80} (80th percentile value) – the protection that is possible for most users to achieve or exceed.
- Method A or Method B, NRS_{A20} (20th percentile value) – the protection that is possible for a few motivated proficient users to achieve or exceed. Note – the 20th percentile value will be the same regardless of the procedure (Murphy, 2006).

To use the NRS_A , users may take the A-weighted noise exposure or sound pressure level and subtract the selected rating value to obtain the “effective” level under the HPD.

5.3.5 Single Number Rating

Within the European Union and affiliated countries the *Single Number Rating (SNR)* is used and specified for compliance. The SNR method requires the user to measure the C-weighted sound pressure level. The SNR is calculated from *Assumed Protection Values* according to the procedure in Annex D of BS EN ISO 4869-2:1995 “Acoustics – Hearing Protectors – Part 2: Estimation of effective A-weighted sound pressure levels when hearing protectors are worn” (ISO, 1995). As with the NRR, the tests are completed by independent laboratories; however, the test frequencies are slightly different than for those used to compute the NRR.

5.3.6 HML Method

The HML procedure takes into account the noise environment. Along with the SNR rating the user will also see ratings for H (high-frequency noise), M (mid-frequency noise), and L (low frequency noise). For example, an HPD may be labelled SNR 28, H=33, M=24, L=14; which means the estimated attenuation varies with the spectrum of the noise. Since the HML method targets the noise spectrum it is potentially more accurate for predictive purposes than the SNR rating. To use the *HML ratings* the user must know both the A-weighted and C-weighted sound pressure levels for the noise environment.

5.3.7 Sound Level Conversion

Australia and New Zealand used the *Sound Level Conversion (SLC)* rating, till 2005. The SLC is an estimate of the attenuation achieved by 80 percent of wearers (mean attenuation minus one standard deviation), assuming the users are well-managed and trained in the proper use of the device. As with the NRR and SNR, the SLC attenuation data are determined by independent laboratories.

To choose HPD using this method the C-weighted noise level is measured and the appropriate SLC value HPD is chosen to reduce the number to a suitable level.

Example

Workplace measured at 98 dBC

Required protected level 75 dBA

$98 - 75 = 23$ so a HPD with about SLC 23 is chosen.

5.3.8 Classification Method

The AS/NZ 1269 standard recognises that wearing time is a most critical parameter in obtaining protection and that variation in the noise environment will often render accurate calculation redundant. Indeed a high attenuation protector will have its performance degraded significantly if not worn all the

time or the user enters another area. Therefore the simplified class system was introduced to replace the requirements for octave band, or C weighted measurement and it was intended that the focus of the risk management strategy be moved to engineering controls rather than technical fine tuning of an exact match between noise environment and hearing protector, a goal which is increasingly difficult in any complex noise environment.

Hearing protectors are chosen in a simple 5 class system which graduates the noise hazard into 5 dB increments and assigns a class of HPD to cover each level of increased risk.

The focus of the risk management strategy needs to be on wearing time and the contributory factors of comfort, fit, care and maintenance, applicability to the area or work and clear policy and follow through.

Table 5.1 - AS/NZ Class Hearing Protector Required and comparison with the former SLC₈₀ method

L_{Aeq,8h} dB(A)	Class	SLC₈₀
Less than 90	1	10-13
90 to less than 95	2	14-17
95 to less than 100	3	18-21
100 to less than 105	4	22-25
105 to less than 110	5	>26
110 or greater	requires specialist advice	

If the noise environment is narrow band in character with significant tonality or has significant high or low frequency components or exhibits other complexities, then the octave-band method should be used.

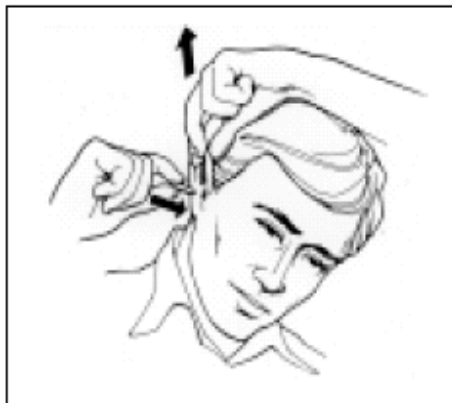
5.4 FITTING

All hearing protectors need to be fitted when initially introduced to a worker. A determination of ear health and physical attributes should be undertaken to ensure a good seal is achieved. If multiple sizes are available they should be checked to ensure the best fit for comfort and wear ability. Evidence indicates

that instructions for inserting earplugs into the ear canal have a considerable effect on the noise attenuation of the devices (Tikka et al., 2017).

5.4.1 Foam Earplugs

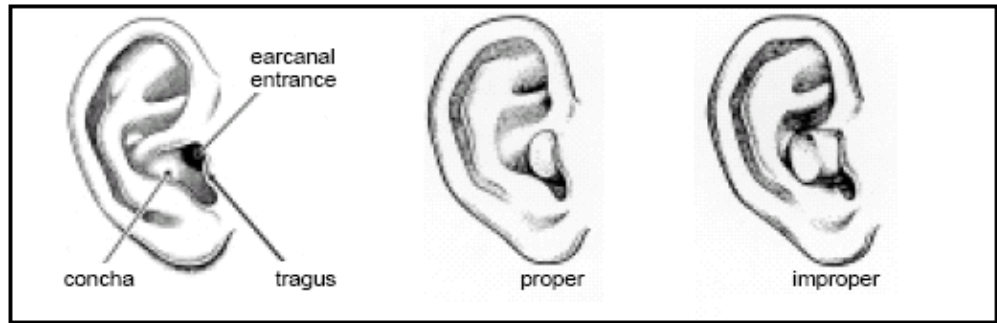
Most foam plugs are designed to be rolled down by the user and inserted into the ear canal. After insertion the plug slowly expands and conforms to the individual ear canal shape. The following roll-down procedure is described in EARLOG₁₉ (Berger, 1988): “to insert foam earplugs roll them down between the thumb and index finger into a very thin crease-free cylinder. The cylinder should be as small in diameter as possible. Crease-free rolling is accomplished by squeezing lightly as one begins rolling, and then applying progressively greater pressure as the plug becomes more tightly compressed. Be sure to roll the plug into a cylinder rather than other shapes such as a cone or a ball.”



By pulling up on the Pinna (external ear) or pulling down on the lobe, you can straighten out your ear canal, allowing for the correct and full insertion of the plug into the canal. Each person needs to determine which method works best for him or her.

(Source: Illustration provided courtesy of Aearo Technologies)

Figure 5.9 - Pinna Pull Insertion Technique



(Source: Illustration provided courtesy of Aearo Technologies)

Figure 5.10 – Proper versus Improper Insertion of Foam Plug

A plug is properly inserted when it is flush with or inside the tragus. Earplugs that extend beyond the tragus (outside the ear) are not properly inserted.

Unlike other types of earplugs, foam earplugs should not be readjusted while in the ear. If the initial fit is unacceptable, they should be removed, re-rolled, and reinserted. If the second fit is still unacceptable that style may not be suitable for that individual; an alternative plug of the same rating should be supplied.

5.4.2 Pre-molded Earplugs

Pre-molded earplugs come in varying sizes, such as small, medium, and large. Since up to ten (10) percent of wearers can have two different size ear canals, each ear needs to be fit separately (Berger, 1988). HPD manufacturers provide ear gauges for sizing the ear canal. To obtain a proper fit on multi-flanged plugs at least one of the flanges should completely seal along the interior wall of the ear canal. Essentially an airtight seal is formed, creating a blocked-up feeling to the wearer. As with foam plugs, using the “pinna pull” technique illustrated in Figure 5.11 is recommended for pre-molded plugs.

5.4.3 Custom-Molded Earplugs

Taking ear impressions for custom-molded earplugs needs to be completed by a trained professional, such as an audiologist, or physician. The wearer

should receive one-on-one training from the professional on how to properly insert the custom-molded plugs.

5.4.4 Semi-Insert/Canal Caps

Semi-insert earplugs, also known as canal caps, are quick and easy to use, but are only recommended for short durations in high-noise areas. Because of the pressure exerted by the band used to seal the earplug against the entrance to the ear canal, continuous and effective use of this device becomes very uncomfortable, even painful, usually after thirty (30) minutes. To insert canal caps simply push the earplugs or pods into the entrance of the ear canal. Typically, the band is positioned under the chin, but may also be worn behind the head or over the head. However, in these latter two positions less attenuation is provided, and the band often conflicts with the wearing of hard hats. The “pinna pull” technique is useful for seating the pods or plugs effectively at the entrance of the ear canal.

5.4.5 Earmuffs

Although most earmuffs can successfully fit a large percentage of people, the fitter should check the following:

- Does the headband expand and contract enough to position the cups securely over each pinna (outer ear)?
- Can the entire pinna comfortably fit inside the earmuff cup?
- Does the cup’s cushion seal against the head all the way around the ear, or are there excessive gaps caused by bone structure, bulky eyeglass temples or facial hair? Studies have shown a 3-7 dB reduction in attenuation by eyeglass temple ‘leaks’ (Berger, 2000, p.411).

If gaps are present, earmuffs can increase the level of noise reaching the eardrum, especially in noise environments that are in the 125-250 Hz range through the “resonance effect”.

To increase success in earmuff fitting, make sure the site stocks ones with easily adjustable bands and good cushioning. Earmuffs should be checked regularly because cracking and hardening of cushions can cause leaks. Earmuffs can be subjectively field-fit tested if the individual in a noisy environment lifts one or both cups. A proper fit should result in a noticeable increase in noise perception.

5.5 VISUAL CHECKS

Visual checks on HPD fit should be conducted, not only during the initial fitting, but also during day to day work activities. The series of photos exhibited below demonstrate both proper and improper fitting HPDs. These photos are useful for quickly identifying improperly fitted HPDs so that corrective measures, such as re-training or re-fitting the user, may be immediately taken to ensure workers are properly protected from high noise.

Examples of Visual Checks for Proper HPD Use

All photos courtesy of Elliott Berger, E-A-R / Aearo Technologies, Indianapolis, IN (USA) www.e-a-r.com/hearingconservation



Proper Insertion:
the plug has good deep insertion past the tragus.



Improper Insertion:
the plug is not deep enough or is too big for this ear canal.



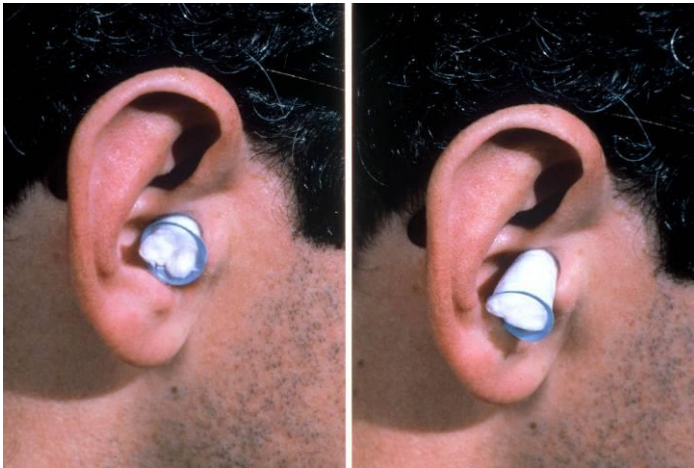
Proper Insertion:
note the end flange is just past the tragus.



Improper Insertion:
the end flange sticks out past the tragus.

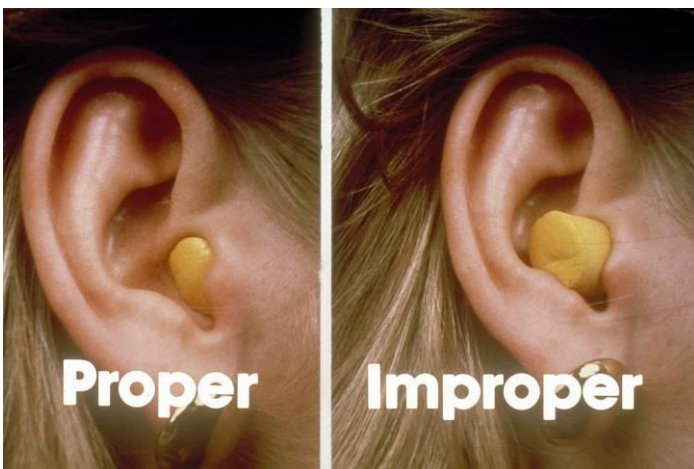


Here are examples of the fit of a one-sized three-flanged earplug in extra small (left photo, third flange just barely enters the ear canal), medium (centre photo, third flange seals the ear canal), and extra-large ear canal (right photo, back edge of third flange is flush with canal entrance). NOTE - All three fits are proper for this type device, as it is not essential for the outer most flange on one-sized multi-flange plugs to seal the ear canal, as the lead flanges provide the acoustical seal.



The left photo shows a proper insertion of a formable earplug, which is fibreglass down in a sheathing material.

The photo on the right is an improper insertion, as the device is too loose, or is not inserted deeply enough to be of benefit.



The EAR Classic foam plug shown in the left photo is a proper insertion, as the end of the plug is just past the tragus.

The photo on the right photo is an improper insertion of the Classic plug.



Note how the ear lobe extends beyond the bottom of the earmuff cup, which will cause air leaks and a significant reduction in the delivered attenuation. This earmuff is not properly sized for this individual.



Excessive hair over the ears can break the seal of the earmuff cups, significantly reducing the overall attenuation. The same affect is true for safety glass temple bars. All gaps or penetrations should be minimized as best as possible to achieve effective attenuation.



This earmuff is too big for this user. The headband is fully closed, but does not rest on the top of the head, as it should. Be careful to ensure HPDs are compatible with the wearer's anatomy.



The earmuff head band on the left still maintains its original spring-loaded shape, while the muff on the right shows a head band that has been bent back enough over time to render this device less effective. The earmuff on the right should be discarded.



Both earmuff cushions show permanent impressions, which allow air leaks and reduces the attenuation. The cushions need to be replaced.



These are the temples of doom. The indentions of this person's temples do not allow the earmuff cups to seal properly against the sides of the head, thus allowing noise to leak through. This person is not a good candidate for earmuffs due to the shape of his head.



These muffs are the property of H.C. Small holes have been drilled into the earmuff cup to personalize or identify the owner of this device. Unfortunately, attenuation is sacrificed and these muffs need to be removed from service. Be careful to inspect earmuffs for unintentional, and sometimes intentional, modification that can defeat the attenuation.

5.6 WEARER FIELD TEST TO CHECK FITTING

There are a number of field tests the individual wearer can perform on themselves to fit check their HPDs. It should be noted here that many of these tests are not typically performed by the hygienist on workers in the field. These tests include (Berger, 1988):

- The Tug Test – Gently tug in and out on the end of the plug, handle, or cord. If there is resistance and if the wearer feels a gentle suction on the eardrum, then a good seal has been achieved.
- The Hum Test – After inserting one earplug, the wearer should hum or say “ahhh”. If one ear is properly sealed, creating the occlusion effect where bone conduction becomes noticeable, then the user’s voice will seem louder in the sealed ear. If not, an adequate seal is unlikely and the plug should be adjusted or removed and reinserted until this effect is achieved. When both ears are properly sealed the wearer’s voice should be perceived in the centre of the head.
- The Loudness Test – With earplugs inserted while standing in a noisy environment, the wearer should cup both hands over the ears. If there is a perceptible difference in noise level, the HPD is probably not

inserted well enough to form a good seal. A well-fitted earplug should not result in a significant difference.

Conversely, the perceived noise level should increase markedly if the user breaks the seal of each earplug or raises the cup of an earmuff when in noise.

5.6.1 Individual Hearing Protector Fit Testing

Even with appropriate focus on noise control, reliance on HPDs as the last line of defence against occupational noise exposure is inevitable, as in certain jobs is not technically feasible to reduce noise to safe levels. As discussed earlier, one critical failure in this process has historically been the fact the labelled protection values on HPD are not reliable predictors of actual HPD performance. Analysis of laboratory evaluations indicates individual variability in HPD performance is large enough to make any population-based, statistical assessment of HPD performance inappropriate for individual workers.

As part of an effective hearing conservation programme it is important to estimate how well HPDs work for individual users, therefore they must be tested on individual users. New technologies make this possible. Several fit-testing systems have been developed over the past decade. In the United States, at least seven fit-test systems are commercially available. They are: Benson Medical Instruments CCF-200, 3M EARFit Dual-ear fit validation system™, Michael and Associates FitCheck, FitCheck Solo™, Workplace INTEGRA Inc. INTEGRAFit®, Phonak SafetyMeter, and Honeywell VERIPro™. Individual fit testing can be used to select HPDs appropriate for the noise exposure of individual workers; train workers on the protective effect of proper HPD use/insertion techniques; identify workers who may not be obtaining sufficient protection from their HPD of choice, enabling alternate selection; document individual HPD performance for assist in determination of work-relatedness of hearing loss; and for other purposes. The results of a fit test for hearing protection are expressed as a Personal Attenuation Rating. The Occupational Safety and

Health Administration and the National Hearing Conservation Association Best Practice Bulletin: Hearing Protection- Emerging Trends: Individual Fit Testing describes existing testing methods and how to incorporate them in hearing conservation programmes (https://www.hearingconservation.org/assets/docs/AllianceRecommendationForFitTesting_Final.pdf).

