STUDENT MANUAL

Noise - Measurement And Its Effects

January 2009

CONTENTS

CONTENTS (Cont'd)

CONTENTS (Cont'd)

CONTENTS (Cont'd)

CONTENTS (Cont'd)

CONTENTS (Cont'd)

CONTENTS (Cont'd)

ACKNOWLEDGEMENTS

The original version of this manual was developed for BP International Ltd. by Dennis P Driscoll PE, President and principal consultant of Associates in Acoustics Inc. Reorganisation of and adding to the original material has been conducted by Ken Mikl and Marion Burgess at the University of Wollongong to fit the international student manual format and includes revisions made following a trial course in June 2008. The Occupational Hygiene Training Association Ltd would like to acknowledge the contribution of these organisations in funding and developing the material and is grateful for their permission to use and modify it.

Roger Alesbury
Robert Anderson
BP International plc
Elliott H Berger
Trudy Bishop
Aearo Technologies
American Industrial Hygiene Association (USA)
British Occupational Hygiene Society (UK)
Brüel & Kjaer
John Dobbie
Gayle Hunting
Institute of Noise Control Engineering (USA)
Thomas Kupferer
Terry McDonald
Quest Technologies Inc
Fred Tremmel
Noral D Stewart PhD
Laurie L Wells AuD

Supported by

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 @ 21°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
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).

dBC - 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})

E_{AT} - 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 program

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

I - sound intensity. Unit: watts/m^2

I_{oref} - reference sound intensity (10^{-12} w/m^2)

SYMBOLS & ABBREVIATIONS (Cont'd)

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). This metric is 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_{A8hn} for normalized average sound level, but note that for an 8-hr. measurement, L_{A8hn} = $L_{Aeq,8h}$. Unit: dB, dBA, or dBC.

SYMBOLS & ABBREVIATIONS (Cont'd)

$L_{EX,8h}$ - 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 Lg - 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)

m - mass. Unit: kg, lb

MIRE - Microphone in real ear

ms - 1/1000 s (millisecond)

SYMBOLS & ABBREVIATIONS (Cont'd)

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_{oref}	-	reference sound pressure (20□Pa)
p_{rms}	-	root-mean-square sound pressure. Unit: Pa
p_{peak}	-	peak sound pressure. Unit: Pa
Pa	-	Pascal
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
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

SYMBOLS & ABBREVIATIONS (Cont'd)

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

W - sound power. Unit: watts

$W_{əref}$ - 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. Unit: kg/m³*

τ - *transmission coefficient. Unit: dimensionless*

SYMBOLS & ABBREVIATIONS (Cont'd)

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 based in the most part on the international module syllabus W503 – Noise – Measurement and Its Effects published by the British Occupational Hygiene Society (BOHS), Faculty of Occupational Hygiene. The BOHS administers a number of such modules; further information on which can be obtained by visiting the BOHS website at www.bohs.org.

At the time of publication every care has been taken to ensure that the majority of topics covered in the BOHS syllabus for the subject (W503) have been included in this Student Manual. Providers of training courses should check the BOHS website for any changes in the course content.

The authors of this Student Manual take no responsibility for any material which appears in the current BOHS syllabus for Module W503 which is not covered in 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;
- 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 for the most part the syllabus for this course as published by the BOHS. 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.

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

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”.

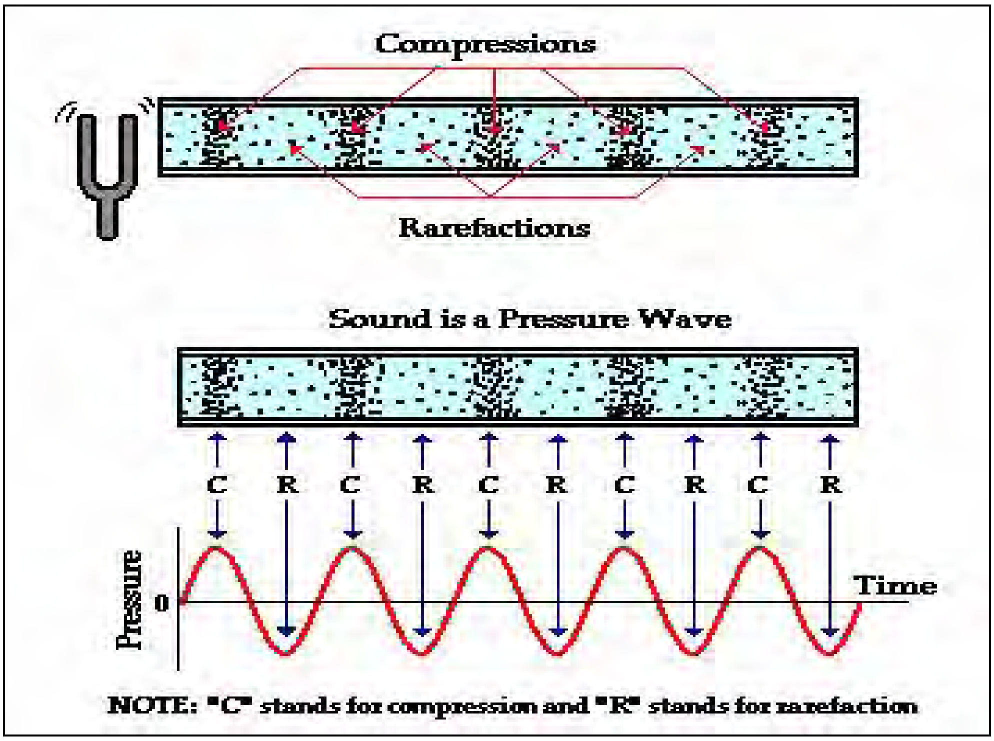
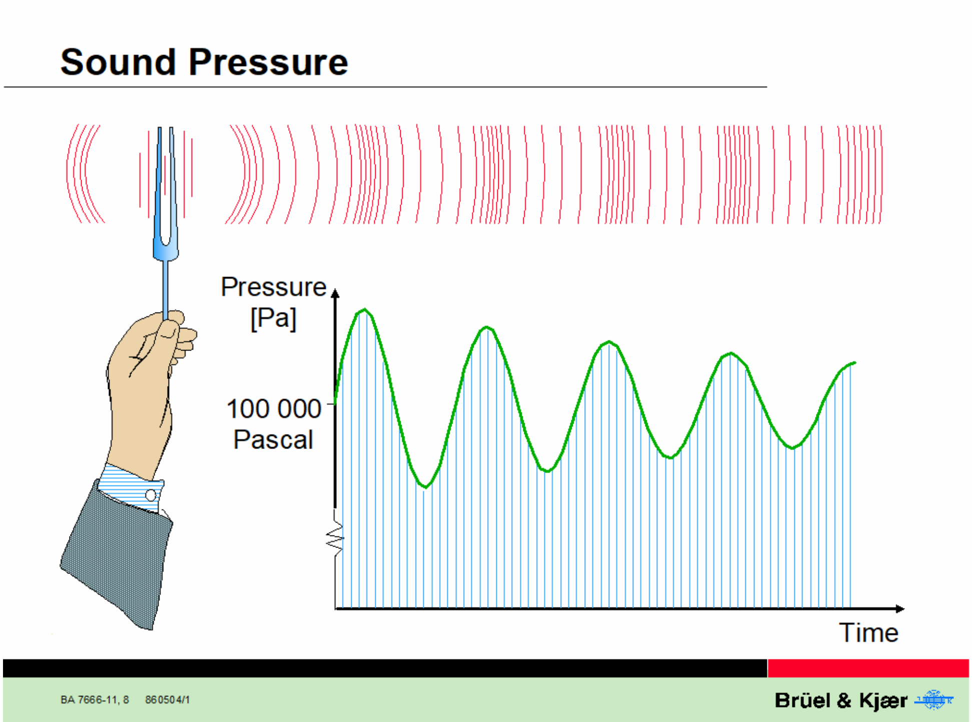


Figure 2.1 – A vibrating tuning fork sets air molecules into motion as illustrated in the top image, which results in positive (compression) and negative (rarefaction) excursions around atmospheric pressure as shown in the bottom illustration.

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 2.2 the sound is created by a tuning fork.

As each molecule is set into vibration, it pushes against the adjacent molecule, ie 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.



(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.

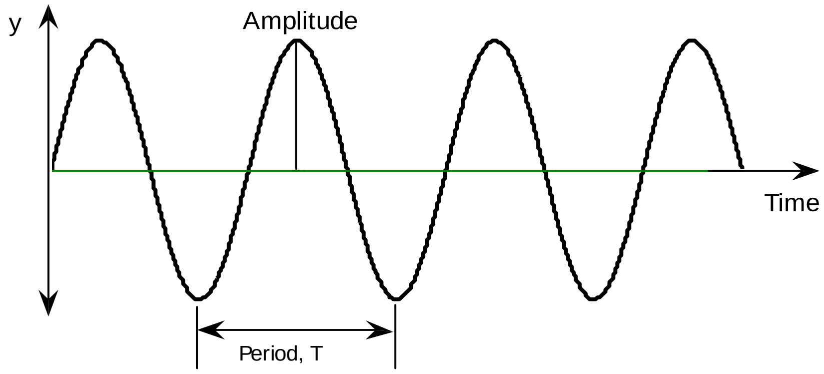


Figure 2.3 - Sound wave, pressure variation around atmospheric pressure

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.
The *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

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

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. 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
1,000 Hz	34.4 mm
10,000 Hz	3.4mm

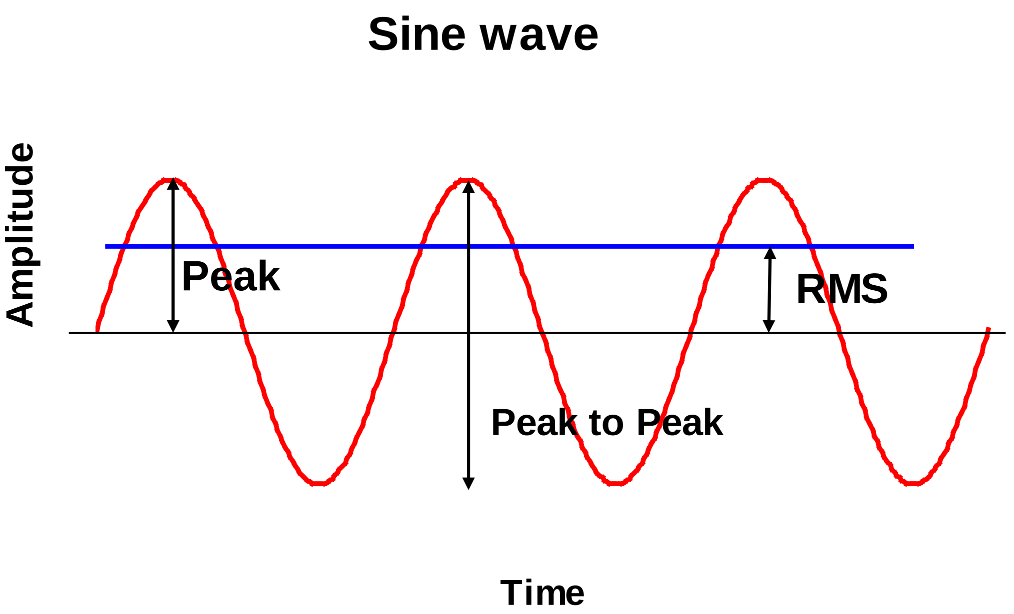


Figure 2.4 - shows some of the various options for measurement of amplitude of the sound wave which is represented here as a sine pressure wave. The peak pressure is the greatest pressure for the sound wave

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. We need an "average" which 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.

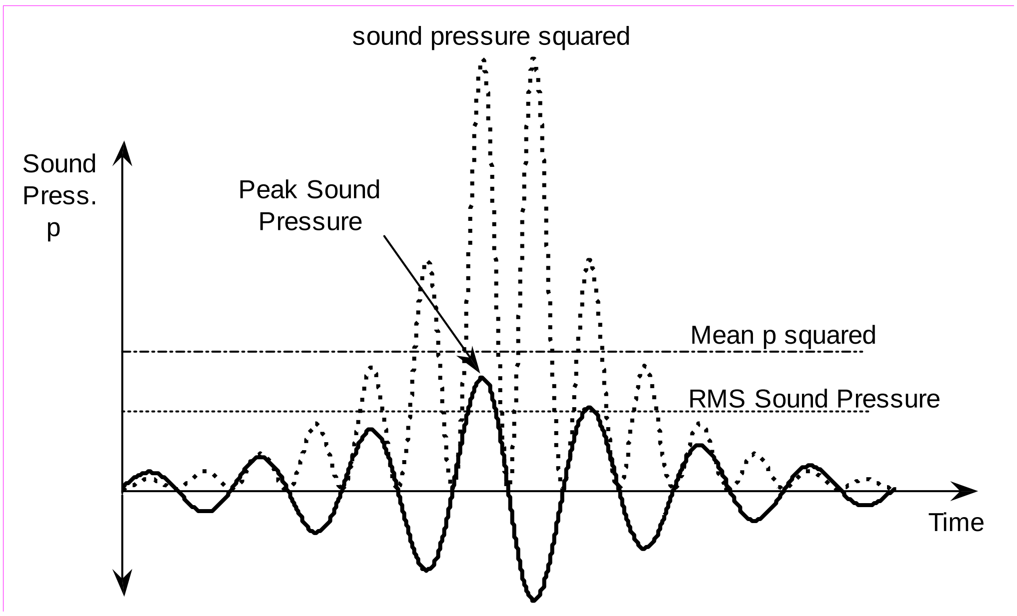


Figure 2.5 - Comparison of the pressure and the pressure squared signal with time

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

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

For more complex signals, there is no simple relationship between the two.

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 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.

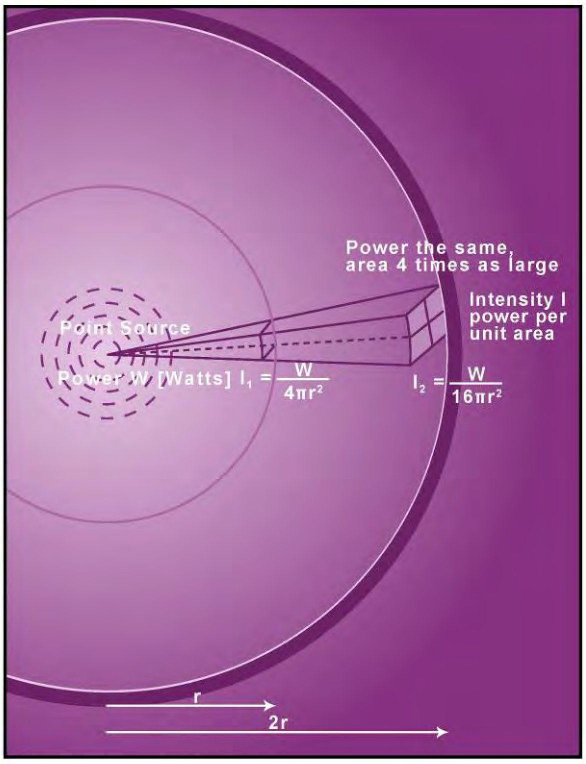


Figure 2.6 - Sound radiating out from source

Sound Intensity - is defined as sound power per unit area (watts/m^2). 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 in 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 4π x1

At 2 metres, r=2 and the surface of the sphere will be 4π—x 4 ie 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/m^2, while the intensity of the sound produced by a Saturn rocket at liftoff is greater than 100,000,000 watts/m^2. This is a range of 100,000,000,000,000,000,000. 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 logarithms[1], 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:

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

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

---

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

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

Reference intensity (I_{ref}) = 10^{-12} w/m^2
Reference power (W_{ref}) = 10^{-12} w
Reference pressure (p_{ref}) = 2 x 10^{-5} N/m^2, or 20 µPa

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

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

And pressure fluctuations are found by:

$I = \frac{p^2}{p\,c}$ (where ρ is air density, and *c* is speed of sound)

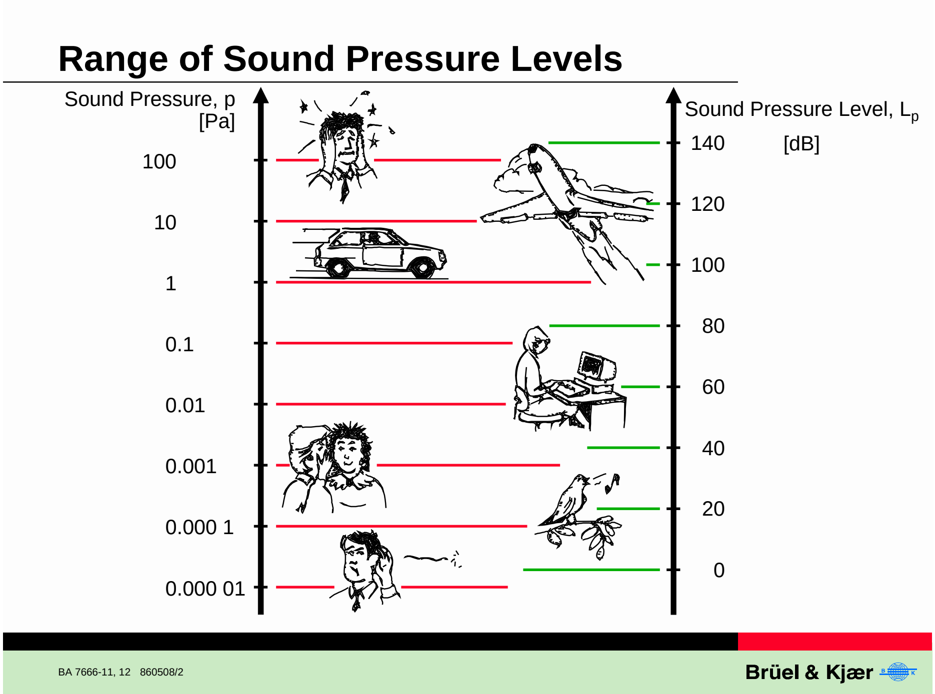
Therefore, the two expressions may be equated and represented as:

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

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

Figure 2.7 presents a comparison of decibels, sound power, and sound pressure.



(Source: Brüel & Kjaer)

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

The workplace noise environment will often be comprised of more than one noise source. Therefore, it is important to understand how the overall noise level varies 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, before we look at use of 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:

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

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:

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

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:

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

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 1.2 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 than10	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 85.0 dB, 89.0 dB, and 90.0 dB. (The final result will be L_{Pt}).

Step 1: Rank ordering these values from low to high gives us 85.0, 89.0, and 90.0 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 20µPa)	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, ie 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. The formula for averaging measured SPLs is as follows:

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

Where,

$\bar{L}_p$ = average SPL, dB

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

n = the total number of values or levels

Example – Determine the average SPL for L_{P1} = 81.0 dB, L_{P2} = 86.0 dB, L_{P3} = 82.0 dB, and L_{P4} = 84.0 dB.