Personal Attenuation Rating

A Personal Attenuation Rating (PAR) is obtained from an attenuation measurement at one or more than one frequency. The PAR has been shown to be more accurate than the NRR because it is calculated per individual and per hearing protection device, while NRR is a generalized estimate of potential sound reduction based on the protection provided to a small population of people. It gives the evaluator an estimate the total noise exposure an individual is receiving when wearing hearing protection.

Different methods can be used to measure the attenuation provided by HPDs. (Murphy, 2014;

<http://www.caohc.org/updatearticles/winter2013.pdf?version=012914>

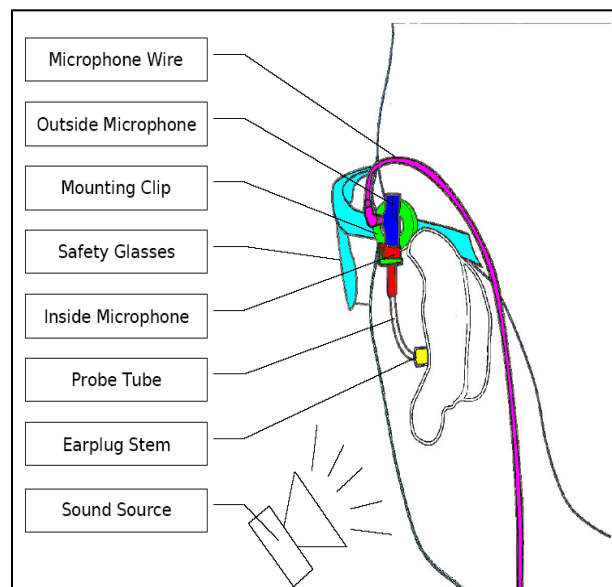
. They are presented next.

5.6.2 Field Microphone in Real Ear (F-MIRE)

Microphone-in-Real-Ear (MIRE) techniques determine HPD performance by measuring sound levels beneath the HPD to be tested. This approach has been difficult to adapt to field use, as placing a microphone under the HPD has historically required placing the cable connecting the microphone to the data acquisition system between the HPD and the ear canal surface, resulting in an acoustical leak. New techniques enable field use of adapted MIRE technologies, referred to as F-MIRE.

One such system, called E-A-Rfit[®], circumvents the leakage problem by using specially probed HPDs with a sound bore integrated to the device. An exterior (reference) microphone measures noise outside the HPD; an interior

(measurement) microphone measures noise through the sound bore. The effect of the probe tube, transfer function of the open ear, and other measurement conditions are addressed in the data acquisition software to provide results comparable to *Real-Ear Attenuation at Threshold (REAT)* testing (see below). The F-MIRE test is completely *objective*, as no response is required of the subject, and only takes seconds to complete. Attenuation is determined by comparison of internal and external sound pressure level. An instrumented ear is shown in the Figure 5.13.



(Source: Courtesy of Aearo Technologies)

Figure 5.11 – F-MIRE Instrumented Ear

Measurement is conducted in a normalized sound field (approximately 90 dBA pink noise). Exterior noise minus interior noise plus compensation factors yield an estimate of individual performance, or *Personal Attenuation Rating (PAR)*.

5.6.3 Real-Ear Attenuation at Threshold (REAT)

Traditionally, HPDs have been evaluated using a threshold-shift protocol. Simply put, a hearing threshold test with the HPD off compared to a test on the same subject with the HPD on. The difference yields a “gold standard” estimate of HPD performance. A system for individual application of this

approach has been developed by Michael and Associates called FitCheck™ (Figure 5.14). Large-volume, high-output headphones are used in lieu of standard audiometric test equipment, and the test signal is pulsed 1/3 octave bands of noise instead of pure tones, but the protocol yields similar results. FitCheck provides individual REAT findings, directly comparable to laboratory test procedures, but it requires the equivalent of two hearing tests per subject. Any REAT protocol is also, by design, subjective. Subjects should be trained to respond to test tones, and should reliably and consistently respond to test tones at threshold.



Figure 5.12 – FitCheck Equipment

(Source: Courtesy of Michael & Associates)

5.6.4. Alternating Binaural Loudness Balance

Loudness balance is a psychophysical method used to estimate the attenuation for earplugs with a sequential approach. This method is used by VeriPro by Honeywell (Howard Leight). It uses headphones to present tones that alternate between the right and left ears of the subject. The subject's task is to adjust the level of the tones such that they are the same volume in each ear or loudness balanced. The task is repeated for several frequencies (e.g. 250, 500, 1000, 2000, and 4000 Hz) and is performed for both ears unoccluded (no earplugs), right ear occluded (right earplug only), and both ears occluded (both earplugs in). The differences between the levels for the three conditions are used to estimate attenuation for each frequency and each ear. VeriPRO also provides a quick assessment mode that estimates the attenuation at 500 Hz.

It should be noted here that the brands mentioned in the examples above are not all the versions available, and availability varies by country. If an industrial hygienist is providing advice or services in this area then they should carry out a search into the available systems at the time and purchase the most appropriate system(s) for the fit-testing method adopted.

Appropriate selection and proper use of HPDs are critical to prevent hearing loss in noise-exposed workers. New technologies and approaches, as discussed above, are enabling individual testing of HPD performance, enabling improvement in HPD selection and fitting. Individual fit testing is the most accurate means to determine HPD performance for each user, as it minimizes, perhaps eliminates, the various issues previously cited with each of the independent-laboratory attenuation rating methods.

5.7 HPD REQUIREMENTS

5.7.1 Require Use

HPDs are should be worn in all areas with sound levels 85 dBA or greater, and that is the regulatory requirement in many countries. The rule of thumb is: “if you have to raise your voice above the noise level to talk to someone at arm’s length away, then hearing protection may be warranted.”

5.7.2 Availability

HPDs need to be readily available at locations or stations prior to entering a high-noise area. For example, process unit control rooms and building entrances are strategic locations for earplug dispenser boxes and earmuff storage. For those facilities where noise sources may be intermittent or unpredictable, all employees in the field should keep HPDs in their possession at all times available for immediate use.

5.7.3 Warning Signs

All work areas and intermittently used equipment (e.g., hand-held tools or mobile equipment) that generate levels of 85 dBA or more should be posted as hearing protection required areas. The figure below shows the typical style of such warning signs. It is important that compliance with the signage is required and that staff in the area are provided with HPD. If disposable HPD are to be used, the dispenser should be available **at the entrance to the signed area** and not at some distant location.



Figure 5.13 – Example of Warning Signage

5.8 TRAINING AND MAINTENANCE

5.8.1 Training

HPD wearers should be trained in the proper use, particularly regarding the insertion in the case of earplugs, and care of their protectors during initial fitting, at the time of their annual hearing test, and whenever

observed to be improperly wearing HPDs. Evidence indicates that instructions for inserting earplugs into the ear canal have a considerable effect on the noise attenuation of the devices (Tikka et al., 2017).

If there is a change in a workplace PPE policy or the introduction of new PPE that could interfere with the correct fitting of the issued HPDs it is then necessary to check the compatibility of both equipment. It will also be necessary to retrain the exposed workforce. Further information on what should be included in a training programme is in Section 6.2

5.8.2 Maintenance

Manufacturers of HPDs supply information on the care and maintenance of their products. This may be via instructions issued with the product or via their website. It is important to read as it will help ensure that they are maintained in the best condition to protect the wearer when worn correctly. A summary of the general information normally supplied is given as follows:

- Earplugs should be routinely inspected before fitting for dirt and to ensure no damage or physical changes (e.g. extreme hardness or deformation) have occurred to the device over time that would inhibit the ability to obtain an airtight seal. Certain foam plugs may be re-used on average 5-10 times before the cell structure breaks down, which can prevent proper insertion and/or an effective seal. Always check with the manufacturer's instructions for care and maintenance of their earplugs. Most multiple use earplugs may be cleaned with a mild soap and water, when needed. Single use earplugs should be discarded at the end of the work shift.

Earmuffs should be checked regularly for cleanliness and for damage to the earcups and cushions as that will compromise their attenuation level. These checks should include looking for holes or leaks in the plastic shells; creases, grooves or tears/splits in the cushions; and, are

the foam liners inside the shell damaged or hardened. The cushions and headband can be cleaned with mild soap and water. Replacement cushions and foams may be available from the manufacturer although it may be more cost-effective to replace the aged ear muffs rather than keeping stocks of replacement cushions. In workplaces or countries where extreme climatic or humid conditions occur it may be necessary to replace the ear cushions or foam inserts more often. The headband should be routinely inspected to ensure it still provides adequate pressure to seal the ear cups against the side of the head.

6. EDUCATION & TRAINING

6.1 INTRODUCTION

There is little point in setting up an occupational noise management programme unless management and workers understand the reason for the programme, the goals of the programme, the components of the entire programme, the responsibilities of staff and the workers and the procedures for the assessment and development of the programme. As the decision on the appropriate noise controls and their implementation may take some time to develop, there is likely to be a need for education and training over a number of stages.

Once it has been identified that a noise hazard exists in the workplace, the employer must understand the importance of implementing noise management and the options available, so that solutions are identified for the particular workplace. Those exposed to the noise must also understand the hazard and the safety systems that are installed to reduce the risk of hearing damage. This also provides the opportunity for explanation to the workers of the possible options for long term reduction of the risk and for them to have meaningful input into the process. Larger workplaces may be able to undertake noise assessments and also to develop workplace noise controls. Additional training may be necessary to develop their competencies in these areas.

Standards, codes of practice and other documents often provide guidance for the content for training courses for the various personnel at a work place where there is a noise hazard. These documents may include suggested course syllabus which address the specific needs and which should be followed in those jurisdictions where they apply. For other jurisdictions the following suggestions for a syllabus for training programmes are loosely based on the suggestions for course outlines and syllabus from the parts of AS/NZS 1269.

6.2 TRAINING IN USE OF HEARING PROTECTORS

Once a noise hazard has been identified, some immediate action is required to protect employees. If no engineering solution can be introduced immediately then a hearing protector programme must be implemented while other noise control methods are being considered.

While risk is being managed through a hearing protector programme it must be holistically implemented. It is not sufficient to just provide protectors and tell the staff to use them. It is important they understand where to use them, how to use them properly and in particular the importance of wearing them all the time in the noisy areas. Evidence indicates that instructions for inserting earplugs into the ear canal have a considerable effect on the noise attenuation of the devices (Tikka et al., 2017), and is therefore necessary for the success of such intervention.

The following topics summarise the recommended inclusions for any training session. The level to which each topic is covered depends on the needs of the particular workplace and in most cases many of these topics can be dealt with in an overview manner. Generally one to two hours should be sufficient in the first instance. Audio visual material can be used to cover most of the topics but it is essential to have 'hands on' demonstrations of the use of the types of hearing protection that are provided in the workplace.

Any form of protective device can be an annoyance. The temptation to not wear hearing protection may be greater than for other forms of protective devices as there is no immediate outcome of the exposure to the hazard, other than a temporary loss of hearing and maybe ringing in the ears. Unfortunately these effects can also be outcomes from recreational activities like enjoying loud music or noisy sports cars and there can be the perception that they are of little concern. So it is essential to provide regular follow up education sessions to motivate and remind the workers of the importance of protection of their hearing. These follow up sessions can revise the topics covered in the first session and provide a good opportunity for reviewing the condition of the hearing protectors and discussing any particular difficulties

workers may be encountering. These revision sessions need not be lengthy and can be in the form of informal 'tool box' OHS sessions.

6.2.1 Ear, Hearing and Noise

- a) Discuss the importance of hearing, how the ear works including how hearing loss occurs and how hearing is tested (audiometry).
- b) Demonstrate types of noise including low and high frequency noise, constant, and intermittent noise and impulse noise and highlight those which are in the their workplace.
- c) Discuss noise levels, decibels, noise measurement and noise exposure. Give illustrations of various noise levels, ranging from a soft whisper to a jet engine.
- d) Identify high noise areas in the relevant workplace, e.g. by showing a floor plan of the premises.
- e) Discuss management and worker responsibilities and obligations related to the hearing protector programme.

6.2.2 Importance of Protecting Hearing

- a) Explain the importance of protecting hearing including the difficulties experienced by people with hearing impairments and tinnitus. Discuss the implications beyond hearing loss, such as social isolation and increased rates of depression.
- b) Overview relevant legislation and discuss of the relevant noise exposure criteria.
- c) Explain engineering controls that are in place, such as barriers and enclosures. Highlight any of their limitations to explain the continuing need for wearing hearing protectors until further measures are in place.
- d) Explain the need to maintain the equipment to reduce noise exposure and to inform supervisors of any change in noise levels.

6.2.3 Selection of Hearing Protectors

- a) Summarise the outcomes of the noise assessment including identification of noise areas and tasks and the types of noise encountered over a work shift.
- b) Explain where the hearing protector zones will be located, the types of signage in those zones and, if appropriate, the different types of hearing protection to be worn in each zone.
- c) Explain the selection of protections including types of hearing protectors, the benefits, drawbacks and limitations of hearing protectors, the importance of using the appropriate protectors in each noise zone. Briefly explain the effects of overprotection (isolation, poor communication).
- d) Demonstrate the types of protectors that are available in the workplace.

6.2.4 Use and Proper Fitting of Hearing Protectors

- a) Emphasise the importance of wearing the hearing protector at all times while in the noise hazard area, i.e. explain the accumulating effects of noise and the highly destructive effects of removing the hearing protector even for a very short time.
- b) Demonstrate fitting techniques, how to conduct a self-evaluation, and check if each individual can use their selected protectors correctly.
- c) Discuss the importance of comfort including use in hot and cold environments, perspiration, dirt and dust and the precautions when used in combination with other safety equipment, e.g. hard hats, respirators, goggles and similar.
- d) Summarise good and bad habits; explain the reasons for not modifying the hearing protectors and the need for good hygiene in particular washing hands before use of ear plugs.
- e) Provide the opportunity for the employees to discuss any medical, physiological and psychological factors that may be applicable.

6.2.5 Maintenance and Storage

- a) Demonstrate how to clean the protectors.
- b) Show where and how the equipment is to be stored.
- c) Demonstrate how to inspect for defects and explain if policy is to obtain replacement parts or to replace faulty protector.
- d) Explain what to do if any problem occurs.

6.3 TRAINING TO UNDERTAKE NOISE ASSESSMENTS

In small and medium sized workplaces it may be more cost effective to engage an acoustical consultant or occupational hygienist to undertake workplace noise assessments on a regular basis. In larger companies there could be occupational health and safety personnel and engineering staff who could develop the competencies to undertake noise assessments, develop appropriate noise management plans including the implementation of basic noise control measures to minimise the use of hearing protectors.

It is usually necessary to revise and build upon the education and training these personnel have obtained. The following topics can be used as the basis for training courses and are similar to standards and industry best practice. A workplace noise assessment requires a good understanding of the principles of noise measurement, the criteria for of occupational noise assessment and the options for noise management to reduce the hazard. To properly develop the competencies the following topics should be thoroughly understood and the personnel should be required to demonstrate that they do have the competencies. The training courses would generally be 3 to 5 days. Refresher courses of 1 to 2 days are suggested on a regular basis, typically every 5 years to update skills including the use of modern instrumentation.

6.3.1 Goals and Objectives

Those carrying out workplace noise assessments should be able to demonstrate a thorough understanding of -

- a) The objectives of the assessment.
- b) The basic physics of sound.
- c) The mechanism of hearing and the harmful effects of excess noise.
- d) The correct usage and limitations of sound measuring instruments required to gather data for noise assessments.
- e) The information needed and methods used to determine occupational noise exposures.
- f) How to record results and explain them to people in the workplace.
- g) The relevant statutory requirements, Codes of Practice and Standards.
- h) The options for development of a noise management programme.
- i) The principles of engineering noise control and noise management measures.
- j) When to advise that someone with more specialized knowledge on noise measurement or noise control is required.
- k) The selection of personal hearing protectors and the other requirements for the workplace when hearing protectors are part of the noise management plan.

6.3.2 Basic Acoustics

To control a hazard it is important to understand its source and mechanism of operation. The following topics need to be covered:

- a) The nature and physical properties of sound including; propagation, absorption and transmission.
- b) The descriptors for sound including decibels, sound pressure level and sound power level.

- c) Types of sound sources including time variations and frequency analysis.
- d) A and C frequency weightings; 'F' and 'S' time weighting.
- e) Signal measurement factors including rms and; peak.
- f) Sound pressure level measurement including equivalent energy level, $L_{Aeq,T}$, $L_{Aeq,8h}$, L_{Cpeak} .
- g) Sound exposure, $E_{A,T}$.

6.3.3 Need for Noise Control

- a) Mechanism of hearing;
- b) Effect of noise on hearing;
- c) Work and social implications of noise induced hearing loss; and
- d) Other effects of noise, e.g. interference with communication, masking of warnings, tinnitus and other physiological effects.

6.3.4 Sound Measurement Instrumentation

- a) Use and limitations of integrating-averaging sound level meters for area and personal noise exposure measurements.
- b) Use and limitations of personal sound exposure meters (dosimeters).
- c) Need for calibration standards and noise measurement procedures including field checks and periodic calibration by laboratories with traceability to national standards.

6.3.5 Measurement of Workplace Noise

- a) Noise assessments, i.e. preliminary assessments, detailed noise exposure assessments, measurements for noise control and monitoring;
- b) Identification of sources and areas which contribute to exposure;

- c) Effect of space characteristics on measurement accuracy; i.e. reflections, standing waves, etc.;
- d) Recording of results; and
- e) Explanation of results.

6.3.6 Occupational Noise Assessments

- a) Details of relevant statutory requirements, Codes of Practice and Standards.
- b) Measurement and determination of extent of hazard with reference to exposure standards.
- c) Consideration of the options for effective noise management.
- d) Report on assessment identifying the options with recommendations for short and long term goals for reduction of the risk.

6.3.7 Noise Reduction

- a) Engineering approach to noise reduction, i.e. reduction at source, transmission path and receiver;
- b) Identification of main sources for attention;
- c) Strategies for noise reduction including vibration isolation;
- d) Guidance on noise limits in specifications on new plant and buildings;
- e) Benefits that can be gained by considering work techniques and ensuring regular maintenance; and
- f) Options for specialist advice from suppliers, manufacturers and consultants.

6.4 TRAINING TO DEVELOP AND IMPLEMENT NOISE CONTROL MEASURES IN THE WORKPLACE

In small and medium sized workplaces it may be more cost effective to engage an acoustical consultant to propose noise control measures. In larger companies there maybe engineering staff who could develop the competencies to undertake noise assessments, understand the requirements

of noise management plans and then develop and implement engineering noise control measures to reduce the hazard.

It would be wise for these personnel to undertake a training course in workplace noise assessment so they understand the assessment of workplace noise, the standards that apply and the goals and objectives of the noise management plan. The following topics can be used as the basis for training courses and are derived from the sections of AS/NZS 1269. A workplace noise assessment requires a good understanding of the principles of noise measurement, the criteria for occupational noise assessment and the options for noise management to reduce the hazard. To properly develop the competencies the following topics should be thoroughly understood. The training course for engineering noise control would generally be 3 to 5 days.

6.4.1 Goals and Objectives

Those developing workplace engineering noise control should:

- a) Possess a basic understanding of the properties of materials in relation to their function with respect to the transmission of sound;
- b) Understand how noise is generated;
- c) Understand how noise is transmitted;
- d) Understand the principles of reducing noise;
- e) Be able to carry out a simple diagnosis into the causes of the generation of noise by machinery; and
- f) Have the skills to begin to apply simple noise reduction/control techniques to machines common in their workplace.

6.4.2 Noise Sources and Transmission

- a) Measurement of sound and properties of materials.
- b) Generation and transmission of sound.
- c) Types of noise i.e. continuous, repetitive and impulsive noise.
- d) Resonance.

6.4.3 Understanding Noise Reduction and Control

- a) Importance of machinery maintenance to minimise noise and vibration
- b) Isolation of noise and vibration sources.
- c) Machinery vibration damping and control.
- d) Control of the radiation of noise from surfaces and adjoining areas.
- e) Use of absorption to control reflected noise.
- f) Partial and full height barriers to reduce sound transmission.
- g) Design of enclosures for plant and machinery.

6.5 CONCLUSION

Although noise is a fundamental physical phenomenon, its monitoring, control and risk management is not always straightforward. A proper understanding of its basic cause and effects is important to the implementation of any successful risk management strategy.

7. AUDIOMETRIC TESTING

Noise-induced hearing loss is a specific condition with established symptoms and objective findings. It is an irreversible hearing loss, often bilateral and sensorineural with damage mainly to the cells in the peripheral auditory organ, which are responsible for transforming the sound waves into neural signals. Noise-induced hearing loss develops gradually after a long period (8-10 years) of exposure to intense levels of noise. This means exposure to continuous noise levels greater than 85 dBA for 8 hours/day or exposure to impact noise (a noise that arises as the result of the impact between two objects), even if for shorter periods, sufficient to cause the degree and pattern of hearing loss found in pure-tone audiometry. The results are displayed as an audiogram. An audiogram indicates the individual's hearing detection thresholds. The results are given in decibels, which indicate the intensity, or how loud a sound has to be for the listener to be able to detect it. Thresholds up to 20-25 decibel hearing level (dBHL) are considered as normal. Several frequencies are tested. Frequency determines the pitch of a sound. Noise-induced hearing loss is usually not a profound hearing loss but may reach up to 75 dBHL in the higher frequencies such as 4 and 6 kHz and up to 40 dBHL in the lower frequencies of 1 and 2 kHz.

7.1 HEARING DISORDERS

Although the occupational setting is almost exclusively concerned with noise-induced hearing loss, there are many other types of ear pathologies and hearing disorders totally unrelated to noise exposure. Familiarization with ear pathology and hearing loss is helpful since non-occupational hearing loss will be encountered in the workforce and may need special accommodations. In addition, NIHL should be differentiated from other types of hearing loss.

7.1.1 Types of Hearing Loss

There are four basic types of hearing loss: conductive, sensory, neural, and mixed.

- **Conductive**

A *conductive* hearing loss occurs when the sound pathway is blocked in the outer and/or middle ear, reducing the vibration that reaches the inner ear. Hearing loss is present because the sound is not transmitted effectively through the outer and middle ear to the normal functioning inner ear. Often conductive hearing loss is treatable and can be reversed. Perhaps the most common conductive hearing loss is that caused by impacted earwax, or cerumen, in which the entire ear canal is blocked. Once the cerumen is removed, the sound pathway is restored and hearing returns to the original sensitivity. Pathologies of the outer ear include (but are not limited to) outer ear infection or otitis externa, perforated eardrum, foreign object in the ear canal, or a deformity to the outer ear due to injury or genetic disorder. Of concern to the audiometric examiner is recognizing when an external ear canal condition either contraindicates performing a hearing test or interferes with proper use of earplugs.

Examples of middle ear pathologies causing conductive hearing loss include otitis media (also known as middle ear infection), a complication of chronic otitis media called cholesteatoma, and a disease process hardening the ossicles called otosclerosis. All of these pathologies require diagnostic audiology evaluation and medical attention. The audiometric examiner is typically not involved in diagnosis of hearing loss and should depend on other medical professionals for this information.

A conductive hearing loss is diagnosed when bone conduction hearing thresholds are better than air conduction thresholds. The difference between air and bone thresholds is called *air-bone gap*, and defines the degree of conductive hearing loss. The maximum degree of conductive hearing loss is approximately 60 dB HL: sound louder than 60 dB HL will reach the inner ear via bone conduction.

- **Sensorineural**

Sensory hearing loss is specific to the cochlea and neural hearing loss is due to pathology within the auditory nerve and/or central auditory pathway. The term sensorineural hearing loss is used if the site of lesion of the pathology has not been differentiated between the cochlea and the neural pathway. As diagnostic tools become more sophisticated it is more likely a site specific diagnosis can be made.

Compared to conductive hearing loss, sensorineural hearing loss is less likely to be medically treatable and more apt to be permanent. Examples of sensorineural hearing loss are age-related hearing loss (ARHL), also called *presbycusis*, noise-induced hearing loss (NIHL), Meniere's Disease, and vestibular schwannoma, which is a tumour on the auditory nerve. Sensorineural hearing loss can also be caused by certain medications which are toxic to the inner ear and there is some evidence suggesting that environmental exposure to certain chemicals can increase the risk of acquiring sensorineural hearing loss. Sensorineural hearing loss is identified on the audiogram when air conduction and bone conduction thresholds are equal and outside the normal range of hearing. In addition to a reduction in hearing sensitivity, the clarity and quality of sound can be affected. This causes distortion of sound and reduces the ability to distinguish between similar sounds.

- **Mixed**

Mixed hearing loss is a combination of both conductive and sensorineural hearing loss. For example, an elderly person may have sensorineural hearing loss due to *presbycusis*, and also have an overlying middle ear infection causing a conductive component. Once the middle ear infection is resolved the mixed hearing thresholds will return to the level of the sensorineural hearing loss. Sometimes mixed hearing loss can be treated successfully by resolving the conductive component. Examples of mixed hearing loss include chronic ear infection, trauma to the ear, and certain ear diseases.

7.1.2 Noise Induced Hearing Loss (NIHL)

Noise-induced hearing loss (NIHL) is of primary concern in occupational settings with high noise exposures. Characteristics of both the sound itself (primarily intensity and duration), and the person exposed to the sound (genetic make-up, health status, and other factors) determine how the ear is affected by noise. In general, if stimulation is too loud for too long, damage to the internal structures of the inner ear occur. The relationship between the amount of noise exposure and the resulting hearing loss is complex, as many individual factors may affect susceptibility, and environmental conditions may increase risk.

- **Impulse/Impact Noise**

Both impulse and impact sounds are short duration bursts of acoustic energy. Impulse noise results from a rapid expansion of gas such as an explosive action or gunfire, and impact noise occurs when two hard surfaces strike together, such as a hammer on metal.

Complex noise (noise containing both continuous and impulse noise) can be more damaging than a continuous noise of the same energy. The acoustic reflex is an involuntary muscle contraction triggered by high-intensity sound. This contraction leads to the malleus (hammer) being pulled away from ear drum thereby attenuating the transmission of vibrational energy to the cochlea.

Biological diversity between individuals can result in a single exposure to impulse noise causing permanent threshold shift in a given individual while another individual may not show hearing damage until multiple exposures over many years have occurred. Research based on animal studies has indicated that there is a “critical level” of exposure, below which, hearing loss increases by about 1-3 dB for each dB of increase in peak level of the noise.

Both impact and impulse noise can cause “acoustic trauma” resulting in significant hearing loss, tinnitus, and a sensation of fullness in the ear after a single exposure. Although some recovery of hearing can occur in the hours immediately following the noise exposure, acoustic trauma refers to permanent hearing damage. As stated earlier, the degree of hearing damage as a result of impulse/impact exposure depends on many factors. Due to individual differences in genetic make-up, general health status, and environmental conditions, the degree of damage is not directly proportional to the noise level and varies from one person to the next. However, above the critical level, hearing loss increases much more rapidly: 3-7 dB of hearing loss for each dB of peak level increase. The critical level for humans is accepted as 140 dBC peak SPL for impulse noise.

- **Continuous and Intermittent Noise Exposure**

Noise-induced hearing loss can occur after exposure to steady or intermittent noise. When shift exposure is 8 hours or less there are some recovery mechanisms which reduce the permanent damage. These however rely on 16 or more hours in a quiet environment. Where the work shift exposure is greater than 8 hours the recovery time is insufficient and the hearing loss will be greater than expected from the overall noise level. Adjustments must therefore be made to the exposure criteria for long work shifts or when the resting area is not quiet as may be the case where crew rest/sleep areas are provided within a vessel or rig.

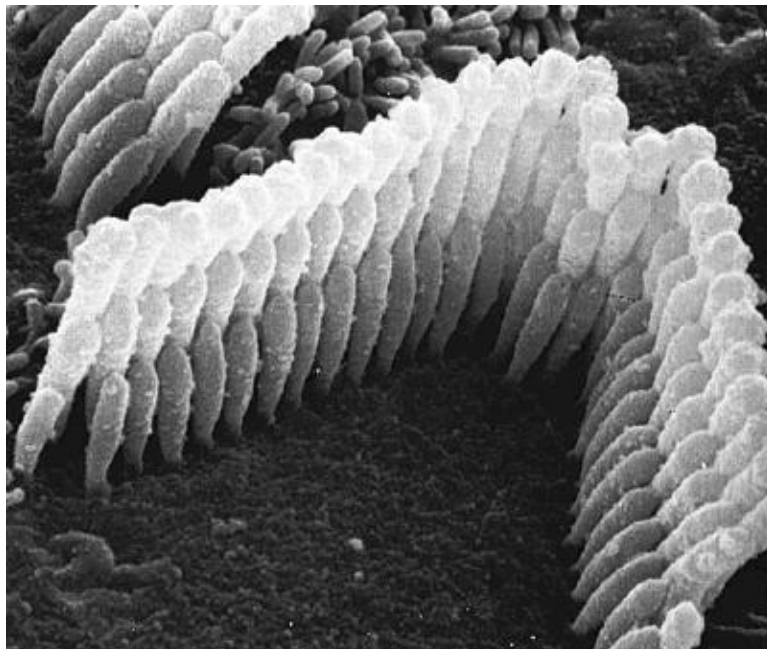
- **Temporary and Permanent Threshold Shifts**

A temporary threshold shift (TTS) is a change in hearing thresholds which shows some recovery within 24-48 hours after the noise exposure stops. The more intense (louder/longer) the exposure, the longer the expected recovery period would be. Hearing loss which persists more than 30 days after the noise exposure is considered to be permanent threshold shift (PTS) since recovery is unlikely.

7.1.3 Auditory Effects of Excessive Noise Exposure

NIHL is a result of structural damage to the cochlea. In general, the larger the hearing loss, the more widespread the damage is within the auditory system.

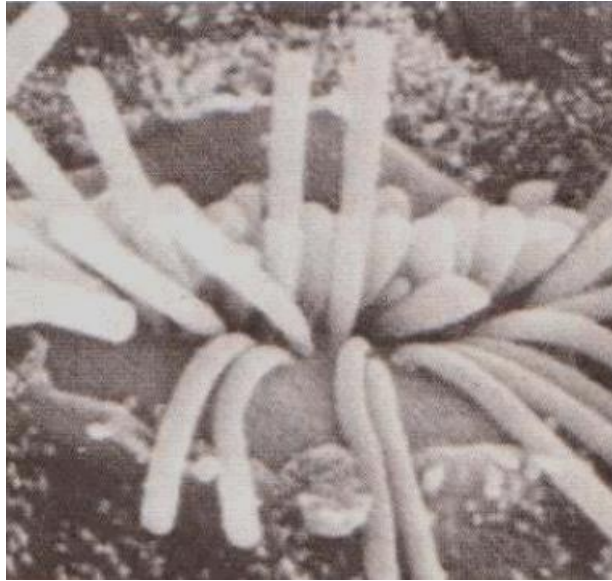
Intense blasts can cause such extreme vibration that the eardrum may perforate and/or haemorrhage, the ossicles can fracture, and in severe cases, the organ of Corti can be torn off the basilar membrane and eventually deteriorate. Hearing loss from this extensive damage would be profound and affect multiple frequencies.



(Source: David J Lim – Image used with permission)

Figure 7.1 - Scanning electron micrograph of normal “undamaged” stereocilia. Credit - David J. Lim. *Functional Structure of the Organ of Corti: A Review. Hearing Research, Elsevier 2b. 22 (1986) 117-146. Retrieved from www.dangerousdecibels.org.*

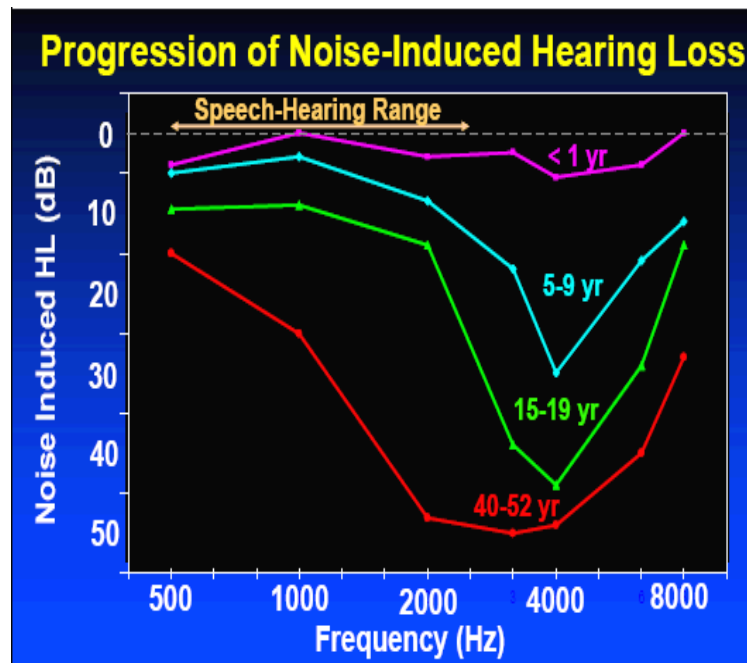
NIHL from continuous, long-term exposure is more likely to be contained within the cochlea, more specifically there will be structural damage to the outer hair cells. The more severe the hearing loss, the more likely the damage extends to the inner hair cells and supporting cells. Figures 7.1 and 7.2 compare normal stereocilia and those damaged by noise.