These values are averaged using the expression:

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

And the individual SPLs are inserted as follows:

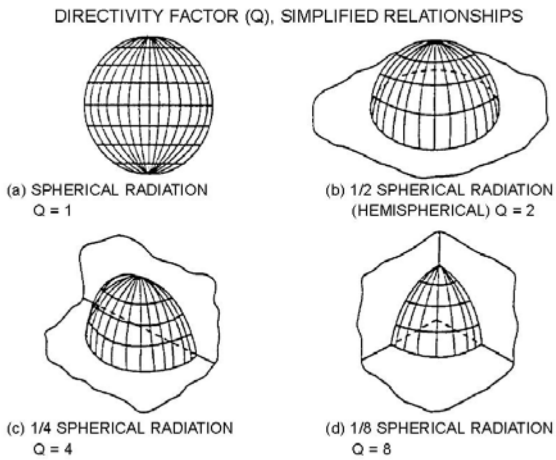
$$\bar{L}_p = 10 \log 1/4 \left(10^{81/10} + 10^{86/10} + 10^{82/10} + 10^{84/10}\right), \quad \text{dB}$$

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

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

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:

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

Table 2.5

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

	1/1 Octave Bands			1/3 Octave Bands		
Band	**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:

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

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 2.4 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 will be 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 are 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	from10Hz
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	

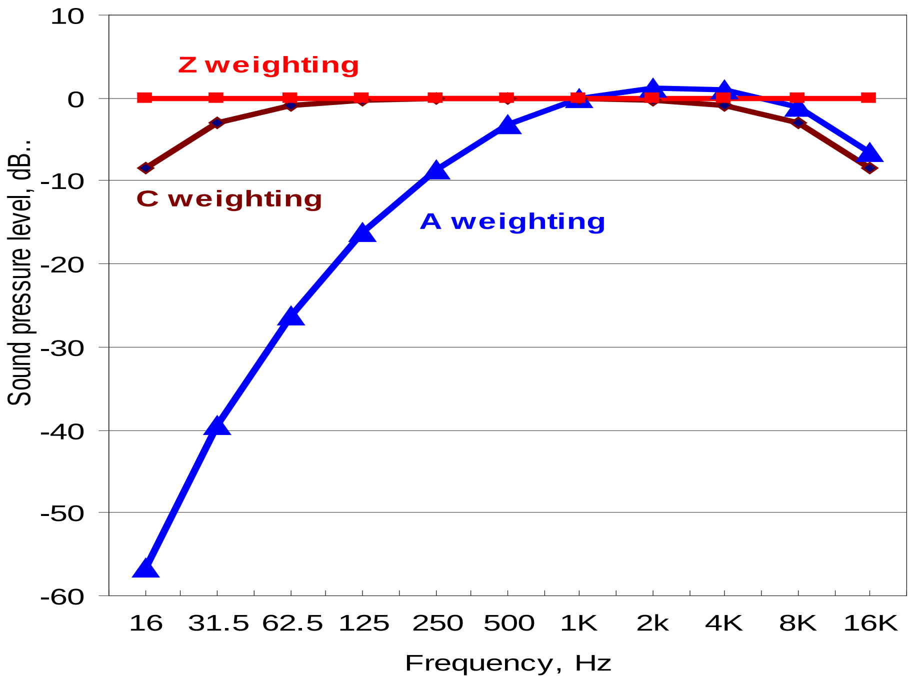
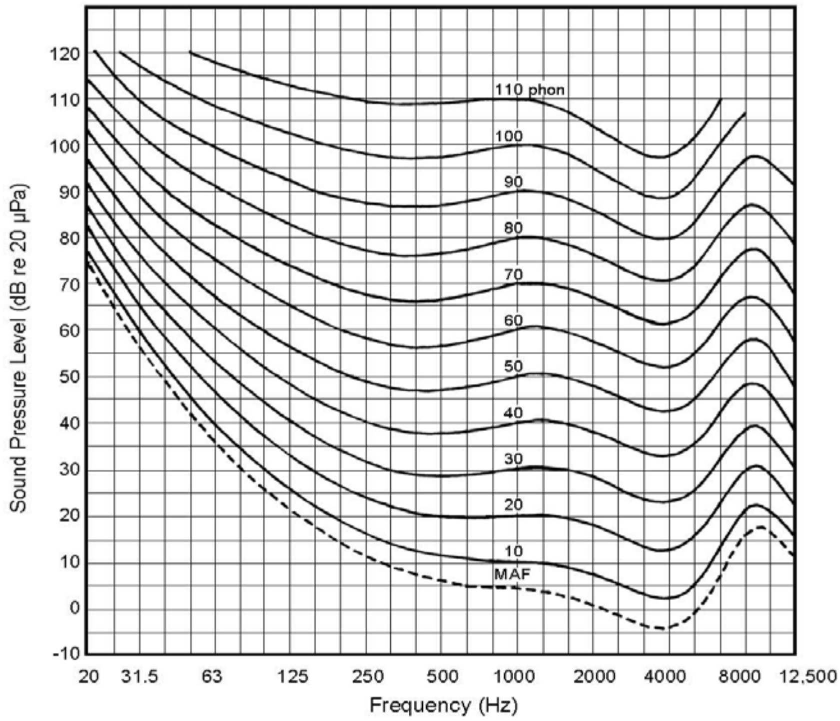


Figure 2.9 - Graphic representation of the A, C and Z weighting filters

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. So a sound at one frequency may seem louder (or softer) than a sound of equal pressure amplitude at a different frequency.

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:

$L_p = L_w + k$, 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. Say we put a 100-watt light bulb in the centre of a room that is 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 we take the same 90 dB PWL machine and place it 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, ie: 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. For example, machines that perform multiple tasks over a full-duty cycle often generate a range in sound levels, such as the shear press example shown in Figure 2.11. The shear press data exhibited has a full-duty cycle of 20 seconds, and the sound levels range from approximately 98-107 dBA.

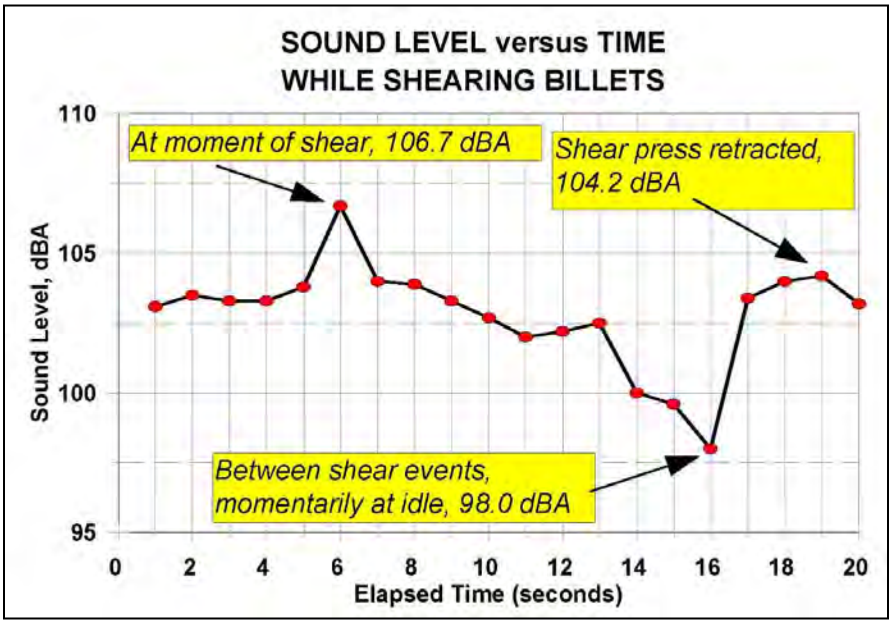


Figure 2.11 - Intermittent sound levels produced by shear press cutting bar stock into individual billets. Measurements conducted over one duty cycle.

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 or by explosions such as gun fire or explosive tools. *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 distinct characteristics. In addition, these short-term events are also called *transient* sounds. However, for occupational noise assessment and from a practical standpoint, all these terms may be considered the same.

2.5 HUMAN RESPONSE TO SOUND

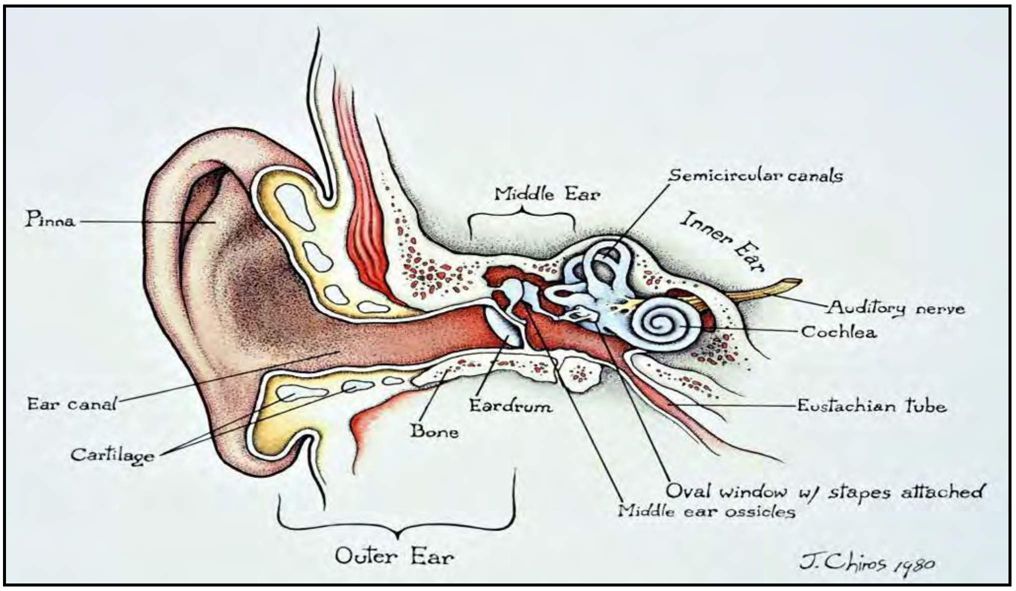
2.5.1 The Ear and its Response to Sound

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 2.12 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 2.12 – 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 2.13, 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.

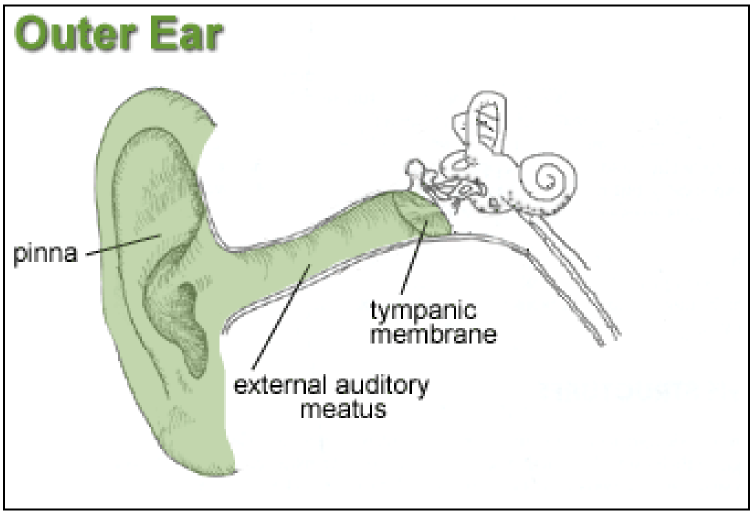


Figure 2.13 - The outer ear contains the pinna, ear canal, and tympanic membrane.

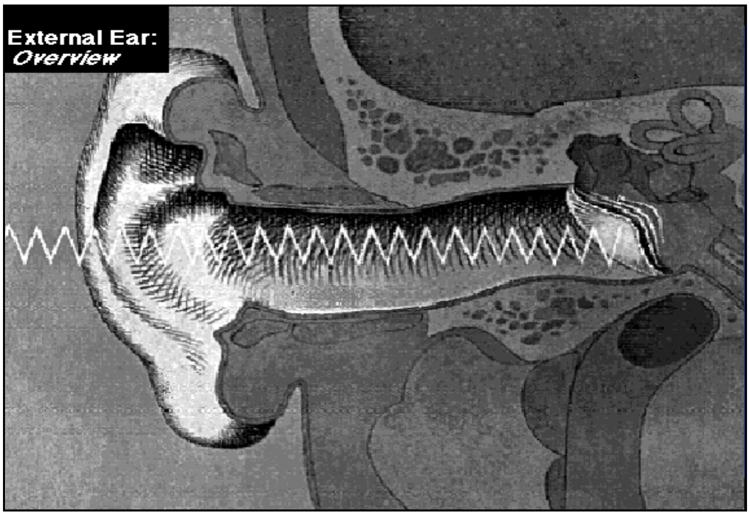


Figure 2.14 - Sound waves are channeled into the ear and enhanced by the shape and resonance characteristics of the ear canal. The eardrum transfers the acoustic vibrations to the middle ear.

Pinna:

The visible, cartilaginous portion of the ear helps to collect sound waves, as illustrated in Figure 2.14. 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 Earcanal:

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 tube, captures the sound vibrations, and passes them to 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. Figure 2.15 exhibits a photograph of a normal eardrum. The tympanic membrane must be in tact for normal transduction of sound to occur.

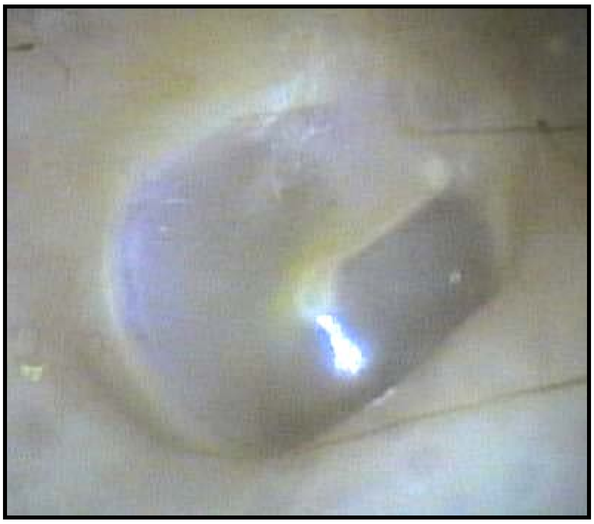
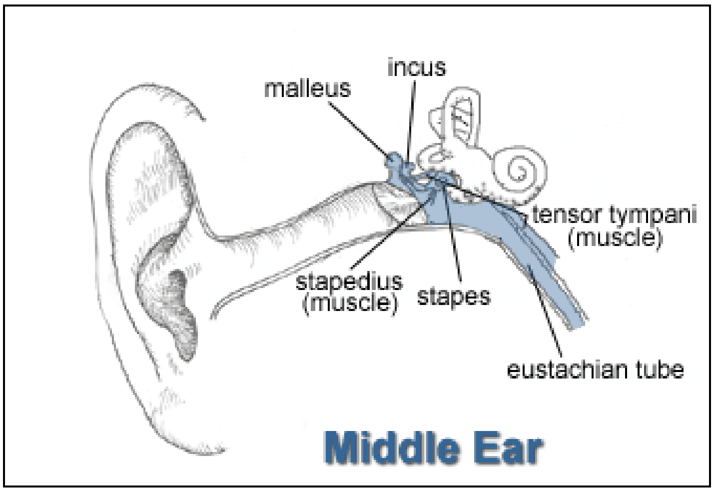


Figure 2.15 - Video otoscope photo of normal eardrum looking down the earcanal reveals the transparent tympanic membrane. The first ossicle, the malleus is visible through the eardrum. The light reflection from the otoscope is a landmark called the "cone of light."

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 2.16 and 2.17. 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 2.16 - The middle ear is the air-filled space between the eardrum and the boney inner ear. It contains the middle ear bones and muscles and the Eustachian tube

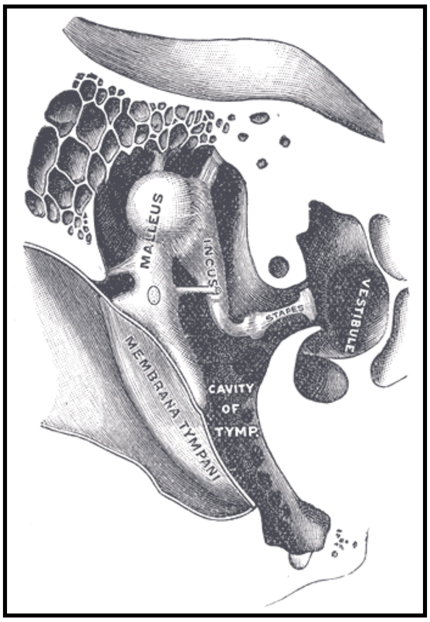


Figure 2.17: Close-up drawing of the middle ear showing the malleus, incus and stapes connecting the tympanic membrane to the inner ear

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, see Figure 2.18, is a fluid filled labyrinth within the temporal bone. It contains the sensory mechanism of both auditory and vestibular systems. Here, mechanical vibration is converted to neural stimulation for hearing and balance.

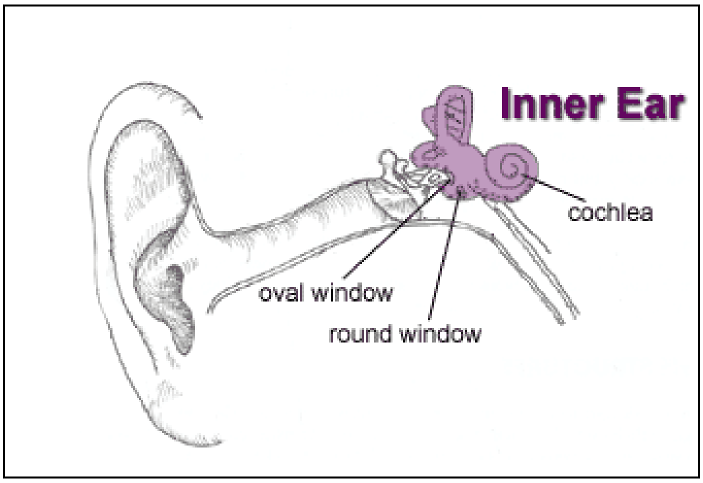
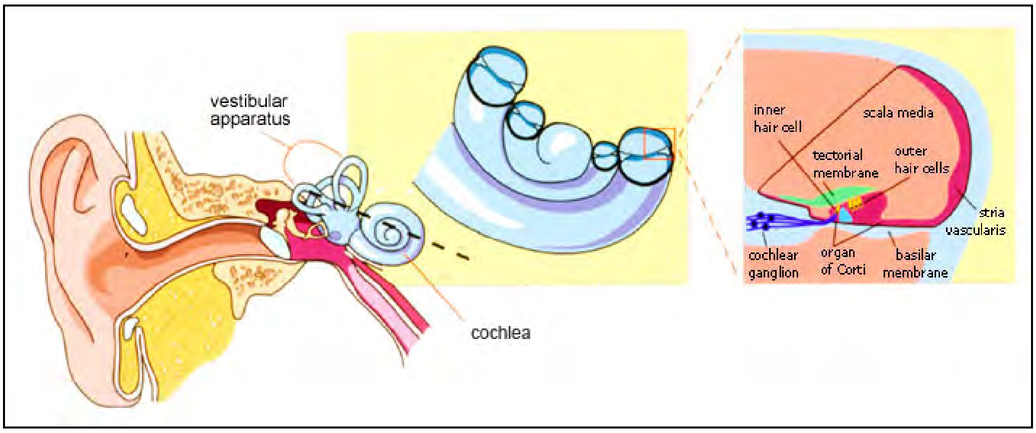


Figure 2.18 - The inner ear is a membranous tunnel encased in the temporal bone. It contains both the sense of hearing (cochlea) and balance (semicircular canals).

Cochlea:

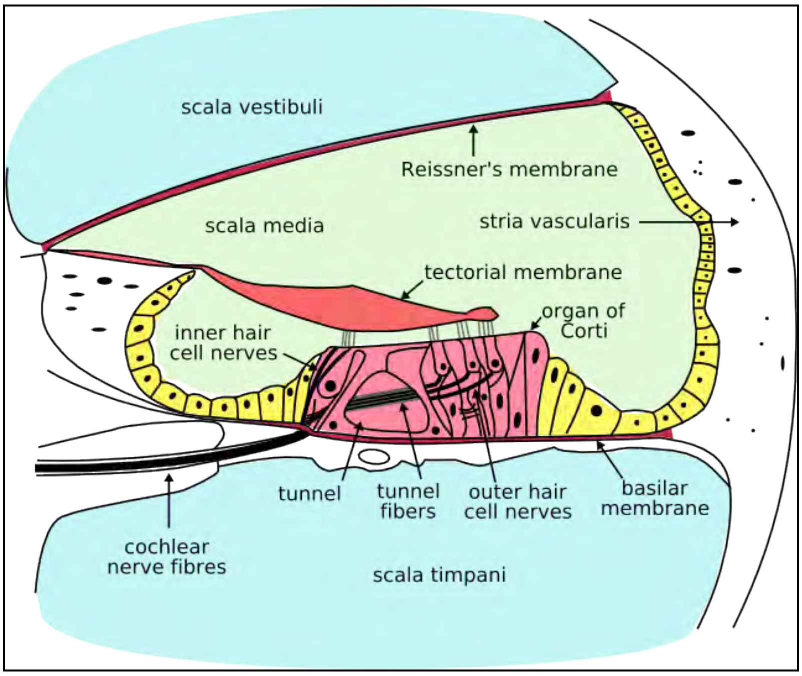
Often visualized as a snail shell, the cochlea is actually a fluid filled tube, which spirals 2.5 times on itself within the temporal bone, as shown in Figure 2.19. The tube is divided into three different parts by membranes.