(Source: Hunter-Duvar, I.M. – Image used with permission)

Figure 7.2 – Scanning electron micrograph of noise-damaged stereocilia. Credit: Hunter-Duvar, I.M. (1977). Morphology of normal and acoustically damaged cochlea. SEM 1977, II, 421-428. Retrieved from www.dangerousdecibels.org.

7.1.4 Progression of Noise Induced Hearing Loss



(Source: Image courtesy of Elliott H Berger, Aearo Technologies Inc)

Figure 7.3 - The progression of noise-induced hearing loss over time for workers exposed to approximately 100 dB SPL. The classic "noise notch" appears first at 4000 Hz. It deepens and spreads to adjacent frequencies over time.

The clinical hallmark of noise-induced hearing loss is a “notch” in the audiogram between 3000 – 6000 Hz, with better thresholds at the adjacent frequencies. Typically, this occurs at 4000 Hz, giving rise to the commonly used term, “a 4kHz notch” or “a 4kHz dip”. Recent research has revealed a higher prevalence of 6000 Hz notches, especially in females, than previously believed, making it more important to include 8000 Hz in the audiometric test protocol. The progression of NIHL has been well-documented. Data from a classic study is graphically represented in Figure 7.3: audiometric tests from a population of jute weavers exposed to occupational noise of approximately 100 dB SPL (Taylor, 1965). Note that over time the audiometric “notch” deepens and spreads to adjacent frequencies. In the first 10 – 15 years of noise exposure, the hearing loss accelerates most at 4000 Hz. Eventually, the hearing loss advances to the point where a notch is no longer detectable.

7.1.5 Tinnitus

In addition to hearing loss, a common result of over exposure to noise is tinnitus, commonly called ringing in the ears. Tinnitus refers to the perception of sound with no corresponding external sound source. Tinnitus is common in the general population, however it much more likely to be a bothersome symptom for those who have a history of occupational and/or military noise exposures. Those who suffer from chronic tinnitus may report having difficulty falling asleep, reduced ability to concentrate, trouble relaxing, and experiencing annoyance, irritability, frustration, and/or despair. Although there are some treatments and coping strategies for tinnitus, there is no known cure.

7.1.6 Age-Related Hearing Loss or Presbycusis

The aging process affects all aspects of the auditory system resulting in hearing loss, known as age-related hearing loss (ARHL) or *presbycusis*. Specifically, hearing loss is primarily due to the loss and deterioration of outer hair cells in the basal turn of the cochlea. The audiometric pattern is a “sloping” audiogram: hearing sensitivity is worse at each higher frequency. The degree of change is highly individualized.

Population studies show that by the later decades of life, there is little difference between the audiometric configurations of *presbycusis* and noise-induced hearing loss (NIHL). Since occupational NIHL typically accrues over many years, the ear is aging as well as suffering cochlear damage from over exposure to noise. Differentiating between the aging affects and the noise affects in an exposed, aging employee is problematic and there is no widespread consensus in the medical or legal community on how this is done. Extensive research using population databases of audiometric thresholds resulted in approval of an American standard (ANSI S3.44) and an international standard (ISO-1990). Data used to develop the standards are based on populations of industrially exposed workers with continuous noise for a standard work week at that time (8 hours/day, 5 days/week). These standards attempt to quantify the amount of ARHL from NIHL. Because sample sizes were small and cross-sectional rather than longitudinal studies were used, the application of the standards to individuals is somewhat controversial.

7.1.7 Non-organic Hearing Loss

The term non-organic hearing loss refers to cases in which there is no apparent organic or physical cause. This occurs when the audiometric findings indicate hearing loss exists, this is alleged to occur when an individual is exaggerating the hearing levels purposely in order to appear as if hearing loss exists to a greater degree than it really does. Other terms used for this condition are functional hearing loss, or malingering. In rare cases there is a psychological condition in which an individual functions as if hearing impaired, although hearing is within normal limits. The clinical term for this is pseudohypacusis and typically requires psychological referral and treatment. Non-organic hearing loss may be suspected when responses during the audiometric test are highly inconsistent, behaviour is inconsistent with the admitted hearing loss, or when there is an ulterior motive for having hearing loss. Cases of suspected non-organic hearing loss should be referred to an audiologist for diagnostic audiology evaluation since there are many clinical tests available to reveal actual hearing levels.

It is important to avoid accusing or labelling an individual who is exhibiting inconsistent audiometric findings; rather consult the appropriate professional since likely legitimate results can be obtained with more time and special testing.

7.2 REHABILITATION

Persons with hearing loss can usually benefit from hearing aids, assistive listening devices, and/or aural rehabilitation. Technological advancements have significantly improved the ability to overcome the disabling effects of mild hearing loss to restore communication and the appreciation of sound.

However, no electrical or mechanical device can ever restore normal hearing.

Workers with hearing loss may require particular solutions in the workplace to ensure they hear salient communication and respond to environmental sounds and auditory warning signals. For more information on assisting the hearing impaired employees, refer to a document: Innovative Workplace Safety Accommodations for Hearing Impaired Employees, which can be retrieved from: <http://www.osha.gov/dts/shib/shib072205.html>

7.3 AUDIOMETRY

Audiometric testing programmes can identify employees at risk of developing permanent hearing loss due to over-exposure of work place noise or by monitoring a worker's hearing thresholds over time, small changes in hearing can be detected, allowing the opportunity to intervene with education, hearing protection, and other preventative efforts. If successful detection and intervention occur while the hearing shift is temporary, this will avoid eventual permanent NIHL.

Secondly, analysis of the audiometric database from a population of workers can provide critical information about the quality of the Hearing Conservation Programme and the hearing health of a given population.

Audiometric testing programmes should be designed for early identification rather than simple documentation of hearing thresholds. As well, plans to

follow-up problematic audiometric findings should be in place. To be useful for trend analysis and to drive HCP decisions, the audiometric data must be reliable, valid, and accessible.

7.3.1 Guide to Audiometric Programme

a) Competent Audiometric Tester

Audiometric tests should be performed by a competent person who received necessary training. The requirements of such training vary by country. The audiometric portion of a programme require a person who can interact with employees in a confidential and respectful manner to solicit accurate, comprehensive information, and to obtain valid audiograms and medical histories.

The moment of the test offers an opportunity to teach employees about hearing and hearing protection in one-on-one sessions with workers. It is a valuable opportunity to review hearing test results and to select and fit hearing protection devices. Audiometric results must be analysed in order to identify abnormal audiograms and those with significant changes in hearing. There is also a need to understand situations that require medical referrals based on the audiometric thresholds.

Follow-up actions need to be managed and rigorous, and accurate recordkeeping is essential. Technical knowledge and trouble-shooting skills are needed to keep computers and audiometric equipment functioning properly. There is particular emphasis on communication between the workplace supervisor and the employee, with prevention of hearing loss and tinnitus as primary goals.

b) Audiometric Database Management

The management and integrity of the audiometric database, including recordkeeping and electronic record management is important in order to ensure that audiograms are being correctly tracked and maintained

in accordance with internal company policies and relevant local and country regulations.

c) Privacy Policies

The audiometric database contains personal medical and identifying information and must be kept confidential. Individual hearing test results and medical history information shall be safeguarded and afforded the same treatment as other medical records.

d) Evaluation of HCP Effectiveness

Audiometric database analysis of population data can reveal trends and audiometric variability. Reviewing individual audiometric records to determine test validity and work relatedness of hearing loss is mandatory in many countries. The effectiveness of a HCP is measured by its ability to reduce noise exposures and prevent occupational hearing loss. The interventions in place should be evaluated periodically.

e) Employees Included in the Audiometric Testing Programme

If there is any chance the employees may be exposed to excessive noise during their employment, an audiogram should be taken at the commencement of employment, often referred to as a base line audiogram, and at the completion of their time with that employer, often referred to as an exit audiogram. All employees who are exposed at or above an $L_{Aeq,8}$ of 85 dBA should be enrolled in the HCP and included in a regular, usually annual, audiometric monitoring programme. Exemptions from the audiometric monitoring programme are considered on an individual basis and should be documented. Visitors to a company site, who are exposed to 85 dBA, should be issued hearing protection devices and instructed in their use.

If local government regulations do not allow for mandatory regular audiometric testing every effort should be made by the employer to encourage those workers potentially at risk of hearing loss to participate in voluntary audiometric monitoring programme.

f) Audiometric Equipment Specifications

Audiometer

An audiometer is an electronic instrument used to measure human hearing sensitivity with calibrated pure tones of specific frequency and varying intensity. Audiometers can be classified in different ways: by the type of signal generated (pure-tone, speech, etc.). Audiometers used in HCP's are pure tone air conduction audiometers.

The most basic air conduction audiometer, termed *screening audiometer*, is designed for pass/refer programmes intended to identify individuals who have abnormal hearing. They have limited features: for example they may have only four test frequencies (500, 1000, 2000, and 4000 Hz) and three different screening levels (20, 25, 40 dB HL). Other screening audiometers have a full range of frequencies from 250Hz to 8k Hz and intensity control from 0-60dB in 5dB steps these are preferable for any HCP.

A *diagnostic audiometer* generates additional test signals such as bone conducted pure tones, speech, narrow band noise, modulated tones, etc. These stimuli are necessary for comprehensive assessment of the auditory system and diagnosis of hearing loss. Diagnostic audiometers are typically used in clinical settings by professionals.

Another way to classify audiometers is by their mode of operation. All of the following audiometers can be used in HCPs. Advantages and disadvantages exist for each type so careful consideration is needed to select suitable equipment.



(Source: Grason-Stadler, Inc – Image used with permission)

Figure 7.4 – Example of a Manual Audiometer with Air Conduction Threshold Finding Capability

- Manual Audiometer:** conventional instrument, as shown in Figure 7.4, which is operated manually by the examiner who selects the frequency and intensity, presents the tone, and records the results. Manual audiometers are stand-alone units which do not interface with computers. They are the least expensive of audiometer types.



(Source: Tremetrics – Image used with permission)

Figure 7.5 – Example of a Microprocessor Audiometer with Built-in Printer

- **Microprocessor or Automated Audiometer:** the audiometric test proceeds automatically by virtue of a computer chip determining the sequence of tone presentations. Figure 7.5 exhibits a microprocessor audiometer. A standardized threshold finding procedure is incorporated. The timing of tone presentations is varied and a consistency of response is required to minimize the likelihood of random responses being accepted as true thresholds. Multiple options are available according to the model and manufacturer; generally speaking these devices are self-contained units with a subject-response button, some data storage capability, and a built-in printer. Often microprocessors interface with a personal computer and software programme. Microprocessors have become popular in HCPs due to the automation and advantages of electronic data storage and recordkeeping. An automated audiometer should be able to operate in a manual mode, allowing the audiometric examiner to manipulate the controls and perform a manual threshold test.

Computer-controlled: a microprocessor audiometer driven by a personal computer. These audiometers may be coupled to a personal computer. Data is collected and stored directly on a personal computer in a software programme dedicated to audiometric evaluation. Many features are possible incorporated including delivery of pre-recorded instructions in multiple languages, cessation of test if ambient noise levels exceed allowable levels, and extensive data storage and analysis capability. They are frequently used in mobile audiometric test vans due to their small size and portability.



(Source: Benson Medical Instruments Co – Image used with permission)

Figure 7.6 - Example of a computer-controlled audiometer. The audiometer functions are accessed with the computer keyboard

- Bekesy, Automated, or Self-recording Audiometer:** the primary difference between this and the aforementioned audiometers is that the test stimuli constantly increases or decreases in accordance with the subject's response. The test stimulus is a continuous tone of varying intensity. The listener is instructed to press the response button as soon as the tone is audible, and release the button when the tone becomes inaudible. The tone increases and decreases in intensity accordingly, and the excursions are traced on the audiogram. Depending on the audiometer options, either the operator or the audiometer software determines the valid threshold by counting the number of repeated responses at the softest level. Figure 7.7 presents an example trace at 3000 Hz for a Bekesy-type audiogram. Results can be difficult to interpret, therefore self-recording audiometers are no longer widely used in occupational settings. Bekesy audiometers may be used for research purposes because the increments for both frequency and intensity can be finer than other audiometer types.

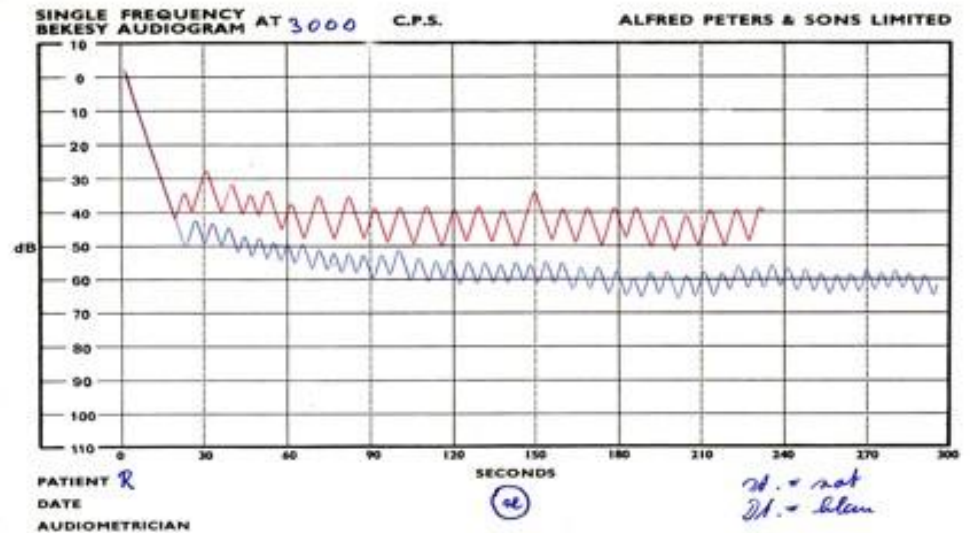


Figure 7.7 - Example of Bekesy threshold tracing at 3000 Hz

Audiometer manufacturers design equipment differently regarding features and functionality. National standards have been established to aid in achieving consistent and comparable results, regardless of the audiometer type. Audiometers must meet the American National Standard "Specification for Audiometers" Standard (ANSI S3.6-2004) Microprocessor audiometers should use automatic threshold procedures consistent with ANSI S3.21-2004.

h) Audiometric Test Booth

A sufficiently quiet test environment is required to obtain meaningful audiometric results. In addition, the test environment must be free of distracting, interfering sounds, such as telephones ringing, audible conversations, production and/or traffic noise, etc. To accomplish this, it is strongly recommended (and in some countries, it is a requirement ANSI 3.1 1999) to use a specially designed audiometric test booth to isolate the listener from background noise. Maximum levels of acceptable ambient sound levels are specified in standards and discussed in the calibration section below.

Research with recent technologies has shown that audiometric thresholds obtained in untreated open rooms through mobile, wireless automated hearing test systems exhibit within subject test–retest reliability comparable to thresholds obtained using conventional computer-automated audiometry conducted in a single-walled, sound-treated booth in a mobile trailer (Meinke et al., 2017). The development of portable, easily operated, economical, and reliable alternatives can facilitate hearing testing in typical worksite locations. Additional research is needed to make sure that such tools are accurate and can meet international sound and hearing measurement standards.

In addition to achieving sufficiently quiet background noise levels, effort is needed to maintain a consistent test environment from one year to the next. Maintaining similar test environments allows comparison of test results across time. Fluctuating noise during a test session can not only invalidate the test results but can be extremely frustrating to the listener, thereby undermining the value of the test. Sound booths must be maintained regularly to keep the doors seals, ventilation fans, lights, panels, etc., functioning properly, providing an optimal test setting. In addition to noise levels, the test environment should also be comfortable in terms of temperature, ventilation, and size. The test environment should invite the listener to both be relaxed and focused on the listening task.



(Source: Tremetrics – Image used with permission)

Figure 7.8 – Examples of two bioacoustics simulators. On the left is a standard simulator with headphones mounted in the test position. The device on the right has sound level monitoring capability at seven octave bands.

i) Performance Checking - Bio-acoustic Simulator

A bio-acoustic simulator or electro-acoustic ear is an electronic device designed to simulate a real listener for the purpose of verifying consistent audiometer stimuli output. Figure 7.8 exhibits two models available from one manufacturer. The premise is that a bio-acoustic simulator has predetermined hearing thresholds which do not vary. Each day that audiometric testing is conducted, a hearing test is first performed on the bio-acoustic simulator. The thresholds should be the same as the day the audiometer was initially calibrated (either as a new audiometer or the day of the annual exhaustive calibration). Changes in threshold levels at any frequency on the daily test, compared to the initial test indicate audiometer malfunction. Bioacoustic simulators are also designed with an optional built-in microphone and octave band noise analyser to monitor ambient noise levels in the test environment. If the ambient noise exceeds the allowable level, a light is illuminated, alerting the person performing the test to discontinue testing until the noise subsides. Documentation of the daily verification checks should be maintained over time as proof of function.

j) Otoscope

An *otoscope* is a hand held device with a light source and magnifier used to view the outer ear. Otoscopy is included in the audiometric testing protocol to assess the status of the outer ear, identify contraindications for performing an audiometric test and to judge the size and direction of the ear canal which aids in the selection and fitting of HPDs. There are no standards or specifications for the otoscope. The condition of the ear canal should be documented on the audiometric test form.