(Source: Griffith and Friedman, NIDCD)

Figure 2.19 **- Illustration of a section through the cochlea**

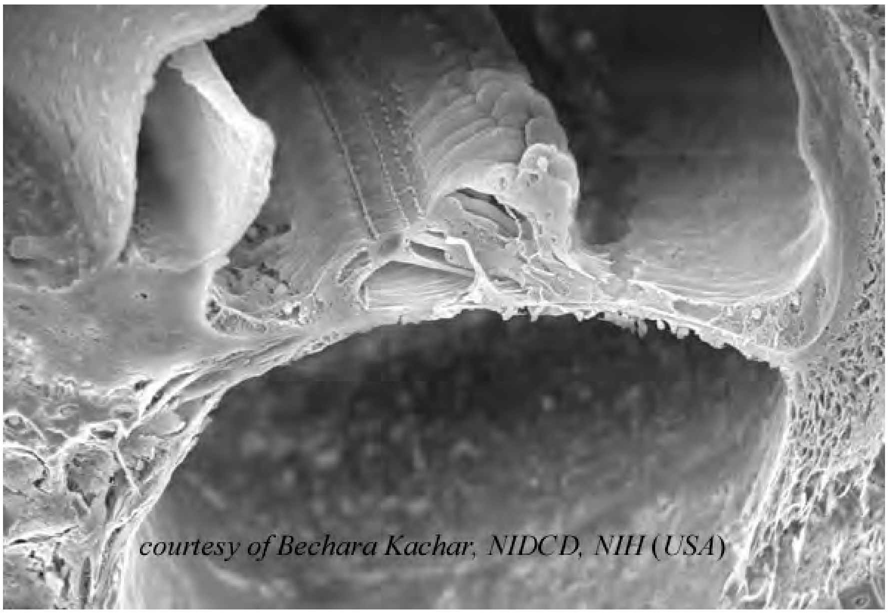
The upper and lower parts, called the *scala vestibule* and the *scala tympani* respectively, both contain perilymph, a fluid rich in sodium. These two compartments are joined by a small passage way, the *helicotrema*, at the extreme end of the cochlea. The centre partition, called the *scala media*, 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 2.20 – A cross section of one turn of the cochlea illustrates the three fluid filled chambers: scala vestibuli, scala media and scala timpani. The oragn 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.

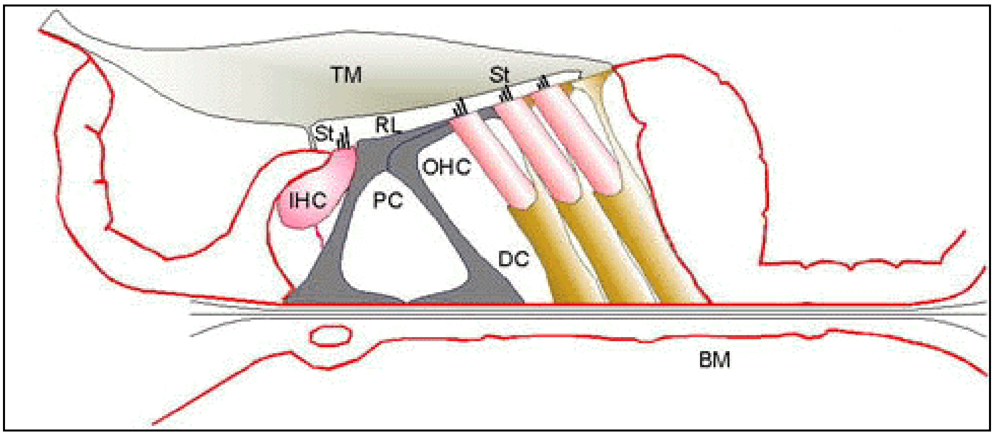
Figure 2.20 illustrates a cross-section of the cochlea and Figure 2.21 presents an electron micrograph of the organ of Corti within the cochlear duct. The length of the cochlea is approximately 35 mm and the beginning of the cochlea is referred to as the “base” and the other extreme is called the “apex.” 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 2.21 – 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 2.22*.* 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*.

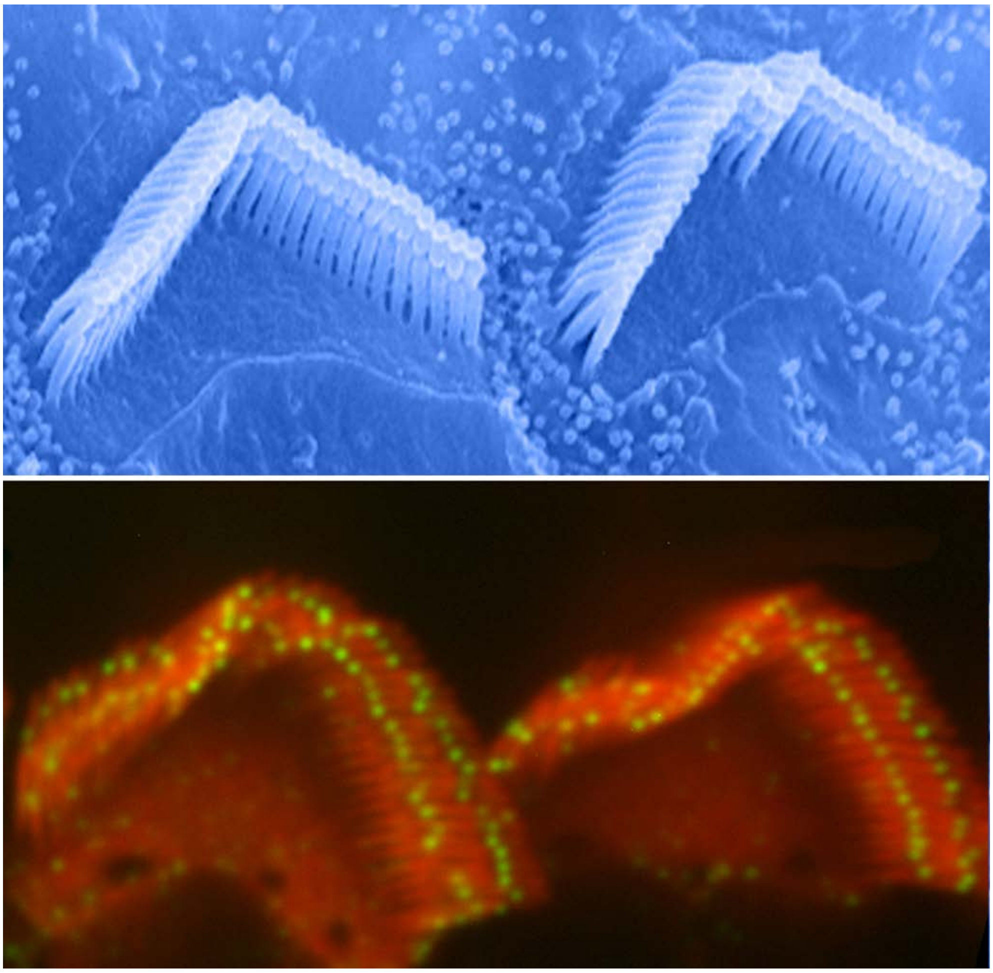


(Source*: Image with permission (Mammano and Nobili) retrieved from: http://147.162.36.50/cochlea/cochleapages/theory/index.htm*)

Figure 2.22 - 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 (green). 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 2.23. 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 2.23 - 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:

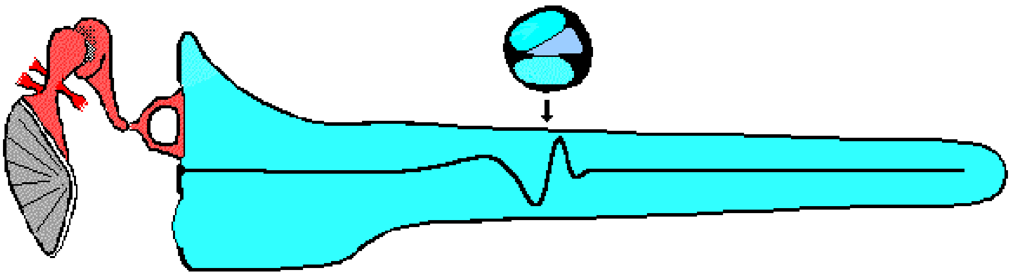
Inner hair cells are arranged in one row on the spiral lamina. There are approximately 3500 inner hair cells in each ear. They also have stereocilia, which are arranged in a "U" shaped pattern from short to tall. The primary difference between inner and outer hair cells is the motor function. Unlike 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 2.24 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 2.24 - 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.

A byproduct of the outer hair cell mobility is a wave initiated by the movement of the basilar membrane. This wave of energy travels the opposite direction through the ear, from the cochlea to the outer ear. This phenomenon is called an otoacoustic emission (OAE). OAEs are measured as acoustic energy in the outer ear canal. Useful for defining and diagnosing ear pathologies, they are an important tool in clinical evaluation of hearing disorders.

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, 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 basal end. So, if the maximum deflection of the basilar membrane occurs in basal end, a high pitch tone is perceived. Refer to Figure 2.25 for a diagram of the tonotopic organization and of a travelling wave.

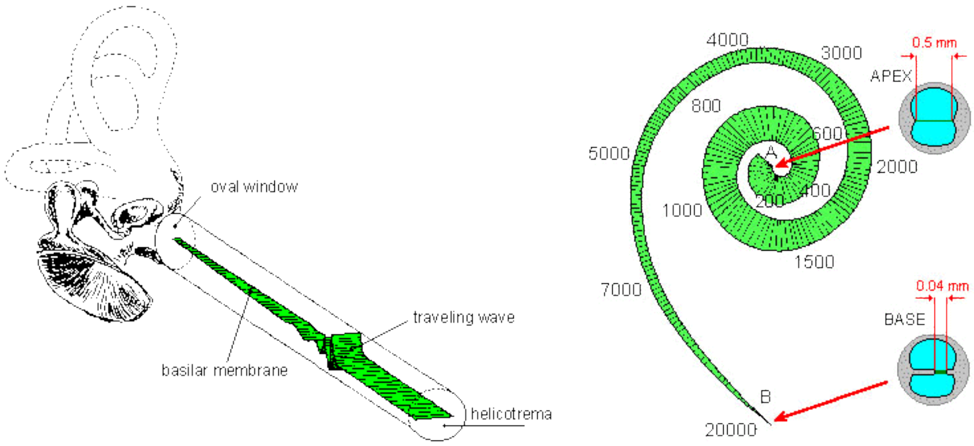


Figure 2.25 – The basilar membrane is tonotopically organized: it is responsive to high frequencies at its basal end and to progressively lower frequencies at the apical end. Properties of the organ of Corti affect the transmission of the vibration creating a traveling wave illustrated in an uncoiled 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/m^2. 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/m^2 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 to frequency. This concept is best illustrated by plotting *equal loudness curves* (see Figure 2.9).

3. RISK ASSESSMENT AND NOISE SURVEYS

3.1 OCCUPATIONAL NOISE MANAGEMENT

Noise and sound surround us, how this impacts on an individual in an occupational environment depends on many factors, some which are able to be controlled and others not. 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.

- **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 of noisy processes and equipment and a ranking of the level of sound level and quality.

- **Assess the Risk**

  Guidance as to acceptable levels and exposures can be obtained from standards and legislation. The measurements obtained in the identification stage may need to be supplemented to make a proper assessment of risk for the employees. The measurement of the “cause” side, ie noise sources is not sufficient to reveal the whole picture Risk also needs to be assessed and monitored from the “effect” side with the measurement of the possible damage caused. This is done by audiometric assessment.

- **Control the Hazard or Exposure**

  There are many ways to control a person's exposure to noise, ranging from eliminating the source or process, changing the process, controlling the noise at source, reducing the noise transmission from the source to the receiver and as a last resort to issuing hearing protection

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;
- 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 RISK ASSESSMENT

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.

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. Issues such as “what is an acceptable level of NIHL?” and “how much noise can be tolerated by a work population?” need to be considered when setting an exposure limit. 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.

Based on the ISO and NIOSH estimates, anywhere from 10-15 percent of workers will be at *excess risk for material impairment* in hearing if exposed unprotected to an 8-hour average of 85 dBA over a 40-year working lifetime. Since the protection goal was to preserve hearing for speech discrimination, to allow for direct comparison between the two reports or studies, material impairment was defined to exist whenever a person's average hearing threshold level for both ears exceeded a 25-dB "fence" at the pure-tone audiometric test frequencies of 500, 1000, and 2000 Hz. Also, excess risk is defined as the difference between the percentage of noise exposed and non-noise exposed people that exceed the 25-dB fence. By design, an effective hearing conservation programme will identity those susceptible individuals exposed to 85 dBA or more in the early stages of NIHL (10-15 percent), before it becomes debilitating, which will permit implementation of more effective measures to better protect them from workplace noise. Consequently, a balance is maintained between preventing excess material impairment for workers and the financial costs to an employer for at that time the commonly used limit was 90 dBA.

In 1990, the ISO approved the second edition of *ISO 1999, Acoustics – Determination of Occupational Noise Exposure and Estimating of Noise-Induced hearing Impairment"* (ISO, 1990). Using different material impairment formulae that excludes 500 Hz and includes 3000 and 4000 Hz, ISO puts the excess risk for NIHL at 6 percent for workers exposed to 85 dBA on a daily basis throughout their working lifetime. Besides consideration for speech discrimination, inclusion of 3000 and 4000 Hz in the formula also considers the perception of everyday acoustic signals and other quality of life issues, such as music appreciation.

In 1997, NIOSH re-analyzed the original research used to develop their 1972 recommended criteria, except in the more recent study NIOSH included non-linear effects of noise exposure, as well as alternative material impairment formulae.

Based on the 1997 research, NIOSH concludes the excess risk is 8 percent for workers with a noise exposure of 85 dBA over a 40-year working lifetime. In the end, NIOSH confirmed their original criteria of 85 dBA as a recommended noise exposure limit.

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).

[http://eur-lex.europa.eu/LexUriServ/site/en/oj/2003/l_042/l_04220030215en00380044.pdf]

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 and select the link to 'Noise at Work'(INDG362 (rev 1)] relate to:

- 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:

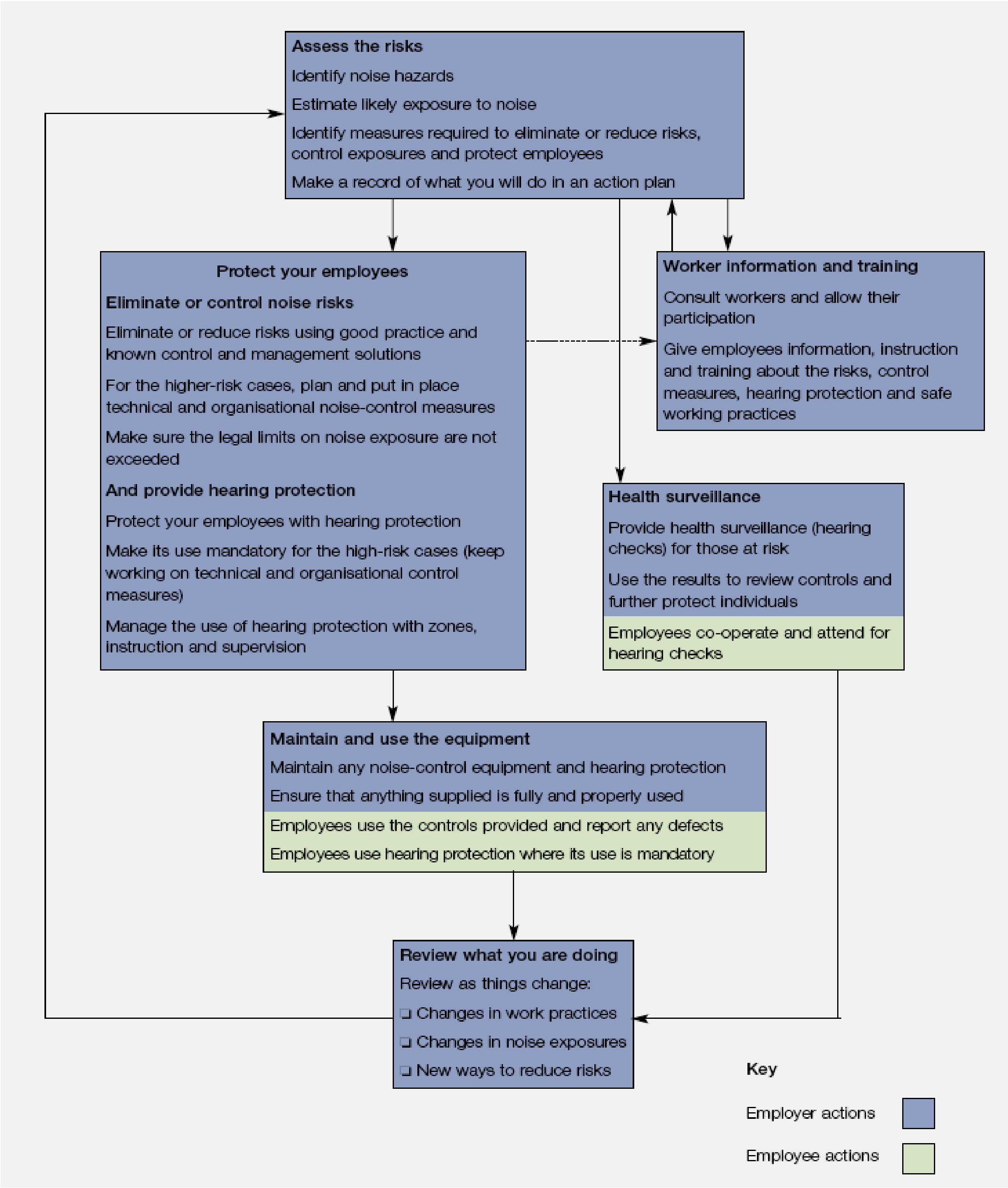
- Lower exposure action values:
  - Daily or weekly exposure of 80 dB;
  - Peak sound pressure of 135 dB;
- Upper exposure action values:
  - Daily or weekly exposure of 85 dB;
  - Peak sound pressure of 137 dB.

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 3.1.



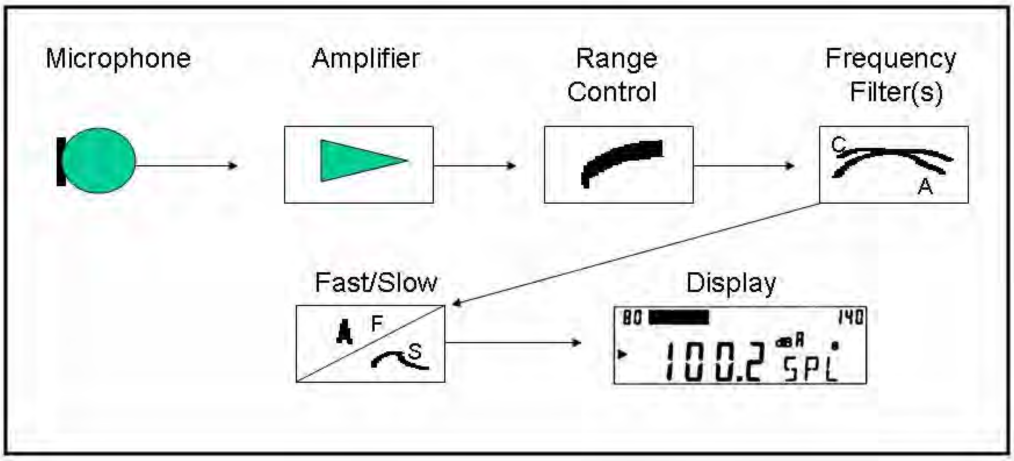
(Source: HSE “Noise at Work” – *reproduced with permission*)

Figure 3.1 – 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 3.2 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. 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*.