7.3.2 Equipment Calibration

Each audiometer should undergo a full laboratory calibration every year, or according to local country regulations. Unlike the daily verification, the exhaustive calibration is performed by a professional calibration service, often the audiometer manufacturer or equipment dealer. An exhaustive calibration consists of the following measurements:

- Sound pressure output,
- Linearity of the attenuator,
- Harmonic distortion,
- Rise and decay time, and
- Overshoot and “off” levels.

The professional calibration service chosen to conduct exhaustive calibrations should use the following minimum equipment requirements: Type 1 sound level meter, artificial mastoid (B&K 4930), frequency counter and timer, manometer, cavities, and couplers. The instrumentation should have annual calibration traceable to N.I.S.T. (National Institute of Standards and Technology). The following services are expected from the service provider:

- Produce copies of current records of the equipment used to calibrate,
- Use of the same calibration system used from year to year,

- Documentation of the measurement error, and
- No unnecessary adjustments to the audiometer.

Caution: each set of headphones is calibrated to one audiometer. Headphones cannot be swapped or used with another audiometer without recalibration.

7.3.3 Understanding the Audiogram

The audiogram is the graphical representation of hearing sensitivity. By convention, frequency (Hz) is plotted from low to high pitch moving from the left to right on the audiogram. Intensity (dB HL) is plotted from soft to loud moving from top to bottom on the audiogram. Air conducting thresholds are indicated by an “X” for the left ear and an “O” for the right ear. Sometimes the graphs are colour-coded: right ear results recorded in red and left ear results recorded in blue. These parameters and symbols may differ between countries so the legend should be consulted when interpreting test results. The degree and configuration of the hearing sensitivity is easily revealed, as is the difference between left and right ears.

The diagram shows an audiogram, note the Hearing Level scale. The lower the hearing level appears on the scale, the louder the presented tone needs to be in order to be heard.

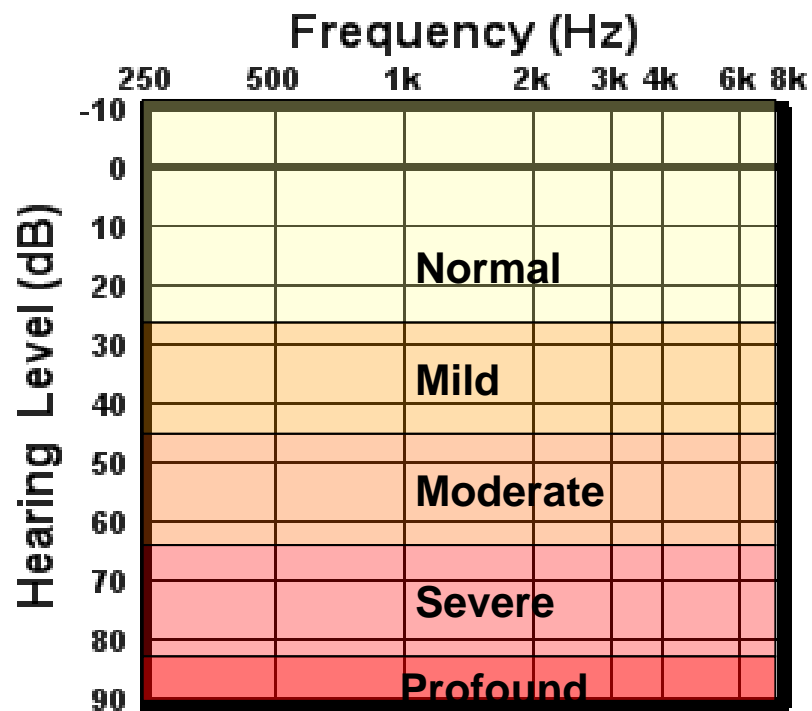


Figure 7.9 - Audiogram illustrating regions of hearing sensitivity

Charting the hearing thresholds on an audiogram reveals the shape or configuration of the hearing loss. Normal hearing is approximately the same at each frequency and equal in both ears. The audiometric shape is *flat* or a fairly straight line across the top of the audiogram.

A *sloping* configuration shows hearing loss rolling off in the high frequencies, which is commonly associated with *age-related hearing loss, or presbycusis*. A *reverse slope*, meaning worse in the low frequencies and improving in the higher frequencies, may occur with middle ear pathology or an inner ear disorder called Meniere's disease. For occupational hearing conservation the classic "*noise notch*" is significant and is indicative of NIHL. Figure 7.10 depicts audiometric results recorded in a tabular format and also plotted on an audiogram. The configuration of the thresholds is easily seen on the graph and reveals a degree hearing loss in both ears with a clear notch around 4000 Hz.

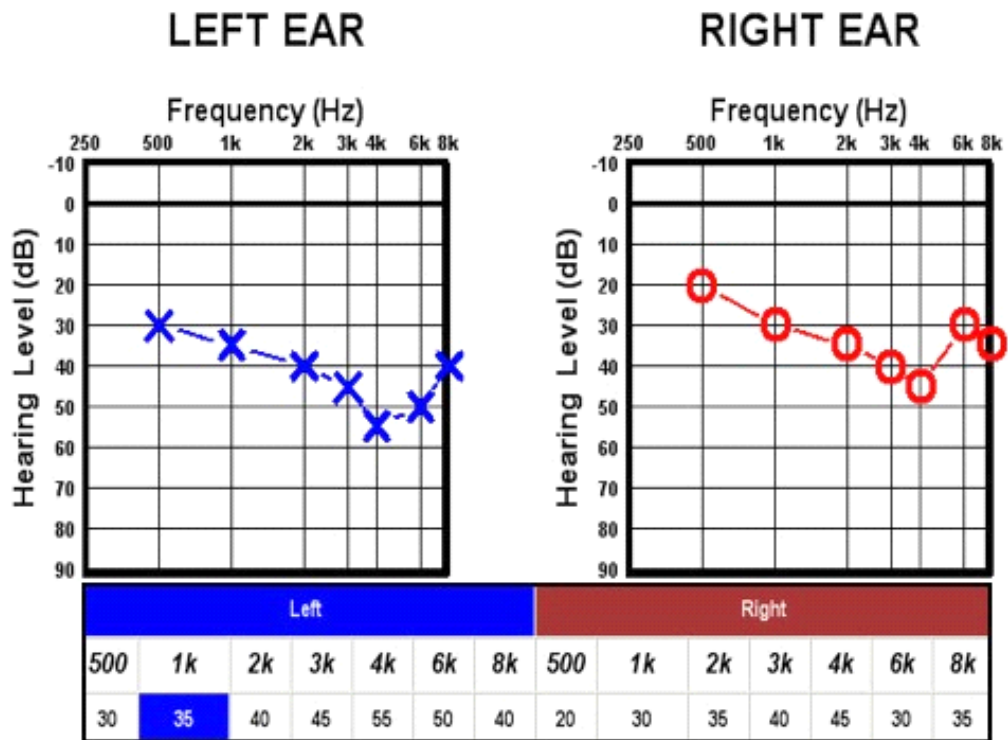


Figure 7.10 - Example hearing test results shown

7.3.4 Validity and Factors Affecting Audiometric Results

A valid audiogram reflects the listener's current audiometric thresholds. The test may be invalid if for example, the employee was exposed to high level noise without hearing protection shortly before a baseline test.

A test may be judged invalid if the thresholds do not correspond to the employee's communication ability, in other words, if the employee easily answers medical history questions but audiometric responses show a profound hearing loss in both ears, the test results are incongruent with the employee's behaviour.

Some employees are difficult to test due to severe tinnitus yielding inconsistent responses to test stimuli. If valid audiograms cannot be obtained at the test site the employee should be referred to an audiologist for a more extensive evaluation. Note: the test/retest reliability of audiometric testing is ± 5 dB. Therefore two consecutive tests that are within 5 dB at each frequency are not necessarily considered inconsistent.

In the US and in some other countries, the current process for determining the presence of an STS allows for the use of an age-correction procedure. The purpose for age-correcting audiograms is to prevent employers from being held responsible for hearing changes due to aging rather than noise exposure. However, because age-correction data are derived from studies of large populations, it is statistically inappropriate to compare individual data to population data, particularly for prevention purposes. In addition, as described above, age corrections can sometimes mask early signs of noise-induced threshold shift [Rabinowitz et al. 2007]. The OSHA age-correction tables, which were derived from the original 1972 NIOSH criteria document on noise exposure, have some potential problems as well. Correction factors are supplied only through age 60, although the prevalence of older persons in the workforce is increasing [Anderson and Hussey 2000]. The tables also do not distinguish among various racial/ethnic groups, although data suggest that susceptibility to hearing loss varies across various race/ethnicities [Hoffman et al., 2017].

Since publication of the original NIOSH noise exposure data [1972], more recent normative data have become available. Hoffman et al. [2010] analyzed data from the National Health and Nutrition Evaluation Survey (NHANES) and found hearing threshold levels in a large sample of the U.S. population that were somewhat lower (better) than those usually used for damage-risk criteria in Annex B of ANSI S3.44, at least for the frequencies 0.5, 3, 4, and 6 kHz. In an analysis of data from the Baltimore Longitudinal Study of Aging, Pearson et al. [1995] found even lower thresholds in their cohort and provided additional data for the age groups of 60 to 69 and 70 to 79 years. If regulators and employers persist in the use of age corrections, then current, representative, non-occupational–noise-exposed models need to be utilized. In addition, more research is needed to determine appropriate methods for distinguishing age-related hearing loss from that induced by noise, while still providing the earliest possible indication that noise is affecting a worker's thresholds.

7.3.5 Audiometric Testing Intervals and Conditions

Audiometric Tests are performed at different intervals and under different conditions over the course of employment. Audiometric testing should be provided at no cost to the employee.

- ***Baseline Test***

The baseline audiogram is the reference test, to which future comparisons are made. Most often this is the first valid test conducted in the HCP. The baseline test should be performed when the employee has had no hazardous noise exposure for at least 14 hours prior to the test, to avoid contaminating the thresholds with temporary threshold shift. If this criterion is impossible to meet, the use of hearing protection devices (HPD) may be substituted; however this practice is discouraged and only should be used as a last resort. Ideally, the baseline test is conducted at the start of employment prior to any work place noise exposure, however should be conducted within six months of enrolment in the HCP. The sooner the baseline is conducted the better for purposes of employee education and documentation of pre-existing hearing loss.

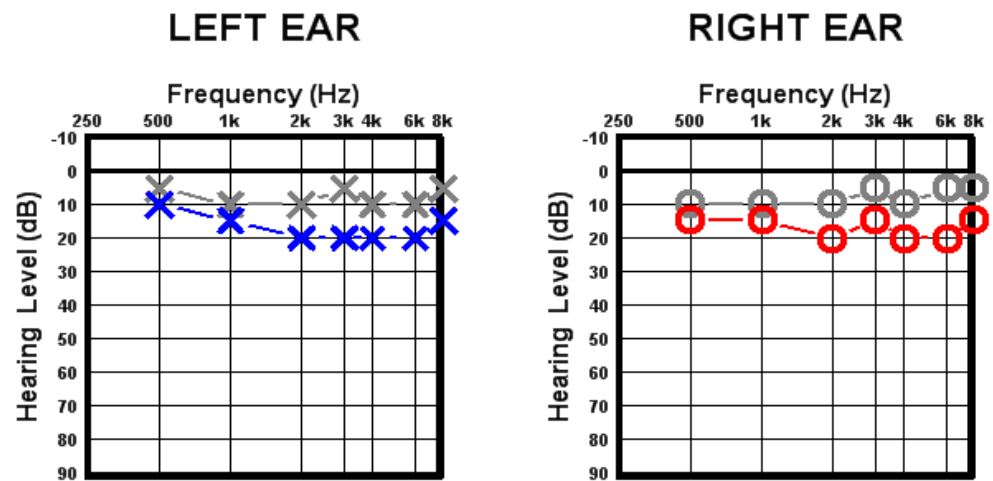
Employees with hearing loss identified on the baseline test should be notified and referred to the employee's personal physician and/or audiologist to further investigate the cause of hearing loss and possible treatment options. These cases should be reviewed

- ***Annual Test***

Annual tests should be conducted within 13 months of the baseline, or previous annual test. Results of the annual test are compared to the baseline audiogram to monitor hearing stability. Changes in hearing are called threshold shifts and a reason for and a solution to them needs to be developed.

- **Retest**

The term “retest” is used when the audiometric test is repeated in order to verify the results of an annual test. When a standard threshold shift is detected, a retest should be done within 30 days of the annual test date. (Retests may be done for purposes other than follow-up of a significant threshold shift and may have different timelines). A retest should be done with no hazardous noise exposure for at least 14 hours (sometimes referred to as a test done on “rested ears”) prior to the test. HPD use may not be substituted for this criterion.



Patient Information	Left							Right						
Frequency(Hz)	500	1k	2k	3k	4k	6k	8k	500	1k	2k	3k	4k	6k	8k
Current	10	15	20	20	20	20	15	15	15	20	15	20	20	15
Baseline	5	10	10	5	10	10	5	10	10	10	5	10	5	5
Shift			10	15	10					10	10	10		
STS			11.7							10.0				

Figure 7.11 - Example of Standard Threshold Shift (STS) calculation. The gray thresholds are the baseline test. The colored thresholds are the annual test. An STS is present when there is a 10 dB or greater difference between the averages for thresholds at 2000, 3000, and 4000 Hz between the baseline and the annual tests. In this example, both ears show STS.

- ***Transfer or Exit Test***

It is recommended that audiometric tests be conducted when an employee has a change in noise exposure permitting removal from the HCP (for example changing from production job to office job) or when terminated from the company. Transfer or exit tests are done for purposes of documenting the hearing thresholds at the cessation of noise exposure. Exit tests may be done within six months prior to the termination date.

- ***Significant Threshold Shift Intervention***

Identification of Significant Threshold Shift is an early indicator of decrease in hearing and requires intervention to;

- Prevent permanent changes in hearing
- Evaluate the need for modifications in the HCP and
- Alert employees to hearing health conditions which may require medical attention.

The time periods in the next sections are very specific to a particular jurisdiction. They can be treated as guidelines and local legislation, standards and company policy should be adopted. Age-correction is not recommended for prevention programmes (see 7.3.4.).

- ***Intervention Procedures***

- Examine the overall noise exposure of the employee to determine if elements of the noise management plan have not been implemented. As an interim measure provide HPD and education programme for the exposed employees while longer term solutions are being developed
- If employee is not using HPD that are part of the existing noise management plan, then the employee should be fitted and trained

on the use and care of HPD and required to use them. Employee should demonstrate proper HPD insertion and removal and know when HPD use is required.

- If the employee currently uses HPD, then the HPD should be refitted and the employee retrained on its use and care. The HPD should be evaluated for suitability for the noise environment and HPD with additional attenuation provided if needed.
- Retest within 30 days of the annual test under the conditions specified for retests.

- ***Workers' Compensation***

Employees who seek compensation for hearing loss may undergo a thorough work related investigation including complete diagnostic audiology and medical examination by an ear, nose, and throat physician, or other competent medical authority. The workplace may also need to be assessed to determine if it was likely to have caused the loss. Workers' Compensation varies regionally and specific regulations should be consulted. Note: calculating hearing impairment is typically done by using a specified formula intended to estimate hearing disability and may be different to the determination of the threshold shift.

8. REPORTING & RECORD KEEPING

A proper risk management strategy must be transparent documented and properly implemented. To ensure this occurs, a system of reporting and documentation needs to be implemented and maintained.

Responsibility must be assigned and documented with key performance criteria assigned to each level of management.

8.1 ORGANIZATIONAL RISK MANAGEMENT PLAN

In consultation with employees an employer should document how all occupational health and safety risks will be managed. The plan requires a clear commitment and allocation of funding should allow for a consultative structure to enable meaningful input from all employees and management. In workplaces where there is the potential for excessive noise exposure, this plan should include a component defining the noise management plan (or hearing conservation programme).

An organisational chart can be used to show the links between OH&S and finance, R&D sections production areas and senior management. The roles and responsibilities for each part need to be incorporated into performance indicators, position statements and job descriptions. In short unless a hazard management plan is seen as an essential part of the work function and culture it will not prosper.

In regard to management of noise this plan should include:

- The level at which noise exposure needs to be addressed within the organisation for both long and short term exposures.
- The relationship of the organizational level to regulatory requirements.
- The decision matrix for determining of implementation types of risk controls.

- Long and short term strategies for risk control.

The conformance to the goals set should be part of the OH&S report to management.

The accounts of the OH&S programmes should be prepared to reflect the cost benefit of implementation strategies where possible. Performance to budget is important and future planning of improvements needs to be incorporated into the ongoing funding estimates.

8.2 HAZARD IDENTIFICATION ASSESSMENTS

All areas of employment need to be risk assessed for their likelihood of excessive noise exposure (*see Section 3.6.2*). The reports need to state how and when the assessment was made and clearly identify hazardous and non-hazardous areas. A plan of the facility can be used to record those areas which have been assessed as non-hazardous. While it is not essential to use a sound level meter at this stage it is important that this assessment is undertaken with the full support of the OH&S committee.

The report on this first stage of noise hazard assessment needs to be agreed to and signed off by the OH&S committee and retained in the OH&S risk assessment file.

8.3 HAZARD CONTROL ASSESSMENTS

Assessments to establish quantitatively the extent of the noise hazards and to develop noise control procedures (*see Section 3.6*) are more detailed and may include engineering, procedural and administrative recommendations. The basis for the recommendations, including the measurement and assessment procedures need to be clearly stated in the report both for future reference and for the purpose of initiation the necessary actions. The recommendations must be discussed and acted upon by the OH&S committee in accordance with the "Organizational Risk Management Plan".

The assessments need to be retained by the OH&S committee and a report on compliance submitted to management.

8.4 HEARING PROTECTOR PROGRAMMES

The basis of all hearing protector programmes is to make it likely that they will be worn at all times when there is a significant risk of excessive noise exposure (*see Section 5*). The Hearing Protector requirement report must state clearly the areas where HP is required. These areas need to be properly identified with obvious signage so that all personnel can recognize them and wear the appropriate HP. The location of stores of hearing protectors also needs to be clearly identified.

The assessments need to be retained by the OH&S committee and a report on compliance, methods of achieving compliance, budget for education and spare parts, and management responsibilities should be submitted to management.

8.5 AUDIOMETRIC MONITORING

An assessment of the level of hearing capabilities for all the personal potentially exposed to excessive noise should be undertaken (*see Section 7.3*).

The reports on audiometric monitoring should provide a meaningful interpretation of the data and recommendations as to the success or otherwise of the noise management programme. Audiometric data as such is historic and identification of a degradation in hearing only confirms a failure in a control system.

Audiometric data is a private medical record and must be stored as confidential material. Management reports should be of a statistical nature and individuals should not be identified without their consent. It is important that good use of this data be made to improve the workplace rather than

simply storing this data in the personal files of the employees with a view to future compensation claims for loss of hearing.

The report and recommendations should be prepared by the OH&S committee and submitted to management.

8.6 CONTINUING RISK IDENTIFICATION AND CONTROL STRATEGY ASSESSMENT

The Noise Management plan should include a component which defines the procedures for ongoing Hazard Identification Assessments. These need to determine the impact of changes in the workplace due to new equipment or processes, changes in materials or building layout and structure or changes in working patterns of noise exposed persons.

Hearing Protector Programmes need to be reassessed as to the possibilities of other control methods. Audiometric data needs to be reviewed to identify any trends that could be indicating systemic failures in the noise management programme

The report, review and recommendations should be prepared by the OH&S committee and submitted to management.

9. **GUIDELINES FOR AN EFFECTIVE HEARING CONSERVATION PROGRAMME**

These Guidelines outline a “best practice” approach for implementing and maintaining an effective HCP. They describe how to measure sound levels and employee noise exposures, use engineering noise controls, select appropriate hearing protection, educate and train management and noise exposed employees, administer an audiometric testing programme, and implement intervention steps to prevent hearing loss.

Readers should feel free to use this Guideline for upgrading their internal HCP and should amend as necessary to ensure compliance with the standards and legislation in their local area. Note: where the word “shall” appears will need to be assessed by internal company representatives to determine if they desire for these requirements to be absolute or simply recommended, which in the latter case the word “should” needs to be used in place of “shall”. Also, for purposes of this guideline, the term $L_{Aeq,8}$ is used to express the 8-hour equivalent average noise exposure.

The following are HCP minimum requirements recommended by several institutions and experts across the globe to effectively manage the risk and prevent NIHL:

1. All work areas shall be surveyed for noise, and a detailed area and equipment survey conducted in areas or for tasks identified as potentially above 80 dBA.
2. A quantitative noise exposure assessment shall be made for all workers whose duties include work in areas and tasks where ambient noise exceeds 80 dBA.
3. Employees, and their management, shall be informed of the results of their noise exposure assessment.

4. Noise surveys shall be updated as often as necessary and should be updated at least every five years. Noise surveys should also be updated after the installation of new equipment or when process or procedural changes occur that may affect noise exposures.
5. Noise control measures shall be used to reduce worker noise exposures below the equivalent of an eight-hour average of 85 dBA. To the extent feasible, engineering controls are preferred. Where feasible engineering controls are not entirely adequate, feasible procedural and administrative controls should be implemented. Where even the combination of feasible engineering controls and procedural/administrative controls is not fully effective, personal protective equipment shall be used. Hearing protection fit testing is recommended.
6. All work areas with sound levels 85 dBA and above shall be posted to require all persons entering such areas to use appropriate hearing protection devices, regardless of time spent in the designated area. Management shall enforce such use of hearing protection in the posted areas.
7. Hearing protection shall be readily available for persons entering areas posted requiring use of hearing protection.
8. Persons whose work involves exposure to sound levels of 85 dBA or more (without regard to duration) must receive initial and refresher training regarding the effects of noise and procedures for preventing NIHL.
9. Audiometric monitoring, conducted and supervised by qualified personnel, shall be conducted annually for employees whose duties involve exposure to the equivalent of an 8-hour average of 85 dBA or more (without regard for personal protective equipment), other than incidental exposures. Procedures shall include appropriate levels of

intervention where employees are found to have suffered temporary NIHL.

10. Permanent threshold shifts in hearing (as described herein) detected by audiometry shall be reported to the appropriate persons and intervention strategies implemented, unless it is determined by a qualified physician or occupational audiologist that the shift was not caused or aggravated by occupational noise exposure.
11. Periodic evaluation of the quality and effectiveness of the HCP shall be performed.
12. Recordkeeping is required in all components of the HCP. Records of area noise surveys, dosimetry, hearing protection available, and audiometric testing shall be maintained for at least 30 years beyond the last date of employment.

9.1 DETERMINING HCP EFFECTIVENESS

Implementation of a prevention programme does not automatically guarantee its success. Therefore, mechanisms for evaluating the quality and effectiveness of the HCP must be included as a critical and ongoing component of the HCP. The following are considered the minimum components of a process for evaluating HCP effectiveness:

Individual HCP Effectiveness: Measuring HCP effectiveness for an individual employee is accomplished by comparing the annual audiometric test to the baseline audiometric test.

Additional investigation is needed for each employee experiencing decrease in hearing.

Population HCP Effectiveness: Measuring effectiveness of the overall HCP programme should include:

- *HCP Compliance Audits:*
Internal HCP audits should be conducted annually to ensure compliance with company policy and with local and country specific

regulations. This audit may be conducted by business unit staff, plant management, or company peers.

- *Audiometric Database Analysis:*

The database should be regularly reviewed for trends. This should include:

- Hearing health of company personnel; that is: prevalence of hearing impairment in the workforce,
- Annual STS rate; that is: the number of newly detected STSs per 100 employees in the monitored population, and
- Other metrics as appropriate such as percentage of audiometric tests completed on time, incidence of temporary threshold shifts detected, etc.

A 2017 Cochrane systematic review of the effectiveness of interventions to prevent work-related hearing loss reported that there is very low-quality evidence that implementation of stricter legislation can reduce noise levels in workplaces. Case studies showed promising effects of engineering control on noise reduction at immediate follow-up but controlled studies and evaluation of the long-term effects are missing. It is unclear if results can be replicated in other workplaces and what the long-term effects are.

Under field conditions the average noise reduction of hearing protection devices is lower than indicated ratings provided by the manufacturers. There is moderate-quality evidence that training of proper insertion of earplugs significantly reduces noise exposure at short-term follow-up but long-term follow-up is still needed. There is very low-quality evidence that the better use of hearing protection devices as part of HCPs reduces the risk of hearing loss, whereas for other programme components of HCPs we found no effect. The absence of conclusive evidence should not be interpreted as evidence of lack of effectiveness.

Rather, it means that further research is very likely to have an important impact.

9.2 SUMMARY

A “best practice” approach for implementing and maintaining an effective HCP may be a little challenging in some workplaces but there are many options for noise control and, as a last resort, for individual hearing protectors. The proper implementation of a HCP should result in the prevention of hearing loss from occupational noise exposure for all the employees.

10. INTRODUCTION TO ENVIRONMENTAL NOISE

The primary reasons for limiting noise in the community are to reduce speech and/or sleep interference, and to limit annoyance. An effect of annoyance is stress that can affect some health conditions. People are not usually annoyed if the sound is of the level and quality they expect in their community, and does not interfere with speech or sleep.

The quality of the sound and a community's characteristics also should be considered. Much depends on the existing conditions and expectations of the community. In densely populated areas, the emphasis is on controlling the overall growth of noise. However, in quieter, less densely populated areas, a new noise that might go undetected in a noisier community can become very noticeable and cause complaints. Often, in these quieter areas, the quality of the sound is as important as the quantity. Unusual sounds such as discrete tones and impulsive sounds are more annoying. Sometimes tones are masked near a source, but clearly audible in quieter areas farther away. The frequency content of sound changes with distance. A source with an acceptable spectrum nearby can sound like a rumble at greater distances. Sounds with strong low-frequency content require special attention (Berglund and Lindvall, 1995, Berglund et al., 1996). Most criteria for environmental noise based on overall sound levels measured outdoors assume a balanced or relatively even sound spectrum. When there is strong low-frequency component the sound can more easily penetrate buildings. Thus, such sounds are often more annoying indoors than outdoors.

The first step is to check the local / national regulations for the assessment and criteria for environmental noise. Approaches to regulating environmental noise vary significantly between countries and also within a country, state, city, and/or local municipality. In fact, it is not unusual to find places where no regulation exists. When no regulations exist, it is appropriate to evaluate the acoustical impact, that is the change in sound before and after the source of interest, and strive to minimize the acoustical impact to reduce the potential for complaints. Companies that operate multiple facilities can face

significantly different environmental noise challenges depending on the location.

An occupational health or safety professional may need to evaluate environmental noise for several reasons:

1. Compliance of noise produced by facilities operating in regions with noise codes or ordinances,
2. Determination of acceptable noise levels and noise characteristics for new equipment,
3. Evaluation of site suitability for a new facility,
4. Resolution of complaints from neighbors, and
5. Social and corporate responsibilities.

Historically, research on environmental noise has concentrated on sources related to transportation (airports, trains, highway and street traffic, etc.), military (aircraft low-level flyovers, heavy vehicles maneuvering, firing ranges, etc.), and ventilation systems (outside air conditioners and blowers, noise from ventilation stacks, etc.). These sources are widespread, affect large areas, and there are readily available mechanisms to fund the research, especially in cities. This research has emphasized establishing acceptable quantities of sound for typical areas that are affected, and reducing sound accordingly. Less research is available on isolated and unique noise sources in quieter, smaller communities where the noise is unexpected. An occupational health or safety professional is most likely to be faced with noise from an industrial plant disturbing a few local neighbors.

One of the most common environmental noise measures is the equivalent continuous sound level ($L_{Aeq,T}$) (now called time-average sound level in many standards). Some countries use the statistical based units for assessing time varying noise. The most commonly used are statistical based metrics, such as the level exceeded for 10% of the time, L_{A10} , to represent the noise from transient sources and the level exceeded for 90% of the time, L_{A90} , to

represent the noise from continuous sources and background noise when the source is not operating. Another metric is the *sound exposure level* (SEL), symbolized as L_{AE} . The SEL is used to quantify accumulated exposure to noise from a single event by normalizing all data to a one-second average. The SEL is useful for comparing the total noise per event, such as aircraft flyovers, trains passing, highway noise, etc., which allows for rank ordering each event.

Typically, measurements for environmental noise are A-weighted. The C-weighted sound level may be used in special circumstances related to impulsive noise and when low frequency noise is under investigation. A 3-dB (equal-energy) exchange rate is always used for time-average sound levels. Octave-band or 1/3 octave-band levels are sometimes used to evaluate sound quality.

A long-term average sound level over a 24-hour period is often used to describe the acoustical climate of a community. The *day-night average sound level* (DNL), symbolized as L_{dn} , has a 10-dBA night-time penalty added to all sound between 10:00 p.m. and 7:00 a.m. before the average is calculated, which is used predominantly in the U.S.A. A variation of this is the *day-evening-night sound level* that adds an evening penalty of 5 dBA from 7:00 p.m. until 11:00 p.m., and a 10-dBA penalty from 11:00 p.m. to 7:00 a.m. This variation is used throughout much of Europe.

Note that different countries may use different time periods for the day, evening and night hours to reflect the social traditions of the region.

10.1 **COMMUNITY NOISE REGULATIONS**

[This section should be used to describe the community noise regulations applicable to the locale of the course. Examples that may be covered are presented below. However, the instructor and students are encouraged to take time to focus on the applicable noise regulations in their region.]

10.1.1 **European Union Environmental Noise Directive**

In 1996 the European Union (EU) adopted and published The Green Paper on Future Noise Policy (EC, 1996). Noise was recognized as one of the primary environmental problems in Europe, adversely affecting more than 170 million EU citizens. Based on the foundation laid down in The Green Paper, in May 2002 the EU formally approved the Environmental Noise Directive 2002/49/EC (EU, 2002).

The Environmental Noise Directive focuses on three action areas:

- determining the exposure to environmental noise
- ensuring that information on environmental noise and its effects is made available to the public
- preventing and reducing environmental noise where necessary while preserving environmental noise quality where it is good

This Directive aims at providing a basis for developing community measures to reduce noise emitted by the major sources, in particular road and rail vehicles and infrastructure, aircraft, outdoor and industrial equipment and mobile machinery.

At this point, no noise limits or measurement methods are set under the directive; however, Member States are requested to rely upon their own legislation until common measurement procedures and noise limits become mandatory. For those States without computational methods, Annex II of the directive recommends following ISO 9613-2: *Acoustics – Attenuation of Sound during Propagation Outdoors – Part 2: General Method of Calculation* (ISO 1996).

10.1.2 **United States Federal Government Guidelines and Regulations**

Most U.S. federal guidelines for community noise are based on the day-night level, DNL (EPA, 1974), , outlined under (the Environmental Protection Act (EPA), 1974). The EPA recommended that DNL should be kept below 55 dBA in residential areas "to protect public health and welfare with an

adequate margin of safety" (EPA, 1974). This level corresponds to that normally present in a typical suburban community of approximately 770 people per square kilometer. This goal did not consider economic or technological feasibility and was not intended as a regulation.

The study recognised that many people lived in both quieter and noisier areas, including densely populated urban areas. This study provided methods to evaluate problems and potential for noise complaints based on DNL. These involved adjusting or normalizing the DNL for specific circumstances before comparing the DNL to criteria based primarily on expectations in densely populated urban areas.

DNL works best for characterizing the long-term acoustical character of a community as influenced by noise sources that are continually present as steady state sounds or frequently occurring events over most of the day every day. DNL does not work well for infrequently occurring loud sounds that may be disturbing to a community without strongly affecting the long-term average sound level. DNL also is not a practical measure for enforcement use by communities because of the long-term evaluations needed to establish it.

Consider the following example:

Example Calculation -

A 24-hour measurement is conducted at the property line of a chemical plant, and the hourly L_{eq} values are shown in the spreadsheet (entered in Column E, shaded in yellow):

DAY-NIGHT AVERAGE SOUND LEVEL

This spreadsheet calculates the L_{dn}

Input Data Required:
Enter the hourly L_{eq} under column E

Hr Start	Hr End	Hourly L_{eq}
07:00 AM	08:00 AM	59.0
08:00 AM	09:00 AM	59.5
09:00 AM	10:00 AM	58.7
10:00 AM	11:00 AM	57.5
11:00 AM	12:00 PM	57.0
12:00 PM	01:00 PM	57.8
01:00 PM	02:00 PM	56.6
02:00 PM	03:00 PM	55.0
03:00 PM	04:00 PM	55.5
04:00 PM	05:00 PM	56.8
05:00 PM	06:00 PM	57.8
06:00 PM	07:00 PM	59.0
07:00 PM	08:00 PM	58.4
08:00 PM	09:00 PM	56.5
09:00 PM	10:00 PM	56.0
10:00 PM	11:00 PM	56.3
11:00 PM	12:00 AM	55.5
12:00 AM	01:00 AM	52.0
01:00 AM	02:00 AM	51.1
02:00 AM	03:00 AM	48.5
03:00 AM	04:00 AM	48.0
04:00 AM	05:00 AM	50.2
05:00 AM	06:00 AM	55.0
06:00 AM	07:00 AM	57.8

The Daytime Average is:
 $L_d = 57.6$

The Nighttime Average is:
 $L_n = 53.9$

$L_{dn} = 61.1 \text{ dBA}$

As shown in the spreadsheet, L_d and L_n are 57.6 dBA and 53.9 dBA, respectively. Next, these results are entered into the DNL formula

$$L_{dn} = 10 \log \frac{1}{24} \left[(15)(10^{L_d/10}) + (9)(10^{(L_n + 10)/10}) \right] \text{ dBA}$$

$$L_{dn} = 10 \log \frac{1}{24} \left[(15)(10^{57.6/10}) + (9)(10^{(53.9 + 10)/10}) \right] \text{ dBA}$$

$$L_{dn} = 61.1 \text{ dBA}$$

It is important to note that despite the fact no hourly average levels are over 60 dBA, we still calculate an L_{dn} of 61.1 dBA, which is due to the 10-dBA penalty applied to the average night time level. Based on an L_{dn} of 61.1 dBA and the EPA criteria, this DNL would be unacceptable for a residential development just beyond the chemical plant's property line.