(Source: *Courtesy Quest Technologies, Inc.*)

Figure 3.2 – Simplified block diagram of the components for a typical sound level meter

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. 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), 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. Class 1 is a precision meter, and Class 2 is a general purpose instrument with lower performance specifications than Class 1. Legislation should be consulted to ensure that the measurements are undertaken with the appropriate class of SLM.

b) Types of Microphones and Their Use

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

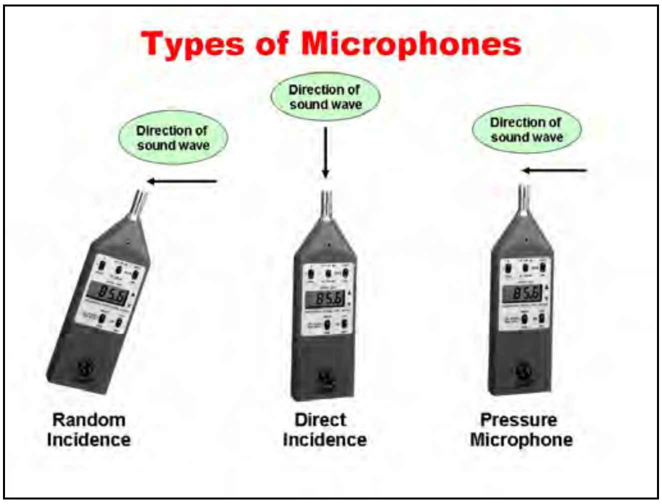
For occupational noise measurement there exist primarily three microphone types, as depicted in Figure 3.3, which are random incidence, direct incidence, and pressure microphones. Random incidence microphones, also called omni-directional, measure sound pressure levels more or less evenly from any direction, 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, ie 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 omni-directional 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 Quest Technologies, Inc.*)

Figure 3.3 - Types of microphones and their use relative to the direction of sound propagation from the source

3.4.2 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".

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 3.4 shows a typical acoustical calibrator used for field calibration.

(Source: *Courtesy Quest Technologies Inc.*)

Figure 3.4 – Typical acoustical calibrator used for field calibration

3.4.3 Frequency Analysis

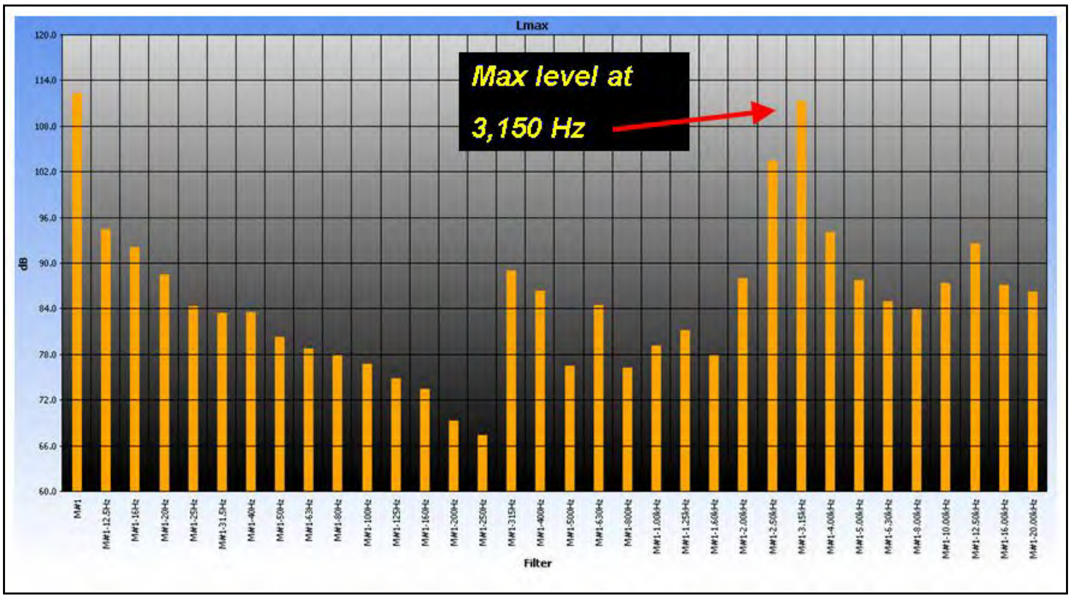
Frequency analysis is a vital tool used extensively for noise control , evaluation of hearing protectors, and environmental or community noise assessment. Frequency analysis is conducted using an SLM with an octave-band or 1/3 octave band filter. The characteristics of these filters were discussed in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

Real-time Analysers:

The most efficient means to measure frequency or spectral data is to use a *real-time analyzer (RTA)*. Prior to the advent of RTAs, frequency measurements had to be conducted using serial-band filters, which required the operator to measure one frequency at a time. This process is fairly time consuming, but also is difficult to complete for time-varying noise sources, especially for intermittent or transient sounds. An RTA solves these challenges by employing digital signal processing technology that allows measurement of all frequencies of interest simultaneously (also known as real time). Figure 3.5 presents the 1/3 octave-band data from an RTA display for an internal combustion engine. As shown in the figure, this engine has a peak frequency of concern at 3,150 Hz, which may be used for noise control purposes, such as selecting a silencer to maximize attenuation at this frequency.



(Source: *Courtesy Quest Technologies Inc.*)

Figure 3.5 - 1/3 octave-band spectral data for the maximum sound levels generated by an internal combustion engine. This image was taken from the display of a Quest Technologies RTA model DLX

RTAs were initially developed in the late 1970s, but they were very expensive compared to serial-band filters, also RTAs were considerably bigger than an SLM with an octave-band filter. In recent years with advances in technology it is now possible to have a RTA in a hand held SLM.

Figure 3.6 exhibits four hand-held RTAs available from different manufacturers. As shown in the figure, these instruments are fairly compact making them ideal for field use.

(Source: *Courtesy Quest Technologies Inc Larson Davis Inc., Norsonic, and Brüel & Kjaer*)

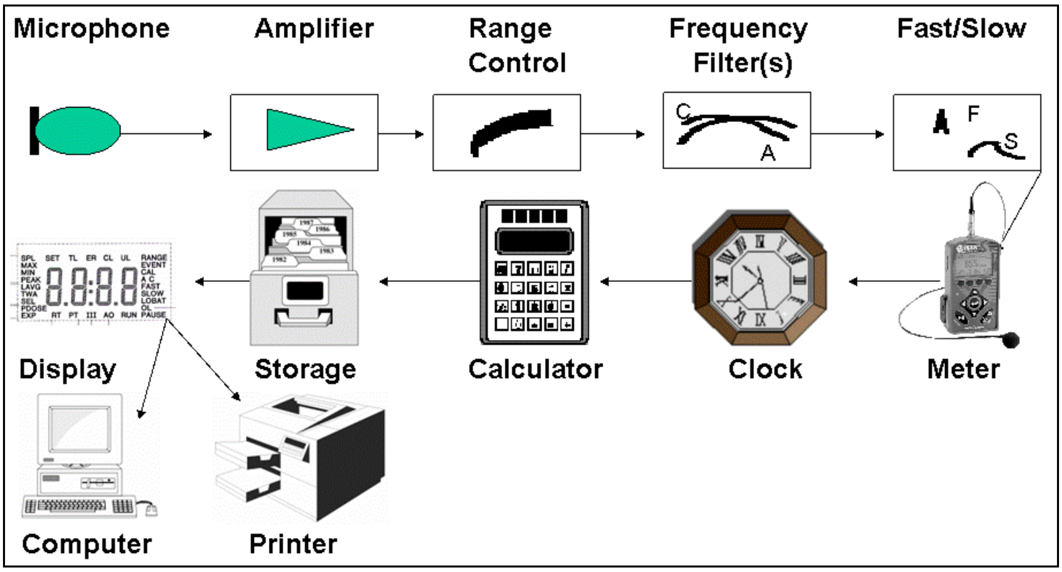
Figure 3.6 - Compact hand-held RTAs

Typical features of a basic RTA include; Type 1 or Type 2 versions with an 1/1 or 1/3 octave-band analyzer, simultaneous measurement with different weighting filters (A, C, Linear or Flat, etc.), user select logging capability (sound level versus time), various environmental noise statistics, etc. Plus, all RTAs have the capability to download data to a computer for post-survey processing and analysis. Usually, the manufacturer has available data management software supporting their RTA.

3.4.4 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 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 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 these are A, C & Z these have been discussed in Section 2. The A weighting is the most common and has a similar frequency response to that of the human ear.

Time Weighting:

Typically meters will have selectable time responses these are Slow, Fast, Max, Impulse & Peak. This requires the meter to calculate the sound levels by integration over differing time intervals within the total measurement period.

For sound field exposure determinations **Slow** and **Fast** response characteristics represent time constants of one (1) second and one-eighth (1/8th) second, respectively. These dynamics determine how quickly the instrument's display is updated with sound level data.

In practice, the “slow” response can be used for providing an indication of the overall level for time varying sounds when an integrating meter is not available.

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 L_S and L_F. 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. .Should the Max be required it is important to ensure that the time constant specified in the regulation or code of practice is used.

Impulse response is defined as having an exponential rise time constant of 35 milliseconds, and an asymmetric decay time constant of 1.5 seconds. It was thought that this could be used to describe impact sources, however it is rarely used now and is not used for occupational noise,

Peak has replaced impulse and max in the occupational environment. The *peak SPL,* L_{pk} *or* L_{peak}, is defined as the greatest value of the absolute instantaneous sound pressure (NB: this is the pressure and not the RMS pressure – refer back to Figure 2.4) within a specified time interval, expressed in units of dB. For occupational noise measurements, the instrument must adequately measure a pulse of 100 microseconds (one ten thousandth of a second) duration.

Equivalent Continuous Sound Level:

For the measurement of varying sound fields it is necessary to average the sound energy over a longer time period, 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 also used and for all practical purposes 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:

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

Where,

i is the ith increment,

n is the total number of increments,

t_i is the duration of ith 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:

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

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 3.8 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.

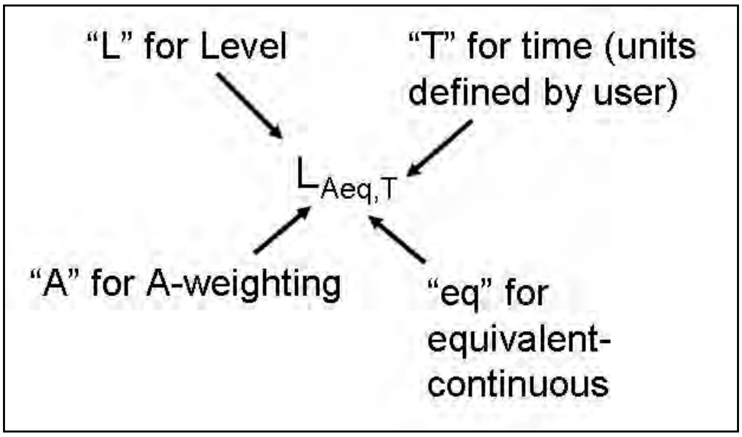


Figure 3.8 - Description of the symbol notation

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:

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

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.

Exchange Rate:

Regulations governing noise exposure specify that unprotected exposure should be limited to a prescribed maximum noise level averaged over a nominal day. This defines a limit, but does not describe how time-varying noise levels should be handled when determining the noise exposure. If the regulatory limit, which is a pressure squared quantity, is multiplied by the work shift duration time, the product can be identified dimensionally as energy. Alternatively, in terms of acoustic power, sound energy is the product of power and time (sound energy = power x time). So, a doubling of either power or time would result is a 3 dB increase in SPL; and a corresponding halving of power or time would result is a 3 dB decrease. This trade-off relationship is called the *equal-energy rule*.

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 tradeoff. 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. 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.

Noise Dose:

In addition to setting a limit for noise exposure, some regulations use the concept of *noise dose, D*. The–use of this term has been largely superseded by the use of the $L_{Aeq,8hr}$ and is only still used in a few jurisdictions. However the use of the word ‘dose’ does help to simplify the concept of noise exposure for training sessions. In particular it helps to explain how the individual noise exposures for the various tasks contribute to the 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.

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.

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

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^{2}hr. 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 limiting value.

Table 3.1 – Values of Pa^2 for a range of sound pressure levels

DECIBEL TO PASCAL-SQUARED CONVERSION									
dB	**Pa^2**	**dB**	**Pa^2**	**dB**	**Pa^2**	**dB**	**Pa^2**	**dB**	**Pa^2**
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^2hr
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^2hr	15.3

To normalise to 8 hour day divide 15.3 by 8 to give 1.9 Pa^2

Then find the value of sound pressure level corresponding to this value for Pa^2 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, ie: 91 dBA.

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 if made for each day in the usual manner. For each day the Pa^2 values are added and the total divided by 5 , ie 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 , ie always normalized to a 5 day week. The resultant $L_{Aeq,8h}$ 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 5 days	1.50 Pa^2
divide by 5	0.3 Pa^2 and from Table 3.1
$L_{Aeq,8h}$	89 dBA

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

Non auditory effects

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 ie lead to hearing damage even without exposure to noise. Some examples of industrial ototoxic agents are solvents including toluene, styrene, trichloroethylene, carbon disulphide, hexane and butanol, and toxic metals including lead, mercury and trimethyltin. Also mixtures of solvents that include xylene, heptane and ethyl benzene have been implicated in some ototoxic studies. Other factors that have been considered to cause greater hearing loss when there is a combined exposure with noise include smoking, vibration ands tress. On the other hand antioxidants and high temperatures may provide some protection from hearing damage.

3.6 ASSESSMENT SURVEYS

3.6.1 Instrumentation Requirements for Surveys

If a SLM is required in facilities with potentially combustible, explosive, or similarly hazardous conditions; caution must used to ensure the meter is intrinsically safe, or a hot-work permit is obtained, prior to working in these environments.

All personal noise dosimeters should at least conform to the requirements for Type-2 instruments. All acoustical calibrators should also comply with appropriate standards, or their latest revision.

Other instrumentation such as frequency analysers, sound sources, statistical analyser’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 instrument.

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 Class 1 and +/- 2 dB for Class 2 calibrators), 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.).

3.6.2 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, 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 an indication of the areas of concern can be obtained subjectively. 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 greater than 80 dBA. If a 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.

The person undertaking the preliminary survey should conduct a walk-through the entire work area. A observations should be made at each piece of equipment, work station, or any desired location for long enough 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, 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 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.

3.6.3 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 exposure assessment 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 or 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 program 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 and the operation of the machinery. This involves talking with management, with supervisors and with employees. Its is only once you have a good understanding of the factors that may 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}, exceed 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 impulse or impact noises in the work area then this should be documented in the report. If there are noticeable loud impact or impulse noises then they should be measured at each location along with the L_{Aeq}.

Modern instruments usually allow for these two measures to be obtained simultaneously while older equipment requires the data to be obtained separately.

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 people 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 prioritise 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.

3.6.4 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 two to five years, to validate or update existing data.

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.

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 windshield 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.

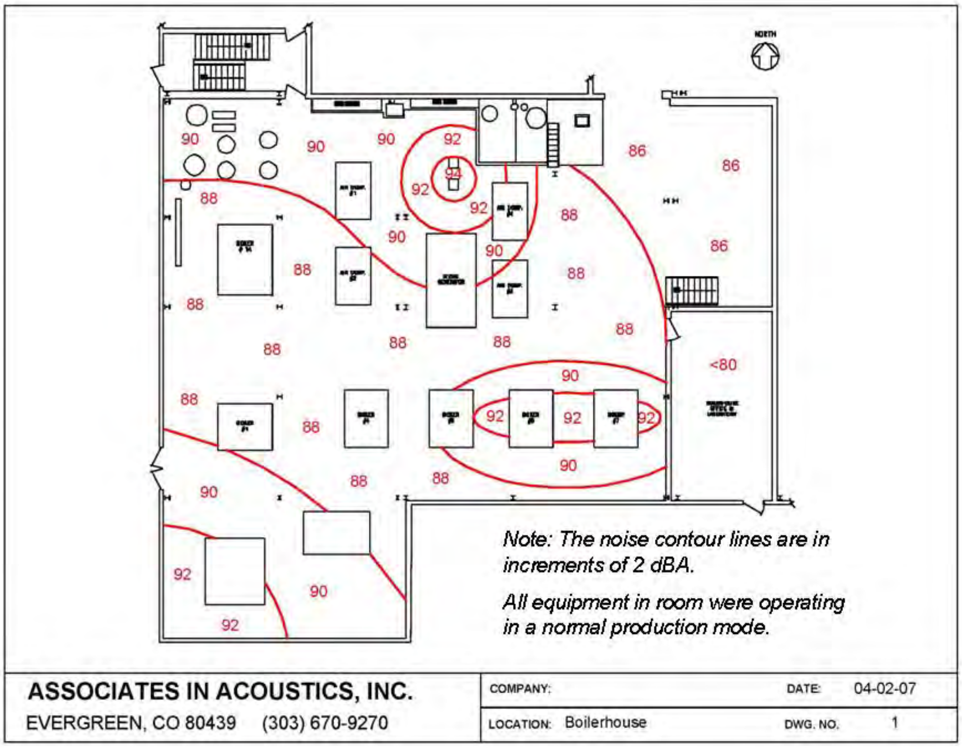


Figure 3.9 - Example of a sound contour map showing sound level contours in 2-dBA increments. This map was generated using AutoCAD 2004 and by manually drawing each contour line within the application programme.

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

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 map should be clearly presented and the areas where the noise levels are at a hazardous level should be identified to prioritise 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.

3.6.5 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 arms 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 persons 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 3.2 - 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 3.5 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

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.
Note: This spreadsheet will normalize all data for non-eight hour workshifts to an 8-hr day.

JOB TITLE: Carpenter
DEPARTMENT: Wood Shop
SHIFT LENGTH: 8 hours

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)

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

NOISE DOSE (%) AND $L_{Aeq,8}$ (dBA):

TOTAL ACCUMULATED DOSE: 551.1 %

CALCULATED $L_{Aeq,8}$: 92 dBA

Calculations are based on a 85-dBA Criterion, No Threshold Level, with a 3-dBA Exchange Rate

Reference Duration is the amount of time it takes to reach a 100% dose at a certain sound level.

$L_{Aeq,8}$ is the average daily noise exposure in dBA, which is normalized to an 8-hour workday.

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 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.
- 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 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.
- Spend the first 30-60 minutes of the sample period in the vicinity of the person or workers being monitored. 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. Once carefully removed immediately press the "Pause" key on the dosimeter, which will internally store the data until downloaded or recorded by the surveyor.

- 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 accidently 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 and/or instrument failure.

<u>Representative Worst-Case Monitoring</u>: 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 be selected for monitoring with personal noise dosimeters.

Three 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

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.