10.1.3 Other approaches to environmental criteria

To overcome the limitations of using a time averaged level like L_{dn} , many jurisdictions have developed legislation that specifies maximum noise limits for various times during the day and night. Some jurisdictions have adopted legislation that limits the allowable increase to background sound levels. Examples of typical background sound levels for various areas are provided in Table 10.1. An increase of 5 dB may be acceptable but any greater increase may require action to reduce the overall noise impact. Code limits are typically more stringent, especially at residential receptors, during the night time hours when noise-sensitivity is highest. Code limits may be permissive or non-existent for non-sensitive industrial or commercial receptors.

Table 10.1 – Example of Typical Background Sound Levels

Type of Area	Guidance for Average Background Noise Levels, $L_{A90,T}$		
	Time of Day [†]		
	Day (0700-1800)	Evening (1800-2200)	Night (2200-0700)
Rural i.e. negligible transportation	40	35	30
Semi-rural and low density transportation	45	40	35
Near some commerce or industry	50	45	40
Near dense transportation	55	50	45
Borders of industrial areas	60	55	50
Within industrial areas	65	60	55

[†] For Sundays and Public holidays the 'night' may extend for another hour or so to 0800 or 0900 hr.

10.2 FACTORS OTHER THAN ABSOLUTE SOUND LEVEL INFLUENCING COMMUNITY REACTION TO NOISE

Most noise regulations are based on sound level, possibly with lower limits at night or penalties for sounds with tonal or impulsive characteristics.

However, research indicates many important factors influence community reaction and annoyance produced by noise. Those identified by the US EPA (1974) were:

- Frequency content of the noise,
- Duration of the noise,
- Time of day noise occurs,
- Time of year the noise occurs,
- History of prior exposure to the noise source,
- Perceived attitude of the noise source owner,
- Special characteristics of the noise that make it especially irritating,
- Ratio of intruding noise level to normal background noise level.

Other studies have identified additional factors that are very much related to community reaction and annoyance. These include whether the complainant believes s/he is being ignored or treated unfairly, or perceives the noise as:

- Unnecessary, or unnecessarily loud,
- A threat to personal health or safety,
- A threat to economic investment (property value),
- Beyond his or her control.

A most important factor is the difference in sound level between a new noise and other expected and existing noise in the neighborhood. The most significant finding of the EPA community reaction studies (EPA, 1974) was that widespread complaints and legal actions are likely when the average level of non-distinctive noise from a single source is regularly more than 5 dB above the average level of other existing sounds in the community. Vigorous community action results for differences of 20 dB. Some noises such as discrete tones are more irritating or difficult to ignore because of the way they

sound. People expect not only quiet, but a pleasant sound quality if sound is audible. These unpleasant and distinctive sounds often cause complaints if they are detectable at any level.

The acoustical designers of vehicles, appliances, and other products today spend much of their effort on "sound quality." Some common industrial sources such as high-pressure or material-handling fans or positive-displacement blowers produce strong discrete tones. Power presses can produce repetitive impulsive sounds. Speech and music have information content that makes them difficult to ignore. These factors affect the quality of the sound in the community even at otherwise acceptable levels.

10.3 SOUND PROPAGATION OUTDOORS

Often a primary question one needs to answer is what will be the effect on environmental noise when an industrial plant is built, expands, or adds new equipment outside the building, or a residential subdivision encroaches upon the facility's property line? To answer this question it is important to know what factors affect outdoor sound propagation, and how to estimate attenuation to select locations. Both ISO 9613-2 and ANSI S12.18, *American National Standard for Outdoor Measurement of Sound Pressure Level* describe similar procedures for outdoor sound measurement, including a discussion of the attenuation effects due to the various elements mentioned above (ISO, 1996; and ANSI, 2004). These standards are useful, not only for measurement procedures, but also for estimating sound pressure levels (SPLs) at different locations from the source. Referring to ANSI S12.18, for sound radiating from a point source in a free field, the SPL per octave band at a given distance may be calculated from:

$$L_p = L_w - A_{\text{total}} - 10.9 \quad \text{dB}$$

where,

L_p = the octave-band sound pressure level (SPL), in dB, at the location of interest,

L_w = the octave-band sound power level (PWL) of the source, in dB,
and

A_{total} = the total attenuation at each octave band, in dB

The total attenuation (A_{total}) for each octave band is calculated by:

$$A_{\text{total}} = A_{\text{div}} + A_{\text{air}} + A_{\text{env}} + A_{\text{misc}} \quad \text{dB}$$

where,

A_{div} is the attenuation due to geometrical divergence,

A_{air} is the attenuation due to air absorption,

A_{env} is the attenuation effects of the environment, and

A_{misc} is the attenuation resulting from all other factors, such as foliage, barriers, etc.

Because high-frequency sounds have relatively short wavelengths their sound energy will decrease rapidly with increasing distance due to atmospheric absorption. Conversely, low-frequency sounds with much longer wavelengths will often carry several kilometres from the source and are often the cause of complaints from citizens. This variation by frequency should be accounted for when calculating the total attenuation. Once the individual attenuation values are known for each octave band, they can be logarithmically added together, and the resultant value may be used along with the known PWL to estimate the SPL.

10.3.1 Geometrical Divergence (A_{div})

As sound propagates outdoors it generally decreases in magnitude with increasing distance from the source. These spreading losses are due to *geometrical divergence*, which occurs as sound waves propagate and expand from a source, and in turn become less intense as they dissipate over larger spherical areas. The divergence is not a function of frequency, and attenuation is estimated by:

$$A_{\text{div}} = 20 \log r/r_0 \text{ dB}$$

where,

r = distance from the point source in metres (m), and

r_0 = reference distance of 1 m.

For distances far from the source, the geometrical divergence results in a 6-dB decrease per doubling of distance from a point source. For a line source,

such as a busy highway or long runs of noisy pipelines stretching perpendicular to the measurement location (i.e., a petrochemical plant), the geometrical divergence will be a 3-dB decrease per doubling of distance.

10.3.2 Air Absorption (A_{air})

Sound energy decreases in a quiet calm atmosphere by two mechanisms: (1) heat conduction and viscosity in the air, and (2) relaxation of air molecules as they vibrate (Kurze and Beranek, 1988). The atmospheric absorption losses depend on frequency, temperature and relative humidity. Of these three factors, relative humidity is the dominant variable, followed by the frequency and then the temperature.

10.3.3 Environmental Effects (A_{env})

Sound propagating from a source is also attenuated by the environment, such as the ground, wind and temperature gradients. For distances less than 30 metres, the attenuation is essentially independent of meteorological conditions, and A_{env} is then comprised of ground effect alone.

The magnitude of the reflected sound will depend upon the type of ground surface, the angle of incidence (Ψ), and frequency (Piercy and Daigle, 1991). ISO 9613-2 and ANSI S12.18 classify ground surfaces for grazing angles less than 20° as follows (ISO, 1996; and ANSI, 2004):

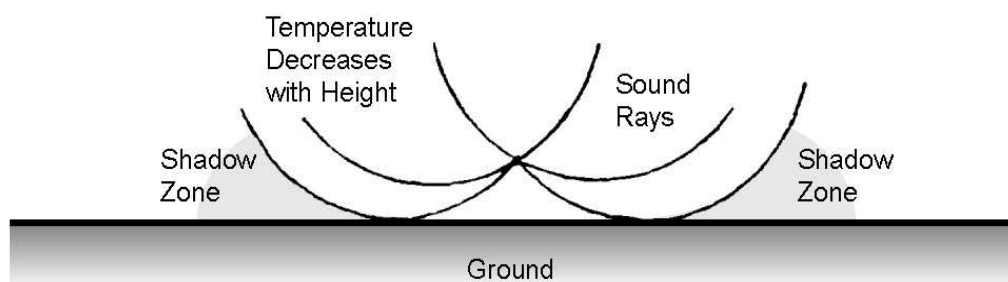
- *Hard Ground* - Open water, asphalt or concrete pavement, and other ground surfaces having very low porosity tend to be highly reflective, absorbing very little acoustic energy upon reflection. Tamped ground, for example, as often occurs around industrial sites, can be considered as hard ground.
- *Soft Ground* - Ground covered by grass, shrubs, or other vegetation, and all other porous grounds suitable for the growth of vegetation such as farming land.
- *Very Soft Ground* - New-fallen snow is even more absorptive at low frequencies than grass-covered ground, as is ground covered in pine needles or similarly loose material. It is recommended by ANSI that

measurements above snow-covered ground be avoided unless operation of the sound source is intimately tied with the ground condition.

- *Mixed Ground* - A ground surface which includes both hard and soft areas.
- Note that at *angles off the ground greater than 20°*, which can commonly occur at short ranges or in the case of elevated sources, soft ground becomes a good reflector of sound and can be considered hard ground.

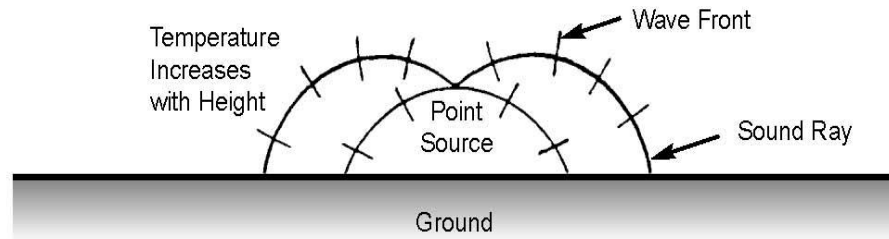
In addition to ground effects, as temperature changes, there is a corresponding change in the speed of sound, which effects propagation.

It is a natural phenomenon that temperature usually decreases with increasing elevation during daytime hours, and increases with elevation at night. Under normal daytime conditions, the velocity of sound is greatest at lower elevations, and sound waves bend or refract upward as depicted in Figure 10.1. This often results in a shadow zone near the ground, and the attenuation significantly increases with distance. This additional sound reduction may typically be 10-20 dB or more above the expected attenuation due to ground effects.



(Source: The Noise Manual, 5th Edition – Courtesy AIHA Press)

Figure 10.1 - Wave Propagation During Daytime

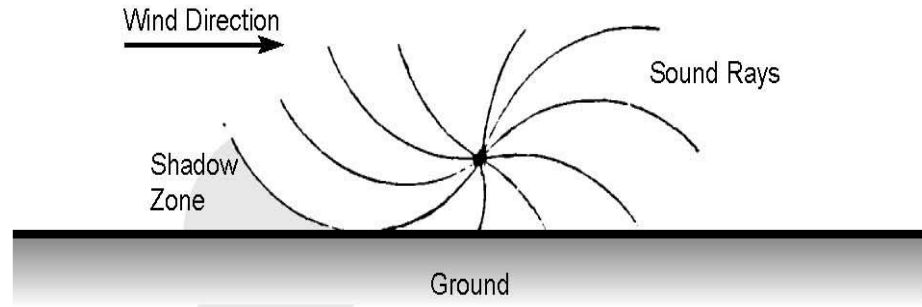


(Source: The Noise Manual, 5th Edition – Courtesy AIHA Press)

Figure 10.2 - Wave Propagation During Nighttime

Figure 10.2 exhibits the sound spreading pattern that occurs during temperature inversions when the temperature increases with elevation. This condition is more common at night due to radiation cooling of the ground, and during sunrise and sunset. Since the speed of sound is faster in warmer upper layers of air, sound waves will actually bend downward as they propagate from the source. This condition results in little to no attenuation due to the environment for several hundred metres, and produces a favourable condition for sound propagation.

Sound wave propagation follows a predictable model in a still environment. However, sound will not conform to any predictable pattern in windy conditions. Figure 10.3 illustrates how sound wave propagation behaves with wind gradients. As sound extends upwind, the spreading waves refract upward and create a shadow zone with excess attenuation near the ground. Because of this condition, it is not recommended that sound level measurements be conducted upwind of the source. On the other hand, as sound radiates downwind, the waves bend downward resulting in a condition advantageous to propagation. This explains why sound levels downwind of a noise source are more easily detected or heard as compared to the listening conditions upwind. Consequently, it is recommended that measurements be conducted downwind of the source.



(Source: The Noise Manual, 5th Edition – Courtesy AIHA Press)

Figure 10.3 - Wave Propagation with Wind

One other phenomenon that often occurs is sound traversing large distances. Since spreading patterns for sound will vary or fluctuate with increased elevation, wind and temperature, it is common to hear or detect sound as a warble or intermittent event several kilometres away. This is especially true for low-frequency sounds, such as a locomotive horn, or an outside warning alarm at an industrial facility.

10.3.4 Miscellaneous Attenuation Effects (A_{misc})

Attenuation of sound resulting from rain, dense fog, and falling snow is practically zero. Therefore, these conditions may be ignored, with the possible exception of snow-covered ground that may change the classification of the ground-surface rating as described previously. For the most part, these conditions affect other environmental factors such as altering the wind and temperature gradients, which are accounted for when calculating the air and environmental attenuation values.

Table 10.2

The attenuation due to propagation through foliage, such as trees and bushes.

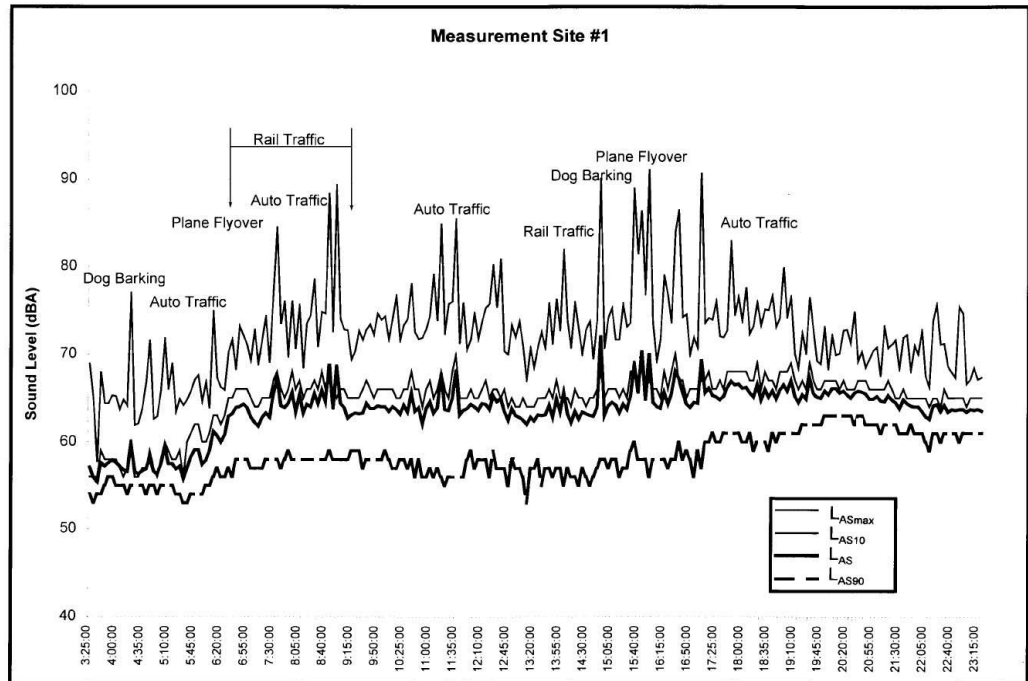
	Octave-Band Center Frequency (Hz)							
	31.5	63	125	500	1000	2000	4000	8000
A_{misc} (dB/m)	0.02	0.02	0.03	0.04	0.05	0.06	0.08	0.12

(Source: From Piercy and Daigle (1991) – Used with permission)

A common misconception is that a few rows of trees can be planted along the property line to help reduce environmental noise. While it is true that trees often block the visual line of sight to the source, and as a result provide a psychological noise-reduction benefit, in reality a series of trees a few metres deep is acoustically transparent and provides no measurable attenuation. Table 10.2 presents the attenuation due to sound propagation through foliage, such as trees and bushes. The type of tree, density of planting, and noise source characteristics are the controlling factors toward their acoustical benefit. A good rule of thumb is that for the first 100 m of dense forest, the average attenuation will be approximately 4-8 dBA provided both the source and receiver are within, or relatively close to, the trees. For distances greater than 100 m, no rule of thumb applies, however, a more detailed discussion of this issue may be found in Piercy and Daigle (1991).