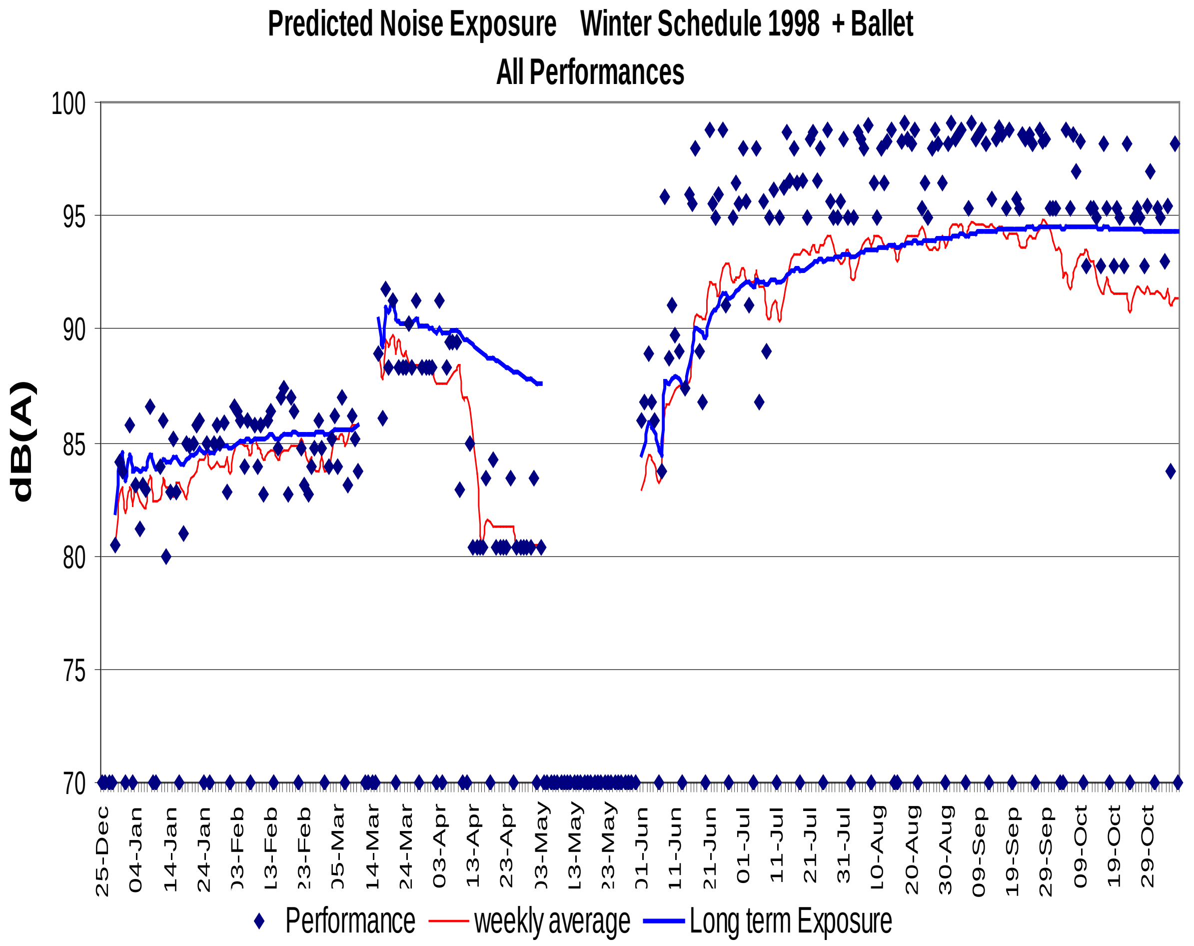
Monitoring should be sufficient to be confident that the upper 5% of exposures can be estimated with reasonable confidence. To establish the number of dosimetry samples required to identify the top 20 percent noise exposed to within a 95 percent confidence level, Table 3.1 should be used (Leidel, 1977).

Table 3.1 - 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≤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 programs. 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. 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 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,
- 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.

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.

3.6.6 Measurements for Development of Noise Control

a) Purpose

Assuming high noise exposures exist (above the criterion level) within the facility, the most effective way to prevent NIHL is to eliminate the risk to workers through implementation of effective noise control measures. Toward this end, a comprehensive noise control survey will assist with identification and/or quantification of the noise characteristics of various sources. It is usual that such noise surveys and the development of noise control methods are undertaken by acoustic specialists.

The protocol for conducting a noise control survey will depend on the goals and objectives for the survey. If the goal is to modify or treat the source of noise, then significantly more detailed survey information will be required as compared to the amount of data needed to simply treat the sound transmission path. Controlling noise at the source requires identification of the origin or source of noise, and definition of its acoustical properties (i.e. frequency spectrum, sound level versus time, etc.). This provides the necessary information for design of the controls.

Treatment of the sound transmission path does not always require clear identification of the root cause of noise, but instead relies heavily on the frequency spectrum and room characteristics to provide the information needed to select the acoustical materials.

Finally, a word of caution, it is rare for a noise control effort to be a one-shot deal. It is a lot like peeling an onion; quite often the noise control programme will require multiple steps or phases to reach the intended goal. It is however encouraging that in many instances the most dramatic and measurable noise reduction will result from successful implementation of control measures designed for the most dominant sources. So it is important to be persistent and patient because, as mentioned previously, the ultimate goal of eliminating the risk to workers is the most effective way to prevent NIHL.

b) When to Conduct

When to conduct a noise control survey will depend on a variety of factors, such as the acceptable level of risk (criterion level) in effect at the facility, the goal of eliminating the need for HCP or the required use of hearing protection, and/or a desire to attenuate a high noise source regardless of the worker noise exposure.

As a minimum, a noise control survey should be conducted whenever noise exposures exceed the criterion level, which at most facilities is an $L_{EX,8h}$ of 85 dBA. In addition, a noise control survey may be initiated to resolve a community or environmental noise concern, such as complaints from neighbors, or when local noise limits or regulations are exceeded.

c) Procedures, Data Analysis, and Interpretation of Results

The initial objective of all noise control projects should be directed toward treating the source. However, if additional noise reduction is required over and above what treatment of the source can provide, or should modification of the source be cost-prohibitive, then the next step would be to implement a path treatment that will effectively prevent excessive noise from reaching the receiver. The survey procedures described below are developed to address the primary objective of treating the source.

The same information collected will also apply for controlling noise along the sound path and at the receiver's position. However, detailed 1/3 octave-band or narrow-band data recorded for source identification are not necessary for path and/or receiver treatment. Measurement of the full octave-band spectrum is usually sufficient to allow selection of the appropriate noise control products for this type of noise control treatment.

One of the most challenging aspects of noise control is identification of the actual source. The following techniques may be used to help identify the origins or sources of noise:

- Start by conducting a quick cursory or walk-around sound survey of each area while observing the overall A-weighted sound level and peak level on the SLM to ensure all high noise areas and equipment are identified for more detailed measurement.
- For all equipment of concern, measure the overall A-weighted sound level, peak level and frequency spectrum, and graph the spectral data. Be sure to document the distance each measurement was conducted from the source.
- For equipment with cyclic or fluctuating sound levels, measure the broadband sound level, in dBA, versus time, and log any peak levels.
- Compare frequency data from similar equipment, production lines, etc.
- Isolate components with temporary controls, or by turning on and off individual items whenever possible.

One of the most effective methods for locating the source is to measure the frequency spectrum and broadband sound level. Once the data are measured, it is useful to graph the results to see the frequency characteristics of the source.

For most noise abatement problems, the measurements can be accomplished with either 1/1 or 1/3 octave-band filters used with an SLM. The advantage of a 1/3 octave-band measurement is that it provides more detailed information or definition about the sound emanating from a piece of equipment.

As an example of this approach consider the case of a vibratory bowl used to feed plastic parts into an injection molding machine. Figure 3.11 exhibits a comparison between the 1/3 octave-band spectrum measured one metre above the vibratory bowl and the level measured approximately 3 metres away at the typical operator's position or background location. As depicted in the figure, the overall or broadband sound level at one meter was 105.8 dBA, as compared to 102.4 dBA at three metres in the background. To assist with the identification of the primary noise sources, it is worth noting that several frequency spectra were measured near all equipment items, not just the vibratory bowl, in the immediate area. However, when each spectrum was compared to the data at the operator's position, only the vibratory bowl noise exhibited a similar spectral shape at the primary frequencies of concern, which as shown in the figure are 500 Hz and above. This similar spectral shape is sometimes referred to as the "acoustical fingerprint." In other words, the acoustical fingerprint of the vibratory bowl noise is all over the sound spectra measured at 3 metres. Note: the data at 500 Hz and above are of primary concern because all sound levels are at or above 80 dBA, with the most critical sound energy above 90 dBA starting at 1,000 Hz and above.

Therefore, as a result of this spectral comparison, it may be concluded the vibratory bowl is the primary noise source controlling the levels measured at the worker's location. This technique of graphical comparison is one of the most effective ways to identify and help quantify the primary noise source(s) making up the background sound level where workers may be located or typically spend a significant portion of their workday.

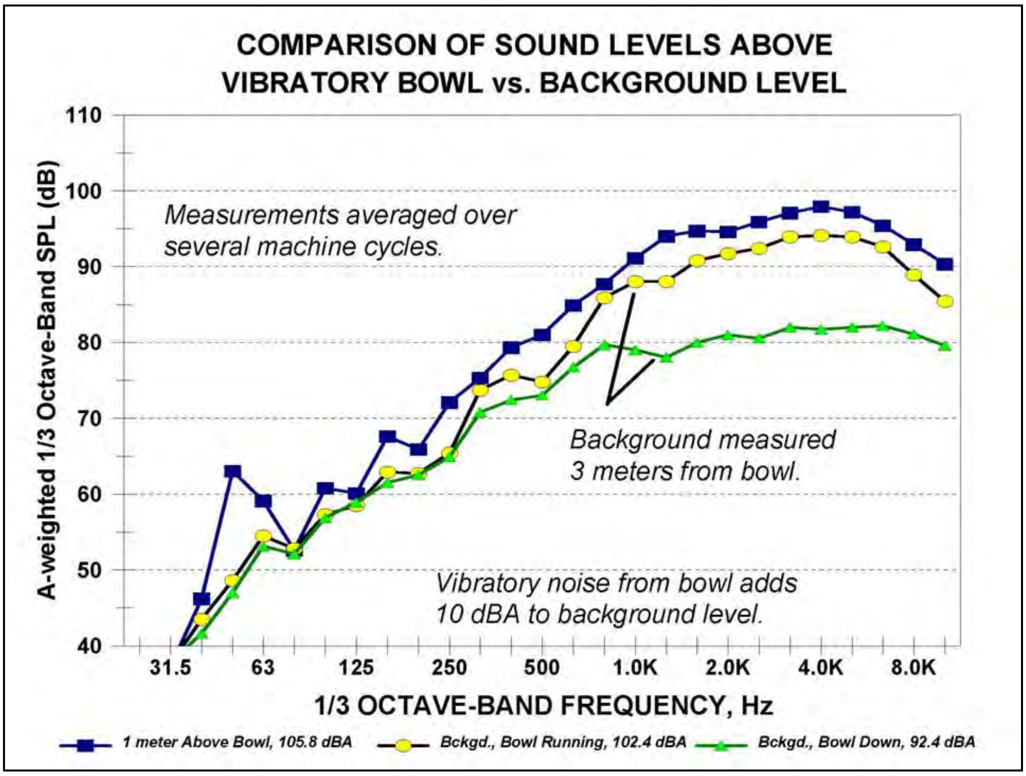


Figure 3.11 - Using frequency data to identify the source of noise. Observe the similar spectral shapes between the measurements one metre above the bowl compared to the background level with the bowl operating at a distance of 3 metres

Next, in Figure 3.11 a second reading is depicted at the operator's position; except this measurement was conducted with the vibratory bowl at idle. Since the noise level at the operator's position decreased from 102.4 dBA to 92.4 dBA, these data reveal that the vibratory bowl adds 10 dBA to the overall level at this position. As a result, we know that if the bowl noise can be eliminated or controlled, the background level will still be at least 92.4 dBA.

Recall the logarithmic math that when one sound level is 10 dB below another sound level it does not for all practical purposes contribute to the higher level. Therefore, to ensure the vibratory bowl noise will no longer contribute to the background level, it will require for the resultant sound level after treatment to be 10 dBA or more below the background.

At this point if our goal is to further reduce the background level below 90 dBA, or even 85 dBA, then it will require a continued effort to identify the remaining dominant noise source(s) and implementation of additional control measures.

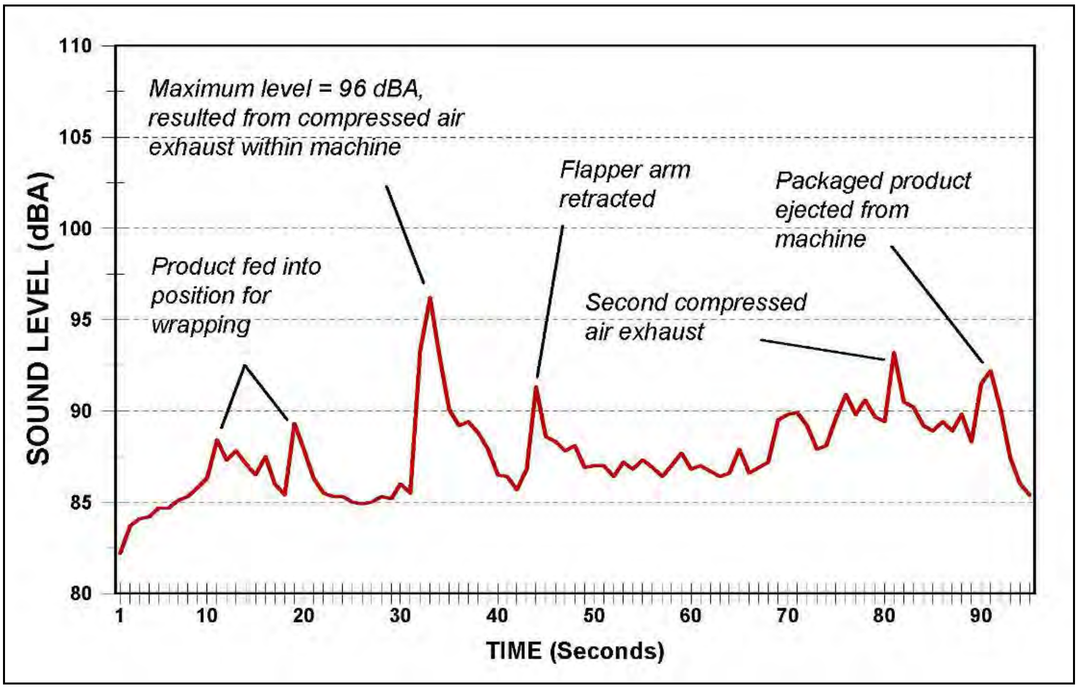


Figure 3.12 - Sound level versus time as measured over one full machine cycle at the workstation for packaging operator

When the sound level fluctuates, with cyclic equipment and/or production, it is useful to measure the overall A-weighted sound level versus time. With this procedure it is important to observe and document which events are occurring at specific times. Figure 3.12 exhibits the sound level measured at the operator's work station over one full machine cycle. Since we are interested in viewing the sound level as it is rapidly changing with time, employing the "fast" response setting and a one-second logging rate on the SLM is recommended.

Certainly, shorter logging rates may be used, but a one-second rate is usually sufficient. The process depicted in Figure 3.12 represents a product-wrapping machine, which has a cycle time of approximately 95 seconds. The maximum noise level of 96 dBA occurs during the release of compressed air, 33 seconds into the machine cycle.

The other important events are also labeled in the figure, which permits the identification of the sources and relative contribution of each activity during the full wrapping cycle.

In industrial settings where there are multiple process lines with the same equipment, it is useful to compare the frequency spectra for like equipment and processes to identify differences in sound level that may be easily remedied with effective maintenance or other adjustments. Figure 3.13 depicts this comparison for two similar process lines, both of which manufacture the same product and operate at the same speed. Part of the process involves the use of a pneumatically actuated device that punches a 1/2-inch hole in the product as a final phase in its production. Inspection of this figure reveals that Line #1 has an overall sound level 5-dBA higher than Line #2. In addition, the spectrum depicted for Line #1 contains what appears to be a fundamental frequency and some of its harmonics that do not appear in the spectrum for Process Line #2. Consequently, it is necessary to investigate the cause of these differences. Often significant differences will be an indication of the need for maintenance, as was the situation for the final punch mechanism of Process Line #1. However, once maintenance corrects this problem, additional noise control measures are still required (for both process lines), if the objective is to reduce the overall noise level significantly below 100 dBA.

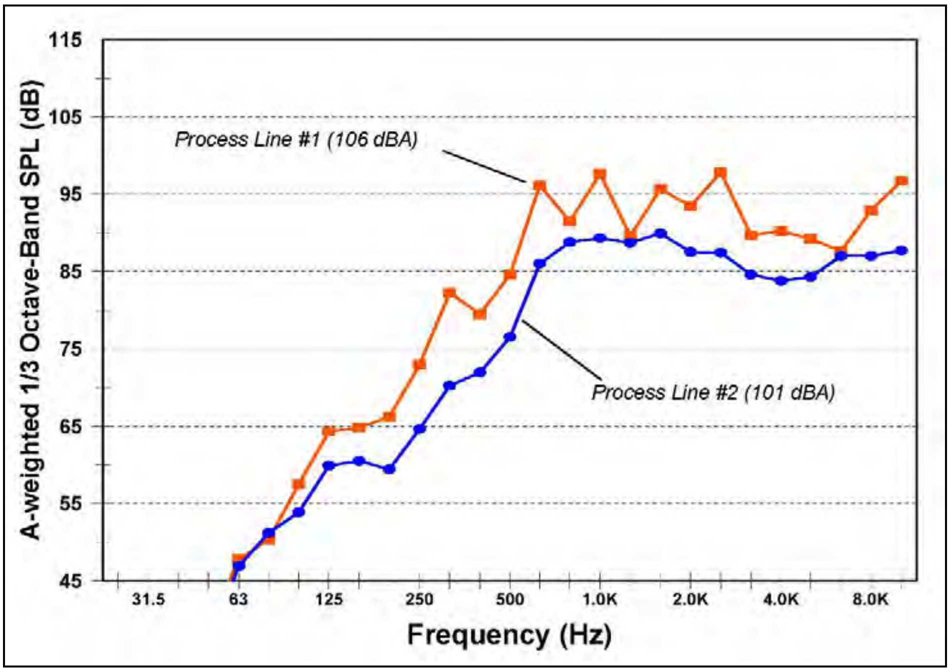


Figure 3.13 – Comparing sound levels of similar machines. Data herein are for the final punch operation for identical process lines operating at the same speed.

As mentioned above, an SLM typically provides a sound level that is comprised of acoustical energy from one or more sound sources. Under optimum measurement conditions, it would be best to measure each equipment item with all other equipment turned off. Although this situation is ideal, it is rarely practical. To work around this condition, it is often effective to use temporary control measures that will provide some short-term noise reduction to allow measurement of another source. Some materials that can provide a temporary reduction include plywood or corrugated-container (cardboard) enclosures, acoustical blankets, silencers, and barriers. Often permanent application of these materials will create long-term problems such as heat buildup, interference with the operator's access or product flow, or a costly pressure drop associated with improperly selected silencers. However, for assisting with the isolation of individual components, these materials can be effective as a short-term control.

When the opportunity is available, another method for isolating a particular machine or component is to turn on and off different equipment, or sections of a production line. To effectively conduct this type of diagnostic analysis the process must be capable of functioning with the item turned off. Also, for this procedure to be legitimate it is critical that the manufacturing process not be affected in any manner. If the process is affected, then it is entirely possible the measurement will not be representative of the sound level under normal conditions. All valid data may then be rank ordered by magnitude of each sound level, as one method to help prioritize sources for engineering noise control.

d) Reporting and Documentation

The noise control survey should be documented with a written narrative report, in a similar manner as the detailed survey previously described. 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 and serial number,
- Department, areas, equipment, and/or process units surveyed,
- Any unusual conditions which would impact results,
- All sound level data tables,
- All graphical comparisons of select spectral data,
- A rank-ordering of sound sources,
- Noise control recommendations, including selection of materials and/or noise control products.

- A list of potential noise control product companies that supply the selected acoustical products, and their local representatives, if available, and
- Conclusions.

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. 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 NIHL. In all workplaces a "*buy quiet*" approach should be adopted when purchasing new or when upgrading items of plant or equipment. A "buy quiet" policy is implemented by including noise limits in the specifications or preferentially purchasing the lower noise plant or equipment.

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,
- 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. Combining the knowledge of acoustics and risk assessment as described in Chapters 2 and 3 with an understanding of the manufacturing equipment and process, including all production and maintenance constraints, a comprehensive and cost effective noise control programme can be designed and implemented. Without an informed approach, the likelihood of success and the effective use of resources will be tenuous at best.

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. This chapter discusses many common noise sources, their acoustical characteristics, and presents design and/or selection considerations for noise control. 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.

Figure 4.1 - Totally-enclosed fan cooled electric motor

The most common industrial motor type is the totally-enclosed fan-cooled variety, as depicted in Figure 4.1. Noise within such motors is usually Aerodynamic, Mechanical or Magnetic

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.

However, 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.