10.4 MEASURING ENVIRONMENTAL NOISE

A person measuring environmental noise must often comply with the requirements of appropriate ordinances and standards. The referenced standards provide technical guidelines, some of which are discussed briefly in this section. The measurement guidelines should match the goal of the sound survey. Some standards require that measurements be conducted under the most favourable weather and physical conditions for sound propagation. This requirement ensures that data are collected during sound propagation conditions that typically correspond to a majority of complaints from neighbours. However, the goal of many environmental noise measurements is to document noise in the community for various propagation conditions. Automatic noise loggers that can be left in location for extended periods of time are of great assistance when assessing environmental noise. It must however be remembered that such automatic loggers will note the level from all the sound in the area and some of this sound may not originate from the source under investigation. Attended noise measurements may be required to supplement the automatic logger data to confirm the noise levels from those sources.



(Source: The Noise Manual, 5th Edition AIHA – Used with permission)

Figure 10.4 – Example Time-History Log

10.5 SUMMARY

Many industrial companies will face the potential of a community noise problem. Each surrounding community is different and will tolerate varying levels of noise. Factors influencing community tolerance include:

- Visibility of noise source. Some members of the community may be more concerned with “visual” noise sources (e.g. stacks, vents, etc.).
- Noise sources that cannot be associated with the operation of the facility or seem foreign to the community. Some members of the community may interpret these sources as potentially dangerous.
- Noise centred within a narrow frequency band (pure tones).
- Noises that can startle the community (impulsive noise).
- Noise that is random in occurrence and duration (may be related to lack of control).
- Low-frequency noise that may cause vibrations and/or resonances within residential structures.

- A very low pre-existing background noise level.

If a community noise problem is suspected, the following information should be considered:

- Review current local noise control ordinance. If there is none, refer to any state guidelines for information on what is expected for monitoring and compliance.
- Conduct perimeter (property line) sound level measurements. Compare to limits specified in the local ordinance. Check for pure tones. Many ordinances have definitions and special restrictions for tone generation.
- Be aware of the time of the noise complaint. Certain sounds may be noticed at greater distances in the evening or early morning due to meteorological effects, as well as lower background noise, and may not be discernible during the day.

Additional follow-up steps may include the following:

- Meet with the community/complainant. This shows that the company is concerned about being a good neighbor. Sometimes the noise complaint is related to another issue and noise is being used to get attention and response.
- Open Communications. Consider creating a "noise hot-line" that the community can call 24 hours a day. Avoidance or quick resolution of a noise issue is always in the plant's best interest. In addition, a well-documented list of complaint calls can be cross-referenced with plant operating conditions to track down possible problems.
- Inform the community of any unusual noise emissions prior to noise generation. Typically, complaints will come when a "normal" noise environment changes. In addition, a noise generated between 7 p.m. and 7 a.m. is generally more likely to cause complaints than an identical noise occurring during daytime hours.
- Elimination of noise sources may also cause complaints - if the old noise source masked a dominant tone or other "offensive" noise.

11. REFERENCES

ANSI (1992). "Guidelines for the Specification of Noise of New Machinery," American National Standards Institute, S12.16-1992, New York, NY.

ANSI (1994). "Acoustical Terminology," S1.1-1994 (R2004), Acoustical Society of America, New York, NY.

ANSI (1996). "Determination of Occupational Noise Exposure and Estimation, American National Standards Institute, S3.44, 1996.

ANSI (1997). "Methods for Measuring the Real-Ear Attenuation of Hearing Protectors," S12.6-1997, Acoustical Society of America, New York, NY.

ANSI (2004). Specification for Audiometers, American national Standards Institute, S3.6, 2004.

ANSI (2004). Methods for Manual Pure-Tone Threshold Audiometry, American national Standards Institute, S3.21, 2004.

ANSI (2004). "Outdoor Measurement of Sound Pressure Level," American National Standard S12.18-1994 (R2004), Acoustical Society of America, New York, NY.

ANSI (2007). "Methods of Estimating Effective A-weighted Sound Pressure Levels When Hearing Protectors are Worn," S12.68-2007. Acoustical Society of America, New York, NY.

AS/NZS 1269.0:2005 Occupational noise management - Overview and general requirements.

AS/NZS 1269.1:2005 Occupational noise management - Measurement and assessment of noise emission and exposure.

AS/NZS 1269.2:2005 Occupational noise management - Noise control management.

AS/NZS 1269.3:2005 Occupational noise management - Hearing protector program.

AS/NZS 1269.4:2005 Occupational noise management - Auditory assessment.

ASTM (1990). ASTM E90-02, *Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions*, West Conshohocken, PA.

Babik KR, Shockey TM, Moore LL, Wurzelbacher SJ. Standardizing industrial hygiene data collection forms used by workers' compensation insurers. *J Occup Environ Hyg.* 2018 Sep; 15(9):676-685. <https://doi.org/10.1080/15459624.2018.1490022> .

Berger, E.H. (1988). "EARLOG₁₉ - Tips for Fitting Hearing Protectors," E-A-R/Aearo Technologies, Indianapolis, IN.

Berger, E. H. and Royster, L. H. (1996). "In Search of Meaningful Measures of Hearing Protector Effectiveness," *Spectrum Suppl.* 1, 13, p. 29.

Berger, E.H. (1996). "EARLog#13 – Attenuation of Earplugs Worn in Combination with Earmuffs," E-A-R/Hearing Protection Products, Indianapolis, IN.

Berger, E.H. (2000). "Hearing Protection Devices," Chapter 10, p. 428 in *The Noise Manual, Fifth Edition*, Edited by Berger, E.H., Royster, L.H., Royster, J.D., Driscoll, D.P., and Layne, M.; published by American Industrial Hygiene Association Press, Fairfax, Virginia.

Berger, E.H., Royster, L.H., Royster, J.D., Driscoll, D.P., and Layne, M. (2000). *The Noise Manual, Fifth Edition*, Am. Ind. Hyg. Assoc. Press, Fairfax, VA.

Berglund, B, Hassmen, P., and Job, R. F. S. (1996). "Sources and Effects of Low-frequency Noise," *J Acoust Soc Am* 99, 2985-3002. <https://doi.org/10.1121/1.414863>

Berglund, B. and Lindvall, T. (eds.). (1995). *Community Noise* [Archives of the Center for Sensory Research Vol. 2(1)], Stockholm Univ. and Karolinska Inst., Stockholm, Sweden.

<http://www.nonoise.org/library/whonoise/whonoise.htm>

Celestina, M., Hrovat, J., & Kardous, C. A. (2018). Smartphone-based sound level measurement apps: Evaluation of compliance with international sound level meter standards. *App Acoust*, 139, 119-128.

<https://doi.org/10.1016/j.apacoust.2018.04.011>

Commonwealth of Australia "Occupational Health and Safety Code of Practice 2008;

[http://www.comlaw.gov.au/ComLaw/legislation/legislativeinstrument1.nsf/0/1A0C4BAEC8DF6965CA257460001C2B4A/\\$file/OHS+code+of+Practice+2008.doc](http://www.comlaw.gov.au/ComLaw/legislation/legislativeinstrument1.nsf/0/1A0C4BAEC8DF6965CA257460001C2B4A/$file/OHS+code+of+Practice+2008.doc)

Earshen, J.J. (2000). "Sound Measurement: Instrumentation and Noise Descriptors," Chapter 3, *The Noise Manual*, 5th Edition, Edited by Berger, E.H., Royster, L.H., Royster, J.D., Driscoll, D.P., and Layne, M.; published by American Industrial Hygiene Association Press, Fairfax, Virginia, 2000.

EEC (2002) Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002. (2002). Relating to the Assessment and Management of Environmental Noise, Brussels, Belgium.

<https://publications.europa.eu/en/publication-detail/-/publication/27d1a64e-08f0-4665-a258-96f16c7af072>

EEC (2003). Council Directive 2003/10/EC of 6 February 2003 on the Minimum Health & Safety Requirements Regarding the Exposure of Workers to the Risks Arising From Physical Agents (Noise), OJ No.L42/38, 15.2.2003.

EC (2006). Council Directive 2006/42/EC of 17 May 2006 on Machinery, OJ L157, 9.6.2006. <https://osha.europa.eu/en/legislation/directives/directive-2006-42-ec-of-the-european-parliament-and-of-the-council>

EEC (1989a). Council Directive 89/392/EEC of 14 June 1989 on the approximation of the laws of the Member States relating to machinery, OJ No L 183, 29.6.1989, p.9. <https://publications.europa.eu/en/publication-detail/-/publication/1732310d-dac3-4a59-924c-ae07829f1f9/language-en>

EEC (1989b). Council Directive 89/106/EEC of 21 December 1989 on the approximation of laws, regulations and administrative provisions of the Member States relating to construction products, OJ No L 40, 11.2.89, p. 12.

<https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A31989L0106>

EEC (1989c). Council Directive 89/686/EEC of 21 December 1989 on the approximation of laws of Member States relating to personal protective equipment, OJ No L 399, 30.12.89, p. 18. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A31989L0686>

EEC (1991). Council Directive 91/368/EEC of 20 June 1991 amending Directive 89/392/EEC on approximation of the laws of Member States relating to machinery, OJ No L 198, 22.7.1991, p. 16. <https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:31991L0368>

EEC (1993a). Council Directive 93/44/EEC of 14 June 1993 amending Directive 89/392/EEC on approximation of the laws of Member States relating to machinery, OJ No L 175, 19.7.93, p. 12. <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1993L0042:20071011:en:PDF>

EEC (1993b). Council Directive 93/95/EEC of 20 October 1993 amending Directive 89/686/EEC on the approximation of laws of Member States relating to personal protective equipment, OJ No L 276, 9.11.93, p. 11. <https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A31993L0095>

EPA (1974). Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety, U. S. Environmental Protection Agency, Report #550/9-74-004, Washington, DC.

EPA (1979). "Noise Labelling Requirements for Hearing Protectors," Environmental Protection Agency, Fed. Regist. 44(190), 40CFR Part 211, 56130-56147.

Gauger D, Berger EH., (2004). "A New Hearing Protector Rating: The Noise Reduction Statistic for Use with A Weighting (NRSA)." In: Report prepared at the request of the U.S. Environmental Protection Agency. Version 2.5; April 29, 2004.

Hoffman HJ1, Dobie RA2, Losonczy KG1, Themann CL3, Flamme GA4. Declining Prevalence of Hearing Loss in US Adults Aged 20 to 69 Years. *AMA Otolaryngol Head Neck Surg.* 2017 Mar 1;143(3):274-285. <https://doi.org/10.1001/jamaoto.2016.3527>

Hoffman HJ, Dobie RA, Ko C-W, Themann CL, Murphy WJ (2010) Americans hear as well or better today compared to 40 years ago: hearing threshold levels in the unscreened adult population of the United States, 1959-62 and 1999-2004. *Ear Hear* 31(1):151-154.

ISO (1990). ISO 1999 second edition, "*Acoustics - determination of noise exposure and estimation of noise-induced hearing impairment,*" ISO 1999:1990, Geneva, Switzerland.

ISO (1995). "*Acoustics – Hearing Protectors – Part 2: Estimation of Effective A-weighted SPLs When Hearing Protectors are Worn,*" ISO 4869-2:1995, Geneva, Switzerland.

ISO (1996). "*Acoustics – Attenuation of Sound During propagation Outdoors – Part 2 General Method of Calculation*" ISO 9613-2:1996 Geneva, Switzerland.

ISO (1996). "*Acoustics -- Rating of sound insulation in buildings and of building elements -- Part 1: Airborne sound insulation,*" ISO 717-1:1996, Geneva, Switzerland.

Kardous, C.A. and Shaw, P.B. (2014). "Evaluation of Smartphone Sound Measurement Applications." *J Acoust Soc Am*, 135, EL186-192, <https://doi.org/10.1121/1.4865269> .

Kardous, C.A., and Shaw, P.B. (2016). "Evaluation of Smartphone Sound Measurement Applications (Apps) Using External Microphones—A Follow-Up Study," *J Acoust Soc Am* 140, EL327–333, <https://doi.org/10.1121/1.4964639>.

Kardous, C. A., & Willson, R. D. (2004). Limitations of using dosimeters in impulse noise environments. *J Occup Environ Hygiene*, 1(7), 456-462. <https://doi.org/10.1080/15459620490465839>

Kurze, U. and L. L. Beranek (1988). "Sound Propagation Outdoors," in *Noise and Vibration Control*, edited by L. L. Beranek, Institute of Noise Control Engineering of the USA, Inc., Poughkeepsie, NY, 1988, 164-193.

Leidel, N.A., Busch, K.A., and Lynch, J.R. (1977). "Occupational Exposure Sampling Strategy Manual," NIOSH Publication No. 77-173, U.S. Department of Health, Education, and Welfare, Cincinnati, OH.

Lord, H. W., Gately, W. S., and Eversen, H. A., (1980). *Noise Control for Engineers*, McGraw-Hill Book Co., New York, NY.

Meinke DK, Norris JA, Flynn BP, Clavier OH. Going wireless and booth-less for hearing testing in industry, *Int J Audiol*, 2017 Jan; 56:sup1, 41-51.

<https://doi.org/10.1080/14992027.2016.1261189>.

Murphy, W.J., Berger, E.H., Gauger, D., Witt, B., McKinley, R., Gerges, S., and Ahroon, W. (2006). "Results from the National Institute for Occupational Safety and Health/Environmental Protection Agency NIOSH/EPA Interlaboratory comparison of American National Standards Institute ANSI S12.6-1997 Methods A and B," *J. Acoust. Soc. Am.* 120(5, Pt. 2), p. 3160.

<https://doi.org/10.1121/1.3095803>

Nast, D.R., Speer, W.S. and Le Prell, C.G. (2014). "Sound Level Measurements Using Smartphone 'Apps': Useful or Inaccurate?" *Noise Health*. 16, 251–256.

<http://www.noiseandhealth.org/text.asp?2014/16/72/251/140495>

NIOSH (1998). “*Criteria for a Recommended Standard,*” Occupational Noise Exposure, Revised Criteria,” DHHS (NIOSH) Pub. No. 98-126, Cincinnati, OH. <https://www.cdc.gov/niosh/docs/98-126/>

NOHSC:1007(2000) “National Standard” Commonwealth of Australia; <http://www.ascc.gov.au/NR/rdonlyres/38A158B3-0F37-4ADC-B050-7758F5529033/0/noisestandard.pdf>

NOHSC:2009(2004) “National Code of Practice” Commonwealth of Australia; http://www.ascc.gov.au/NR/rdonlyres/6EE85D16-7D1C-4FFC-99E7-E611B7290E18/0/Noise_COP.pdf

OSHA (1983). “Occupational Noise Exposure; Hearing Conservation Amendment; Final Rule,” Occ. Safety and Health Admin., 29CFR1910.95, Fed. Register 48(46), 9738-9785. <https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.95>

Pearson JD, Morrell CH, Gordon-Salant S, Brant E, Metter J, Klein LL, Fozard JL [1995]. Gender differences in a longitudinal study of age-associated hearing loss. *J Acoust Soc Am* 97(2):1196–1205. doi: [10.1007/s12070-013-0630-1](https://doi.org/10.1007/s12070-013-0630-1)

Piercy, L. E. and Daigle, G. A. (1991). “Sound Propagation in the Open Air,” in Handbook of Acoustical Measurements and Noise Control, Third Edition, edited by C.M. Harris, McGraw-Hill, Inc., New York, NY, 1991, reprinted by Acoustical Society of America, 1998, p.3.1-3.26.

Rabinowitz PM, Galusha D, Dixon-Ernst C, Slade MD [2007]. Audiometric “early flags” for occupational hearing loss. *J Occup Environ Med* 49(12):1310–1316. <https://doi.org/10.1097/JOM.0b013e31815d1076>.

Roberts, B., Kardous, C., & Neitzel, R. (2016). Improving the accuracy of smart devices to measure noise exposure. *J Occup Environ Hyg*, 13(11), 840-846. <http://dx.doi.org/10.1080/15459624.2016.1183014>

Royster, L.H. (1997). “The Frequency of Abnormal Sound Levels When Using Noise Dosimeters to Establish the Employee’s Daily TWA and the Resulting

Effects on the Measured Noise,” AIHA Conference and Exposition, 1997, Dallas, TX.

Schaffer, M.E. (1991). A Practical Guide to Noise and Vibration Control for HVAC Systems, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Taylor, W., Pearson, J., Mair, A., and Burns, W. (1965). Study of Noise and Hearing in Jute Weaving. J. Acoust. Soc. Am., Vol 38, 113-120.
<https://doi.org/10.1121/1.1909580>

Tikka C, Verbeek JH, Kateman E, Morata TC, Dreschler WA, Ferrite S. Interventions to prevent occupational noise-induced hearing loss. Cochrane Database Syst Rev. 2017 Jul 7;7:CD006396.
<https://doi.org/10.1002/14651858.CD006396.pub4>