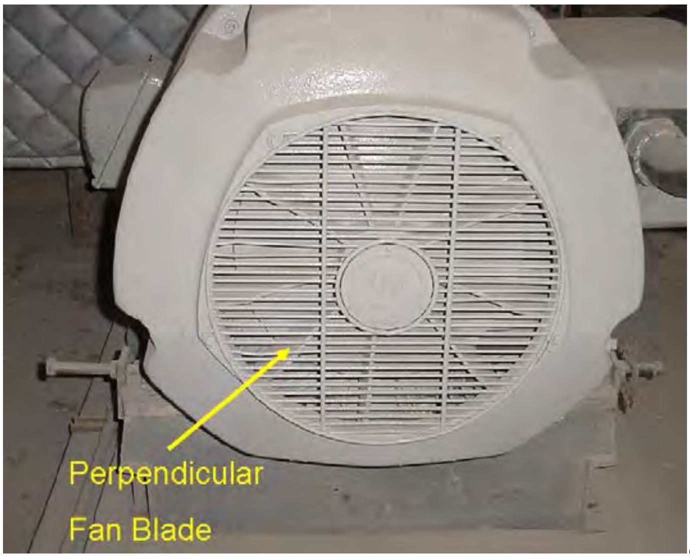


Figure 4.2 - Close up of motor fan, showing the perpendicular (non-directional) fan blades

Figure 4.2 depicts a non-directional fan, which shows the perpendicular fan blades attached to a base plate, also called a hub. From an operational standpoint, this fan works fairly well, except it simply generates excess air noise. Therefore, one prudent step buyers can make use of when purchasing electric motors is to specify a direction of rotation for the motor cooling fan, which will permit the supplier to provide a more aerodynamic fan. These fans only function in one direction of rotation, which permits the manufacturer to use more streamlined or aerodynamic blades or airfoils. From the author's experience, this form of noise control amounts to a noise reduction on the order of 4-6 dBA at a distance one meter from the motor fan.

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:

It is important to keep in mind all 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.

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.

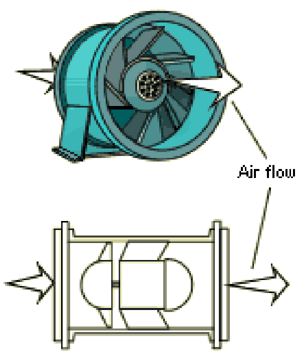


Figure 4.3 – Axial Fan

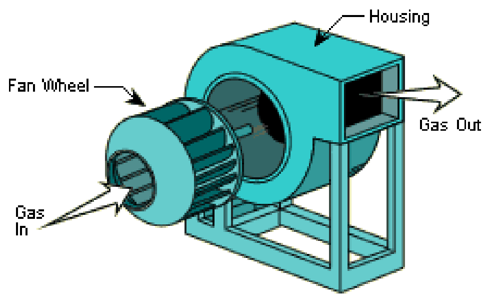
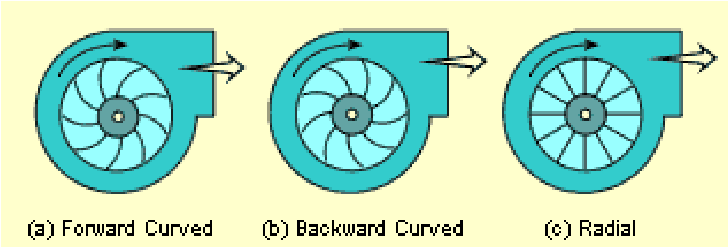


Figure 4.4 – Centrifugal Fan

Types of Industrial Fans:

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 4.3. Axial fans move air by creating a vortex type flow. A centrifugal fan, Figure 4.4, has a number of fan blades mounted around a hub, which moves air by centrifugal force.



(Source: U.S. Environmental Protection Agency)

Figure 4.5 - Various fan blade configurations for centrifugal fans

Controlling fan noise is best accomplished in the design stage. 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 Hearing, 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.

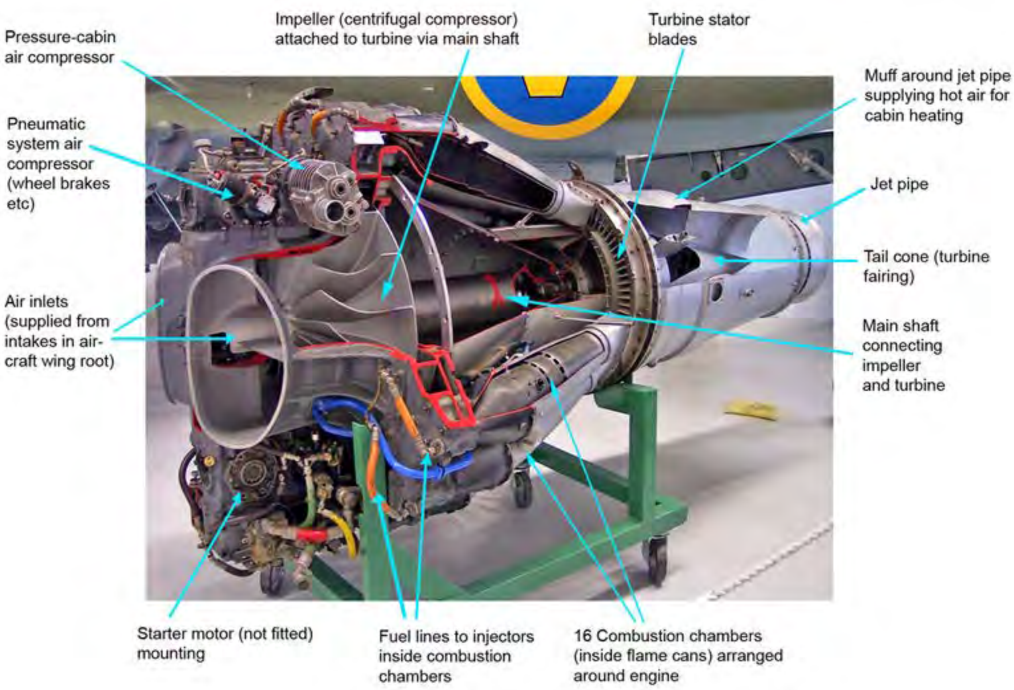
5. Use vibration isolation mounts or hangers, with auxiliary bases, if required, for all fans over 1 hp located near noise-sensitive areas (such as offices, conference rooms, etc.).
6. Attach ductwork to fans with an elastomeric flexible connector.
7. Inlet and discharge transitions should be gradual. 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 takeoff 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

Types of Compressors:

Compressors and pumps can be sources of high-velocity fluid or gas flow noise. Within industry there are two primary types of compressors commonly used: dynamic and positive displacement. The dynamic compressors include centrifugal and axial flow types. Positive displacement types include reciprocating and rotary compressors.



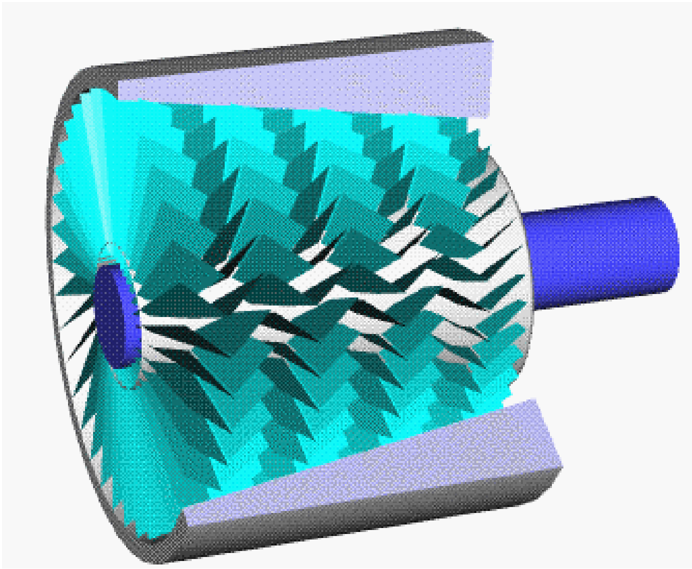
(Source: *DH Goblin with permission*)

Figure 4.6 - Cutaway view of a jet engine, which is a type of centrifugal compressor

Sources of Compressor Noise and Considerations for Control:

A centrifugal compressor, as exhibited by the cutaway diagram shown in Figure 4.6, generates noise due to the interaction between air movement over rotating and stationary vanes within the compressor. This action generates tones at the blade pass frequency and its harmonics. Usually, the compressor casing is substantial enough to attenuation this noise; however, acoustical energy is also propagated into the connected piping system, which can radiate high noise through the pipe wall. 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 insulation.

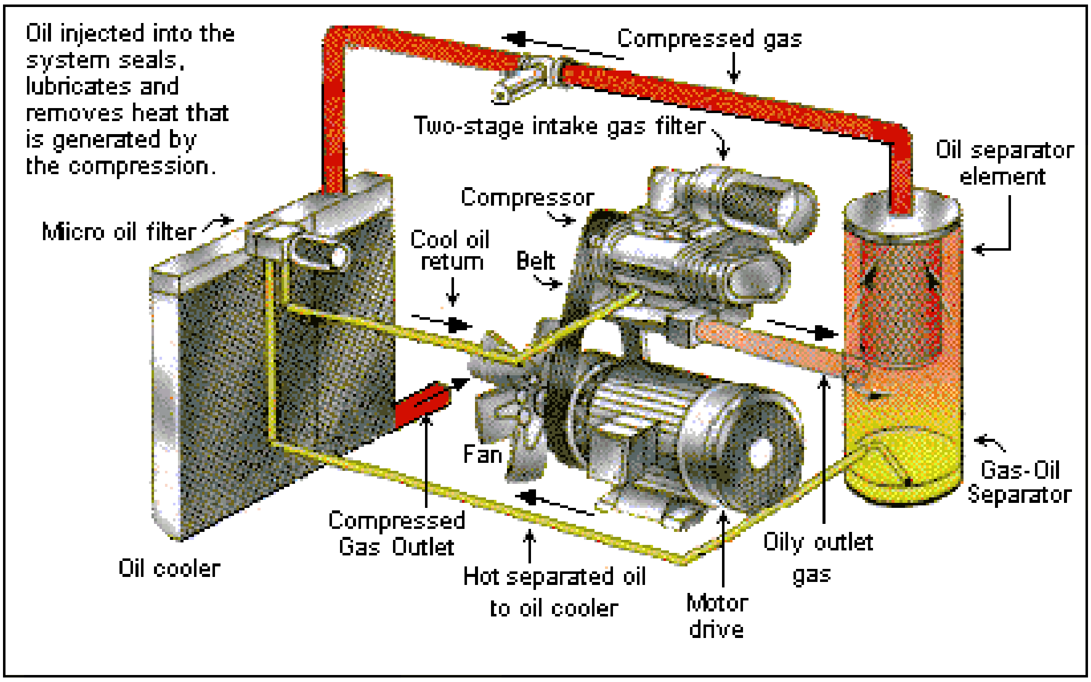
Axial flow compressors use rotating blades to incrementally compress gas, typically through multiple stages, as shown in Figure 4.7. These compressors are used principally in high-flow application, such as gas turbine engines. As with centrifugal units, axial flow compressors produce noise via the connected piping system.



(Source: U.S. National Aeronautics and Space Administration (NASA) – *Used with permission)*

Figure 4.7- Cutaway view of an axial compressor

Rotary screw compressors, as illustrated in Figure 4.8, use helical screws to compress gas flow. This type is usually the loudest, generating strong tones at the lobe meshing frequency and it harmonics. Both in-line silencers and acoustical insulation are required to effectively attenuate their acoustical output.



(Source: U.S. Federal Energy Management Program - *Used with permission*)

Figure 4.8 - Rotary screw compressor system

Reciprocating compressors use pistons attached to a crankshaft to compress gas within individual cylinders. Noise from these units tends to be primarily high frequency without any obvious tonal components. In addition, secondary noise sources include piston and bearing impacts. Overall, reciprocating compressors are typically the quietest of all variety of compressors. These units are commonly used in refrigeration plants, oil refineries, chemical and petrochemical plants, gas pipelines, and natural gas processing plants.

4.5 PUMPS

Pumps are very similar to compressors in that they pressurize and move liquids or gases. Pumps are classified into two major categories: rotodynamic pumps and positive displacement pumps. Rotodynamic pumps are based on bladed impellers that rotate within the fluid to impart a tangential acceleration to the fluid and a consequent increase in the energy of the fluid. 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. Later sections present a series of modifications or design consideration to minimize high-velocity fluid or gas flow in pipes. 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.

Because of the relatively small size of hydraulic pumps, they tend not to be sources of noise generation. Plus, quiet-design hydraulic pumps are readily available from manufacturers, and should always be specified when purchasing a unit. However, the coupling between the pump and motor can generate tonal noise equivalent to the coupling rotational speed. The coupling frequency (in Hz) is simply the shaft rotation speed (in rpm) divided by 60. The pumping frequency is equivalent to the shaft rotation speed times the number of pumping elements (vanes, pistons, gear teeth, etc.) divided by 60. These tonal components are minimized through proper selection of the pump operating parameters, careful installation, and proper equipment maintenance.

The pump will produce some degree of ripple or pulsation in the hydraulic fluid. Improper use of hydraulic hose can be the most dominant noise source associated with the system. These pulsations can cause hydraulic lines and other machine components to vibrate and radiate airborne noise. It is common to use a 90º bend in the hose when connecting a horizontal line to a vertical line. Also, an 180º bend in a hose is universal. Research by one hydraulic systems manufacturer shows these two configurations can raise the noise level by 5 dBA. Figure 4.9 illustrates hydraulic line configurations for short and long runs, as well as the resultant noise condition. Therefore, proper installation of these lines is critical.

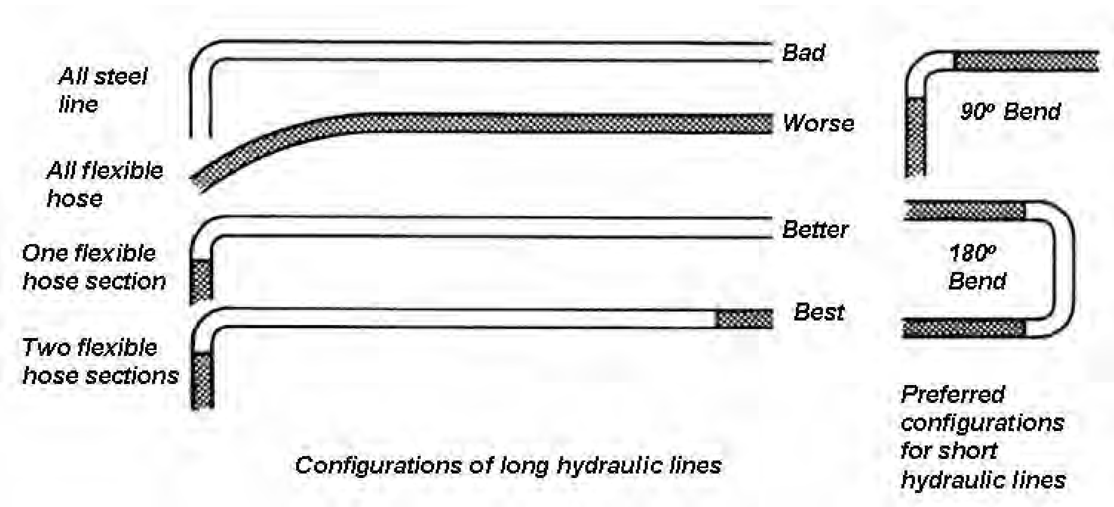


Figure 4.9 - Hydraulic line configurations and their resultant noise conditions

Hydraulic cylinders are mechanical actuators used to exert a linear force through a linear stroke. Hydraulic cylinders are able to give pushing and pulling forces up to millions of metric tons, with only a simple hydraulic system. Noise can result when these cylinders are not maintained properly, improperly isolated, or allowed to be overdriven. Good installation and maintenance practices are required to minimize these noise effects.

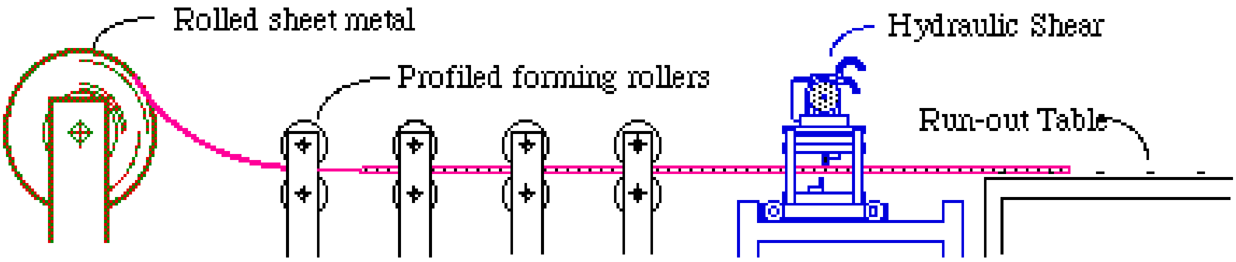
4.7 MECHANICAL IMPACTS

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. For example, air valves are often used to move a mechanical part, such as a push-rod or ram used to insert product into a carton, or cartons into a case pack. Each time the air valve is employed the push-rod extends and retracts, which in turn causes a structural impact at both ends of its stroke. The more the driving force or harder the impact, the more noise is generated.

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.

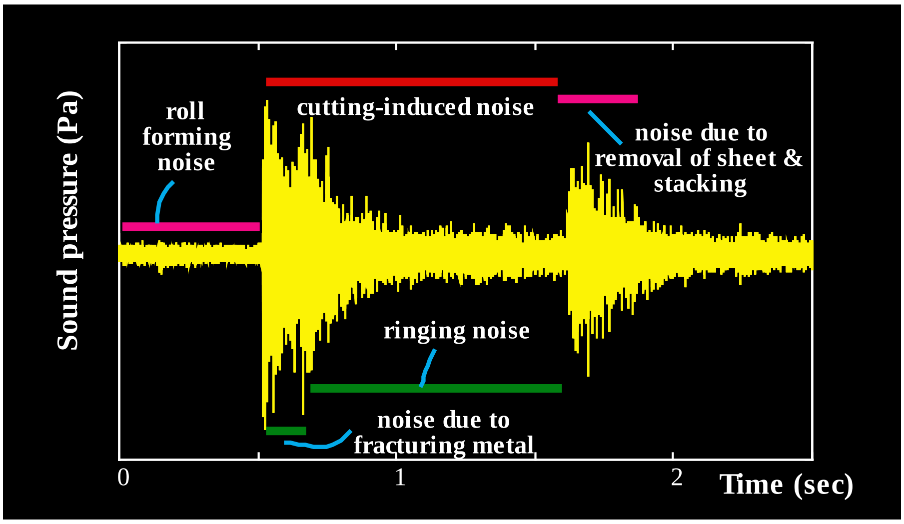
4.8 PANEL OR STRUCTURE RADIATED NOISE

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.



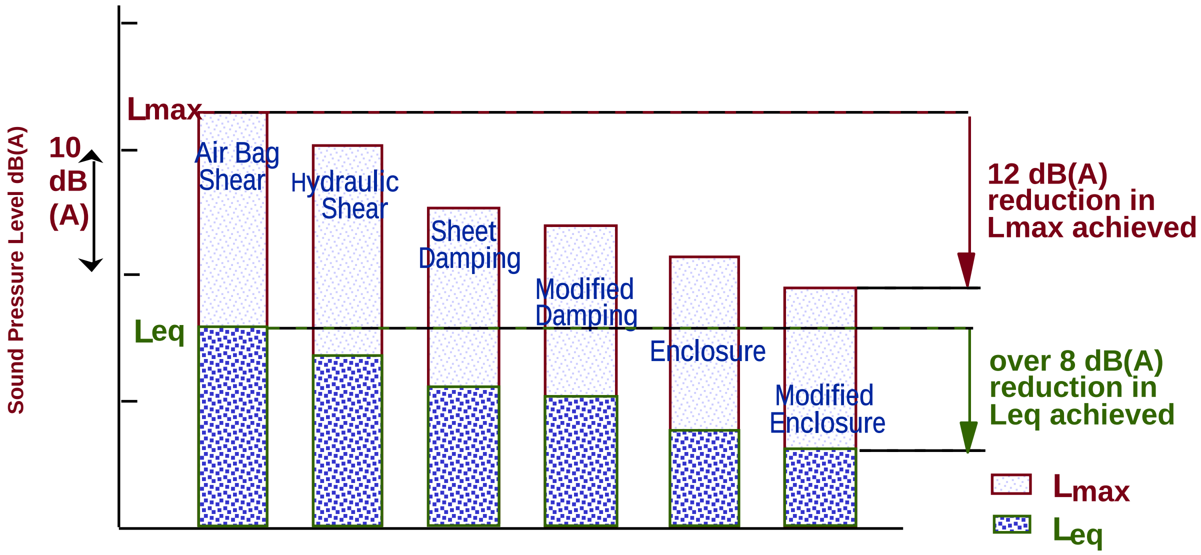
(Source: UNSW at ADFA)

Figure 4.10 – Roll former shear



(Source: UNSW at ADFA)

Figure 4.11 – Noise due to cutting induced noise



(Source: UNSW at ADFA)

Figure 4.12 – Noise reduction on roll former shear

Figure 4.12, example of noise reduction from a roll former shear, where much of the noise was radiated from the cut panel after the impact of the shear. First the type of shear was changed, then improvement was achieved by applying damping to the sheet immediately after the shear. The last step was to install an enclosure which, even though it was carefully designed it only provided limited noise reduction as there needed to be openings for the product entry and exit..

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.

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 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.

For example, many manufacturing plants use case packers or case loaders to insert finished product into corrugated containers for shipping. To examine the effect of impact noise generated by this type, and similar indexing equipment, consider the following case history. At a paint manufacturing facility, the case loader equipment uses a push bar to insert finished cans of product into cardboard or corrugated cases. The push bar is contained in a hollow cylindrical housing positioned perpendicular to the conveyor line, and as each can reaches a set point along the conveyor, the push bar extends and inserts the can into a case on the opposite side of the conveyor. A pneumatic or compressed air cylinder is used to motivate the push bar in both directions (extension and retraction). During the noise survey an average level or L_{Aeq} of 94 dBA was measured over a full duty cycle of the push bar. Close observation of the process revealed the loudest event occurred at the moment the push bar reached full extension, where a heavy impact occurred at the end of its stroke. Figure 4.13 exhibits the effect of the impact force (see the “Overall level before adjustment”). This impact creates not only unnecessarily high noise levels, but also causes excessive wear and tear on the equipment. Therefore, to control the impact noise the following options are recommended:

Option 1: Optimize the Pressure Setting:

Adjust the air cylinder for the push bar to its minimally acceptable pressure setting needed to effectively perform the task. This setting should be documented and maintained over time. In addition, quite often employees may unnecessarily increase the equipment settings without understanding the associated side effects such as an increased noise level. Therefore, the employee education and training component of the hearing conservation programme needs to include a discussion about the noise control programme.

specific information such as the required equipment settings, including those of compressed air systems, the need to limit noise exposure, and a candid explanation as to why employee cooperation is needed to maintain all optimum settings, which are critical toward the success of all noise controls over time. Note – Figure 4.13 shows the “Overall level after adjustment,” which resulted in a 9 dBA reduction.

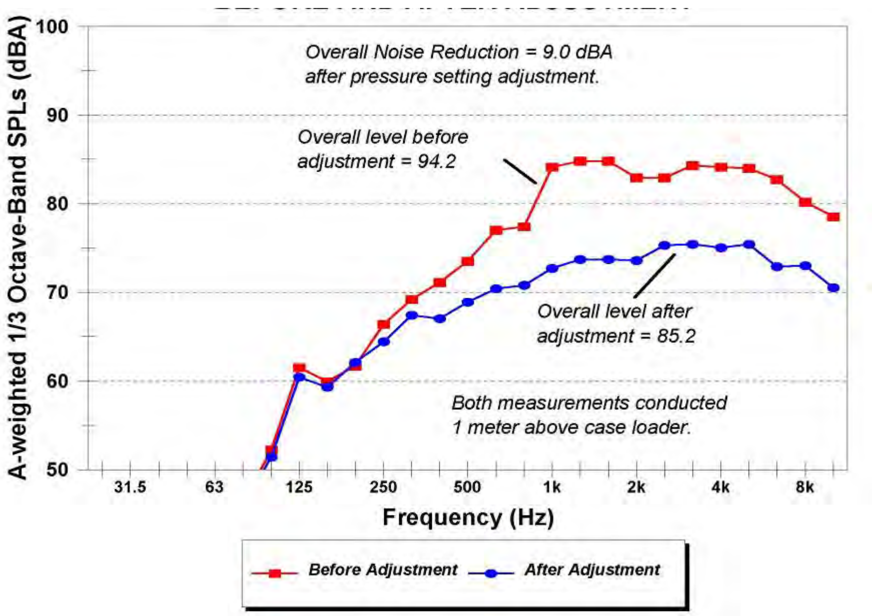


Figure 4.13 - Case loader noise levels before and after adjustment

Option 2: Cushion the Stops or Impact Points:

Should Option 1 not provide the desired effect, or be deemed impractical, then another option for equipment motivated by air cylinders or solenoid values would be to cushion the impact points with a durable neoprene, polyurethane, or rubber pad or cushion. Generally, a material having a shore-hardness on the order of 40-50 is sufficient. However, it is advisable to verify this step with the equipment manufacturer or their designated representative to ensure the device will function as intended. Note – at times the actual impact noise is generated within the air cylinder or valve, and here it is necessary to insert the cushioned stops within the device.

Another common impact noise arises from parts or product material falling onto conveyor chutes, in vibratory feed bowls, hopper bins, etc. The associated noise level will depend upon the potential energy prior to the event. For example, parts dropping 10-20cm above a vibratory feed bowl, which is typically a metal surface, will have more potential energy and a higher impact noise than the same parts dropped a few centimetres above the surface. Therefore, it is important to look for ways to reduce or minimize the potential energy and free-fall height of objects. Consider the example shown in Figure 4.14.

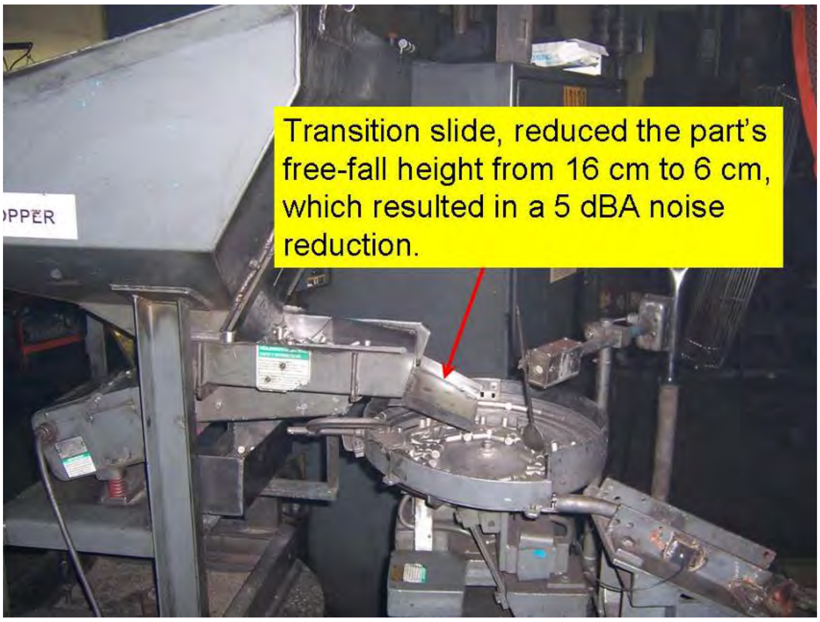


Figure 4.14 – Reduce potential energy by adding a slide transition from feed hopper into vibratory bowl

In this case history, metal ingots are delivered from a hopper via a gravity feed trough into a lower vibratory bowl, which in turn vibrates to orient and deliver parts to the next process station. The initial setup had a 16cm drop between the feed trough and the top of the bowl. The noise level at impact was approximately 93 dBA. To minimize the free-fall height, and potential energy, a transition slide was added to reduce the drop height to 6cm. This step reduced the impact noise by 5 dBA, with the resultant noise level on the order of 88 dBA. Bottom line – always look for ways to reduce the potential energy between impacting parts or components of machines and products.

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. The case history described above for the paint can case loader is a prime example as to how these air cylinders are used to actuate or move components within a machine, except the source of noise there was due to push bar impacts. 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.

The high noise levels are generated as the high-velocity compressed air is mixed with the relatively still atmospheric air causing excessive turbulence. The most dramatic noise level occurs whenever compressed air encounters a sharp object, such as an edge of the machine's casing or the product itself. It is important to note the intensity of sound is proportional to the 8th power of the velocity of air flow (Lord et al., 1980). Consequently, the first step in controlling compressed air noise is to reduce the air velocity to as low a value as practical. This adjustment can result in noise reductions on the order of 5-20 dB. For example, consider the data exhibited in Figure 4.15 that was measured at a machine which forms the tapered necks on aluminium cans. This equipment utilized a compressed air line to load or move cans into position. The initial setting of the air regulator was 55 pounds per square-inch gauge (psig), which was desired by the equipment operator, and resulted in an overall noise level of approximately 122 dBA one foot from the source. By throttling down the air pressure to 30 psig, the sound level dropped to 111 dBA at the same measurement location. Finally, the air pressure was set to 20 psig, which was recommended by the equipment manufacturer, and the noise level decreased to 103 dBA.

Simply by re-setting the air pressure to the manufacturer's specification of 20 psig the initial sound level was reduced by 19 dBA and the equipment still functioned properly. This control measure did not cost anything; in fact, there was an energy savings in the company's cost for producing compressed air. Granted 103 dBA is still excessively high, but it is a dramatic improvement over the original condition. As previously mentioned in the case loader case history, it is vital to educate and train all machine operators and maintenance personnel on the need to run their equipment at the optimum settings needed for production. It is common for an operator to unnecessarily increase the air pressure in an attempt to deliver more power, when in fact this higher pressure setting likely does not increase production, but almost always generates a significantly higher noise level.

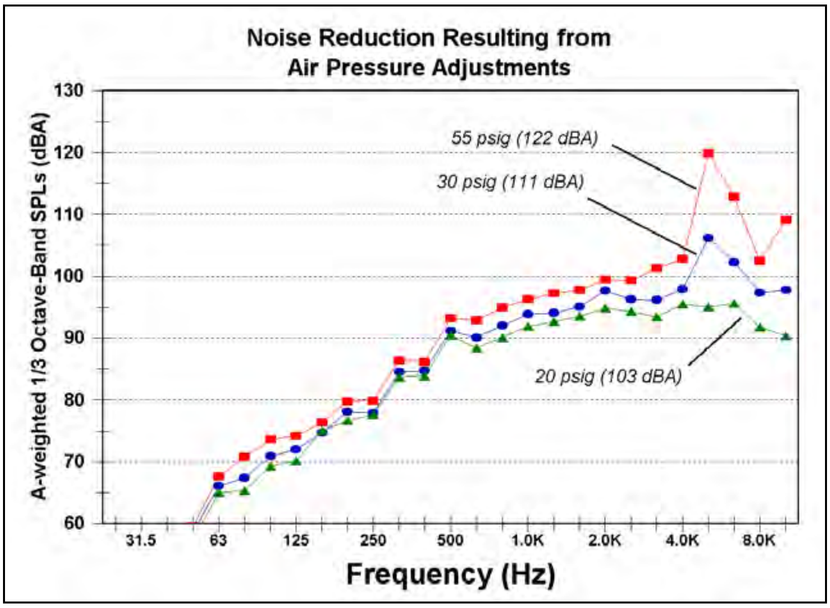


Figure 4.15 - Necker can infeed with air pressure set to 55, 30, and 20 psig. A difference in sound level of 19 dBA exists between the high and low pressure setting.

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. When deemed practical, some effective modifications for high-velocity fluid or gas flow noise include:

- Locate control valves in straight runs of pipe,
- Locate all L's and T's at least 10 pipe diameters downstream of a valve,
- Ensure all pipe cross section reducers and expanders are at an included angle of 15-20 degrees,
- When choke valves are used in the line, turbulent mixing of the medium will almost always exist and create excessive noise, which will propagate over long distances of pipe length downstream of the valve. In other cases, acoustical insulation and/or an in-line silencer are the only available noise control options.
- Eliminate sudden changes of direction and influx of one stream into another,
- Limit the fluid-flow velocity to a maximum of 9.15 metres per second (30 feet per second) for liquids,
- To help ensure noise levels will be less than 85 dBA due to flow or velocity of the medium being transported through a pipe, the following rule of thumb is useful:
- Design the system such that the flow velocity (in feet/seconds) does not exceed 100 times the square root of the specific volume (in cubic feet/lb.) for gases and vapours.
- Maintain laminar flow for liquids (keep the Reynolds Number less than 1,200)
- When vibratory energy is transferred to the pipe wall, use flex connectors and/or vibration isolation for the piping system, and/or acoustical insulation, and

- When excessive noise in the fluid can not be controlled by any of the options above, then installation of an in-line silencer is needed.

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 1/4th 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. For consideration, the following noise control measures should be explored:

- Use vibration isolation at the machine mountings
- Divide vibrating surface areas into smaller sections,
- Add stiffeners to large unsupported metal panels, such as rectangular ducts or large machine casing sections,
- Add small openings or perforations in large solid surfaces,
- Use expanded metal, when practical, in place of thin metal panels, and/or
- Add vibration damping material to panels.

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. In addition, damping materials have two properties that affect the amount of noise reduction achieved when the material is applied to a surface: the material loss factor, η_m, and dynamic modulus, E' (Renninger, 1988; Ungar, 1988; Ungar and Sturz, 1991; Rao, 1995). The material's loss factor is a measure of how efficiently a product dissipates the energy stored in it and the material's dynamic modulus is a measure of the material's stiffness that comes into play when trying to predict the damping material's effectiveness when applied to a surface.

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 can not 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. Each treatment option is described below.

a) Sound Fields

It is important to understand and recognize how sound behaves as it propagates from a source before determining the most effective way to treat the sound transmission path. Consider the illustration shown in Figure 4.16. As sound waves spread outward from a source (plotted as log *r*) they pass through two regions, known as the *free field* and *reverberant field*. In the free field, also termed the direct field, sound travels in a direct line without any interruptions or reflections. Conversely, in the reverberant field sound waves reflect off various surfaces and add to the direct field sound waves causing an increase in the sound level. The boundary between the direct field and reverberant field varies as a function of frequency and according to the absorption properties of the different surfaces encountered. Therefore, the *transition zone* between the two sound fields does not occur at a fixed location or distance from the source.

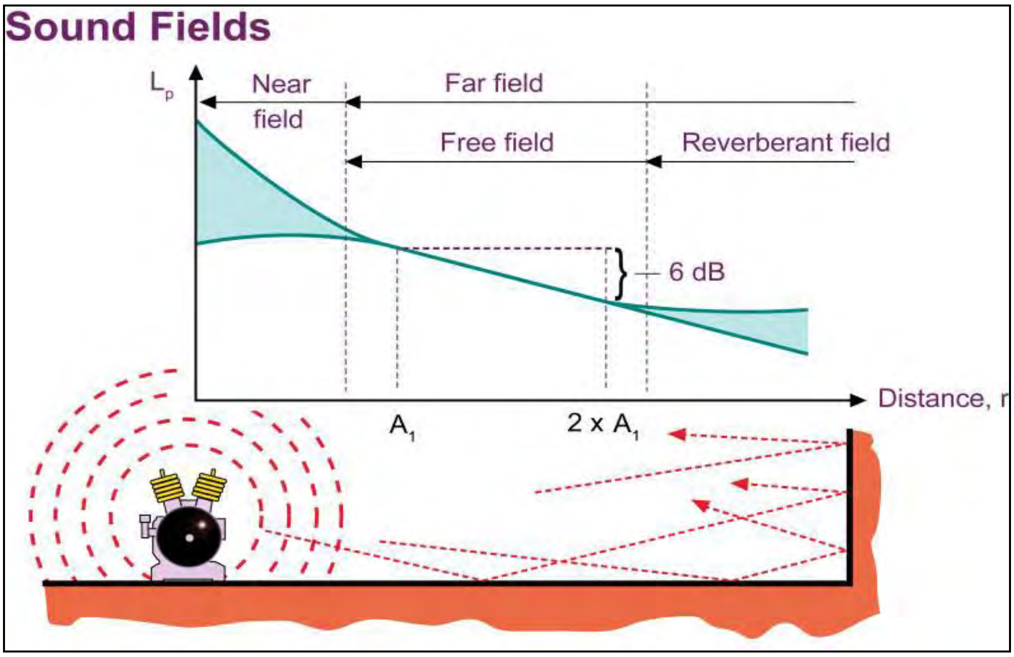


Figure 4.16 - Variation in SPL in an enclosed space with increasing distance from source

In the near field SPLs will noticeably fluctuate with measurement position. As a rule of thumb, the near field typically extends out from the source up to a distance equal to one or two characteristic source lengths (Lord et al., 1980). Next, to minimize the affect of the near field, sound level measurements should be conducted at least one wavelength from the source at the primary frequencies of concern. For example the wavelength at 1,000 Hz is approximately 0.3 metres so it is important to keep in mind that due to non-uniform sound wave fluctuations, the near-field data may not be used to accurately estimate or predict SPLs in the far field.

Further from the source in the free field the sound propagates as if coming from a single source. Measurements taken outdoors with no reflecting surfaces will display in theory, a 6-dB decrease in SPL for every doubling of the distance from the noise source in the far-field measurement region (free-field condition). In practice and in rooms due to the non ideal nature of the sound fields the decrease is usually less. But after a certain distance there will be a plateau in sound level characterized by sound reflections in the reverberant field. This effect is shown by the shaded region in the right-hand side of Figure 4.16.

When the sound wave reaches a solid surface some sound energy is reflected, some absorbed and some transmitted, as illustrated in Figure 4.17.

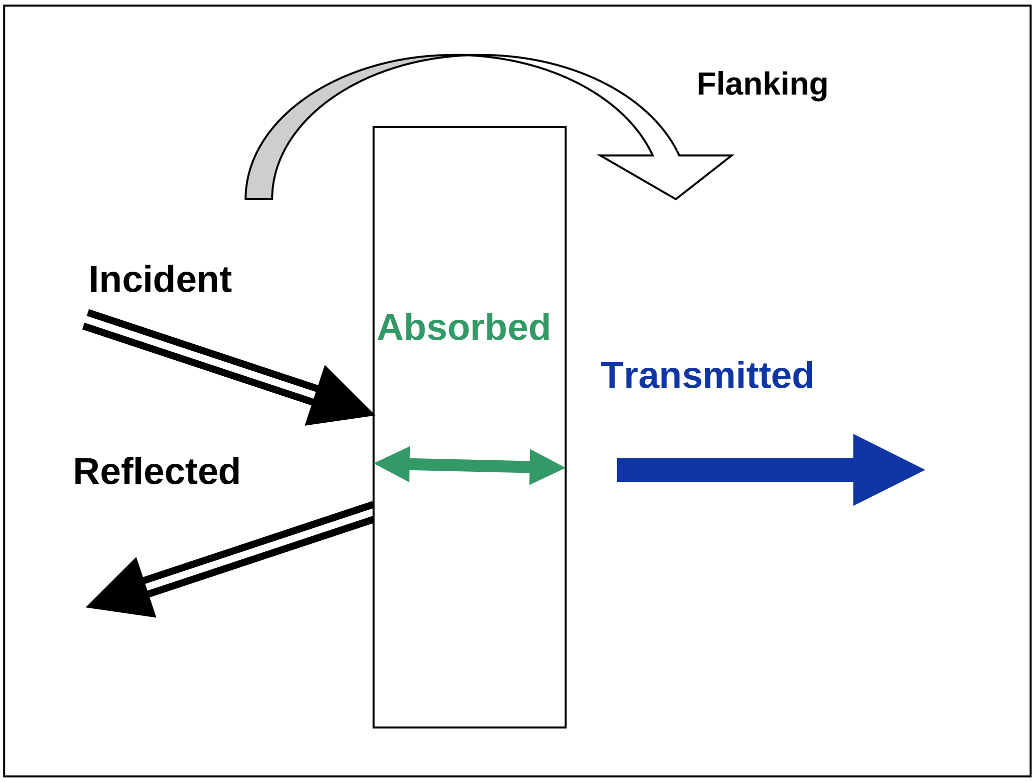


Figure 4.17 - Sketch showing the different components of sound wave interaction with a solid surface

b) Sound Absorption Materials

Sound absorption materials can be used to reduce the buildup 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:

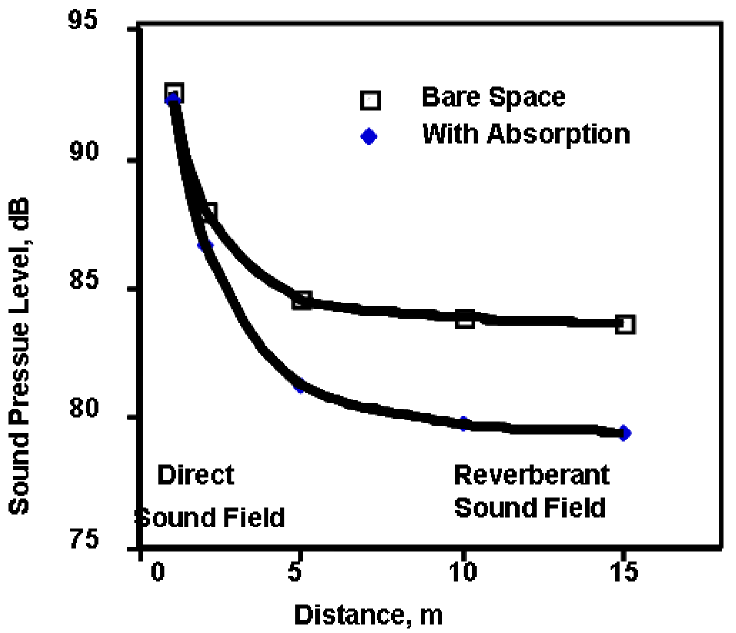
Advantages:

- Can provide a reduction (up to 3 dB) in the reverberant sound build-up, especially in pre-existing hard spaces,
- Works best in relatively small volume rooms or spaces (less than 300 m^3),
- Can be purchased and installed at a reasonable cost, and
- Works best on middle-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 eliminate the need for hearing protection.

Figure 4.18 is an example of the effect of sound absorption in a large room as the distance from the source is increased.



(Source: M Burgess)

Figure 4.18 - Example of the effect of sound absorption on the sound pressure level in a large room as the distance from the source is increased

c) Sound Transmission Loss Materials

Sound transmission loss 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 poor sound transmission properties. Common applications include enclosure panels, windows, doors, and building materials for room construction.

The transmission coefficient, τ, is defined as the ratio of the sound energy transmitted through a wall unit area to the sound energy incident on the wall. Just like the absorption coefficient, the transmission coefficient is dependent on frequency. Generally, most materials transmit low-frequency sound more efficiently than high-frequency sound, so the transmission coefficient is smaller for low-frequency sound. A more useful measure of a panel's ability to attenuate sound is given by the transmission loss (TL) of a partition.

It is important to note that the sound transmission loss performance only applies when the construction is a complete partition, ie sealed to the surroundings all around the perimeter.

Single-number ratings are often utilized as a specification for acoustical performance of a partition or wall, and are commonly used by engineers or architects when selecting materials for reducing sound transmission between two areas or rooms.
There are two common methods for providing a single-number rating of sound transmission loss.

- ISO 717, Acoustics Ratings of Sound Insulation in Buildings and of Building Elements, or regional or national variants on this standard define the Weighted Sound Reduction Index (R_w).
- ASTM 90, Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions, define the Sound Transmission Class (STC). Both methods produce comparable, but not identical results.

Essentially, the test panel is placed in an opening in a wall separating two adjacent reverberant rooms. A random noise generator is used to introduce a high-volume sound in one room, which results in a portion of the sound energy being transmitted through the test panel into the second (receiving) room.

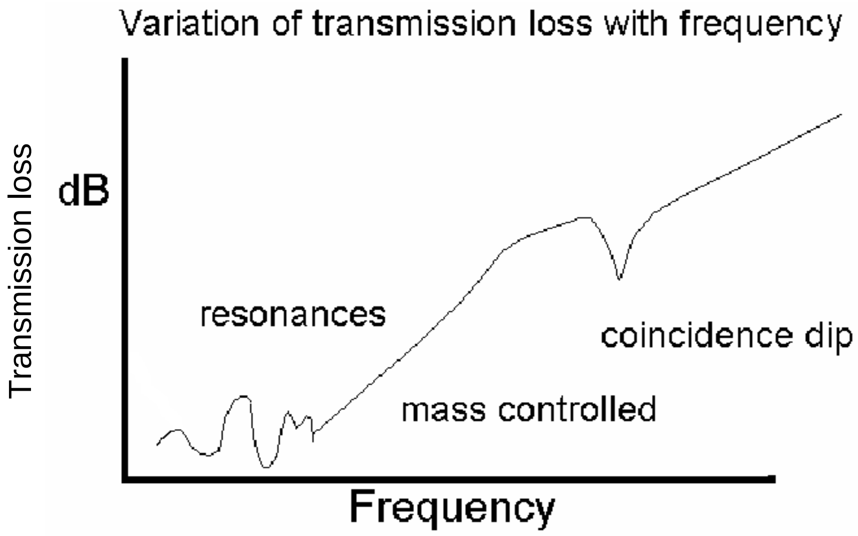
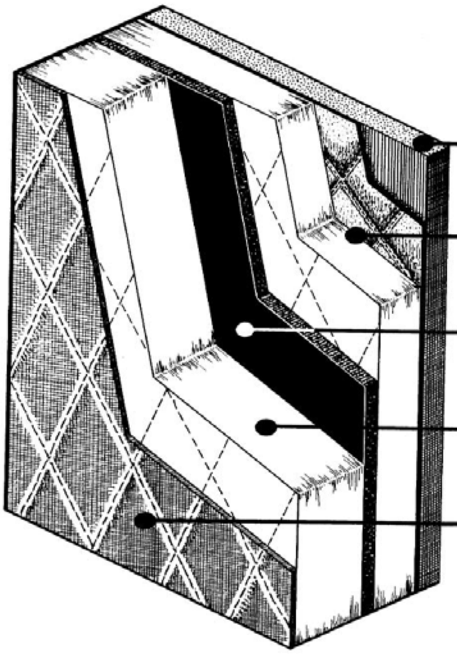


Figure 4.19 - Example of typical variation of sound transmission loss with frequency for a single leaf panel

d) 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.

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

There will likely be times when the TL, R_w, or STC rating of partitions may not provide sufficient sound attenuation for many industrial applications. A higher acoustical performance for a partition can be achieved using a combination of materials in a “sandwich” arrangement, which is called a composite system. Most of the commercially available enclosure panels or partition walls employ composite systems to increase the TL and overall acoustical performance.

e) Doors, Windows and Inspection Panels in Acoustic Walls

There will often be times when it is necessary to install a door and/or windows in an enclosure wall. To achieve the same TL of the original panel, it is necessary to select door and window systems having at least the same TL as the panel. However, this is often difficult to achieve and TL values over the overall wall with the openable elements will be less than the original wall. Figure 4.21 may be used to estimate the new TL of the combined structure.

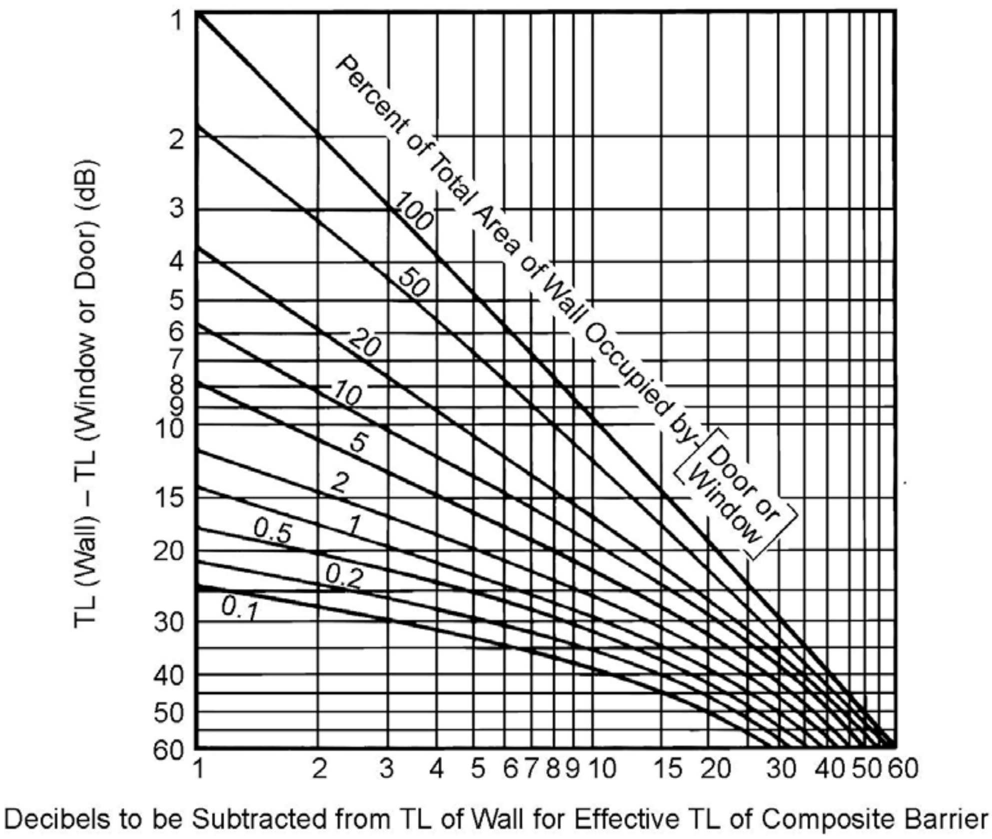


Figure 4.21 - Composite transmission loss of walls with windows and/doors

Using this chart the effect on the overall TL of adding a component with a low TL to a wall that has a high TL can be found as shown in Figure 4.22. Even just a small area of window with the lower TL of 20 reduces the overall TL of the wall from 50 to 29 dB. Doubling, tripling etc the area of low TL window only makes further small reductions in the overall TL. The important message here is that it only takes very small areas of wall with a lower TL to have a great effect on the noise reduction properties of an enclosure wall.

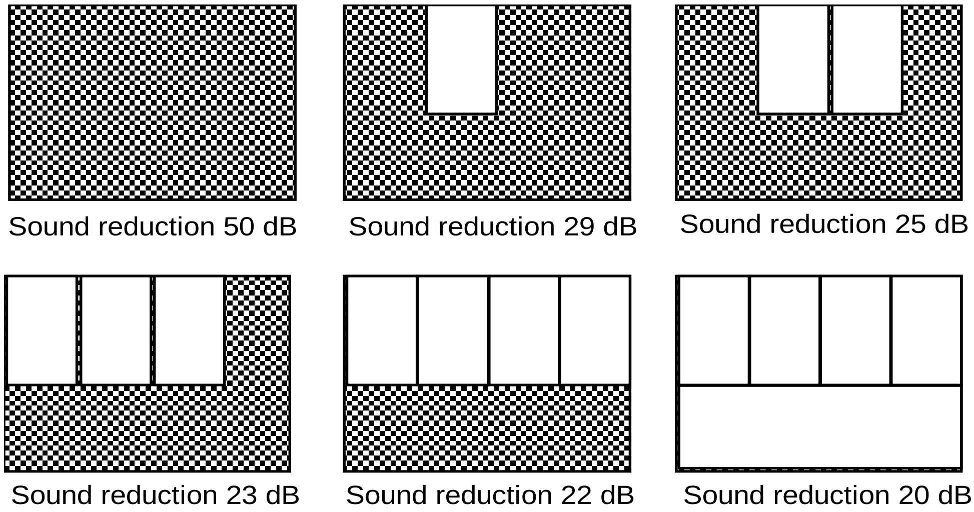


Figure 4.22 - Effect of increasing window size on TL

Example - Determining the Composite Transmission Loss of an Enclosure Wall with a Window.

A window is inserted into an enclosure wall. The TLs of the wall and window are 33 dB and 18 dB, respectively. The window occupies 10% of the total surface area of the wall. What is the composite TL?

Step 1. Determine the difference between the TLs of the wall and window.

TL (wall) - TL (window) = 33 - 18 = 15 dB

Step 2. Use Figure and locate 15 dB along the vertical axis.

Step 3. Draw a horizontal line until it intersects with the 10% total area occupied curve.

Step 4. Extend a vertical line down until it meets the horizontal axis, which is at a point slightly above 6 dB.

Step 5. Subtract the approximate 6 dB resultant from the TL of the wall to obtain the effective TL of the composite wall.

TL (composite wall) = TL (wall) - 6 dB = 33 - 6 = 27 dB

f) 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.

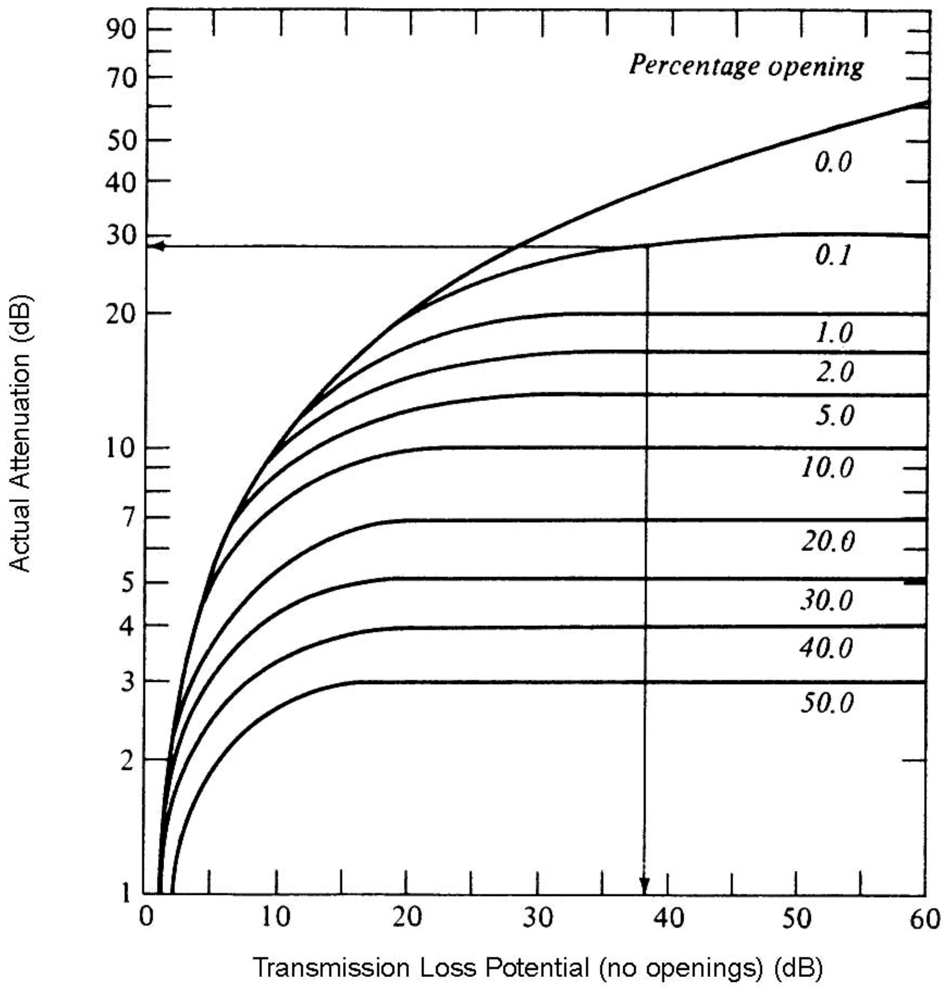
The pros of enclosures are as follows:

- 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.



(Source: The Noise Manual, 5th Edition, AIHA Press)

Figure 4.23 - Effects of openings on the potential transmission loss of panels

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. To account for various openings in an enclosure panel, Figure 4.23 can be used to estimate the actual TL. For example, in Figure 4.23 if a wall section has a rated TL of 38 dB, and an opening on the order of 0.1 percent of the surface area of the wall exists, the actual TL of the wall will be 28 dB. There is a 10-dB loss in potential TL due to this relatively small opening. Therefore, to maintain the acoustical integrity of an enclosure, it is critical to seal all cracks, gaps, and penetrations. When it is necessary to have openings to permit product flow, it is desirable to install an acoustically lined tunnel or chute over items such as the conveyors. This will decrease the reduction in enclosure TL due to these openings.

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.

Guidelines for Building Acoustical Enclosures:

1. *Enclosure Dimensions:* There are no critical guidelines for the size or dimensions of an enclosure. The best rule to follow is bigger is better. It is critical that sufficient clearance be provided between the noise source and enclosure panels to permit the equipment to perform all intended movement without contacting the enclosure and to allow for efficient ventilation, lighting, maintenance, etc.

2. *Enclosure Panels:* The insertion loss or attenuation provided by an enclosure is dependent upon the materials used in the construction of the panels and how tightly the enclosure is sealed.

3. *Seals:* For maximum insertion loss all enclosure wall joints should be tight-fitting. Openings around pipe penetrations, electrical wiring, etc., should be sealed with flexible and non-hardening mastic such as silicon caulk. It is critical to keep in mind small openings in enclosures can significantly degrade the acoustical performance. One of the most important people around during the construction or installation of an enclosure is the individual with a caulking or sealant gun.

4. *Internal Absorption:* To absorb and dissipate acoustical energy the internal surface area of the enclosure should be lined with sound absorbing materials. The manufacturer's published absorption data provide the basis for matching the material thickness and the absorption coefficients at each frequency to the source frequencies with the highest SPLs. The product vendor or manufacturer can also assist with selection of the most effective material.

5. *Protection of Absorption Material:* To prevent the absorptive material from getting contaminated, a splash barrier should be applied over the absorptive lining. This should be of a very light material, such as one-mil plastic film. The absorptive layer can be retained if necessary with expanded metal, perforated sheet metal, hardware cloth or wire mesh. However, the retaining material must have at least 25 percent open area.

6. *Enclosure Isolation:* It is important the enclosure structure be separated or isolated from the equipment to ensure mechanical vibrations are not transmitted to the enclosure panels or any surrounding surfaces, which can re-radiate noise. When parts of the machine do come in contact with the enclosure, it is important to include vibration isolation at the point of contact to minimize any potential transmission path. If the floor vibrates due to motion or movement of the machine, then vibration isolation should be used under the machine.

7. *Product Flow:* As with most production equipment, there will be a need to move product into and out of the enclosure. The use of acoustically lined channels or tunnels, can help minimize the loss in attenuation due to the opening. As a rule of thumb, it is recommended the length of all passageways be at least two times longer than the inside width of the largest dimension of the tunnel or channel opening.

8. *Worker Access:* Doors and windows may be installed to provide physical and visual access to the equipment. It is recommended ideas regarding the location and size of all doors and windows be solicited from machine operators, which not only makes the design more practical, but also improves the likelihood employees will accept the enclosure system. It is important all windows have nearly the same transmission loss properties as the enclosure walls. All access doors should tightly seal around all edges. To prevent operation of the equipment with the doors open, it is recommended an interlocking system be included that permits operation only when the doors are fully closed. To facilitate access some industries support enclosures on hydraulic lifts that can quickly move the enclosure out of the way.

9. *Ventilation of Enclosure:* In many enclosure applications, there will be excessive heat build-up. To pass cooling air through the enclosure, a quiet blower with sufficient air movement capability should be installed on the outlet or discharge duct. Finally, the intake and discharge ducts should be lined with absorptive material.

10. *Fire Prevention:* Keep in mind that although most sound-absorbing materials are listed as fire resistant, fires can and have occurred when sparks and/or excessive internal heat ignites dust, oil mist, etc., that accumulates on the surfaces of the material. In addition, potentially harmful gas may be released by the burning material, depending on its chemical composition.

Therefore, if fire is a potential problem for your equipment and enclosure application, it is recommended an internal fire prevention or suppression system be installed, as is often dictated by local fire codes.

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. Consider the following case history:

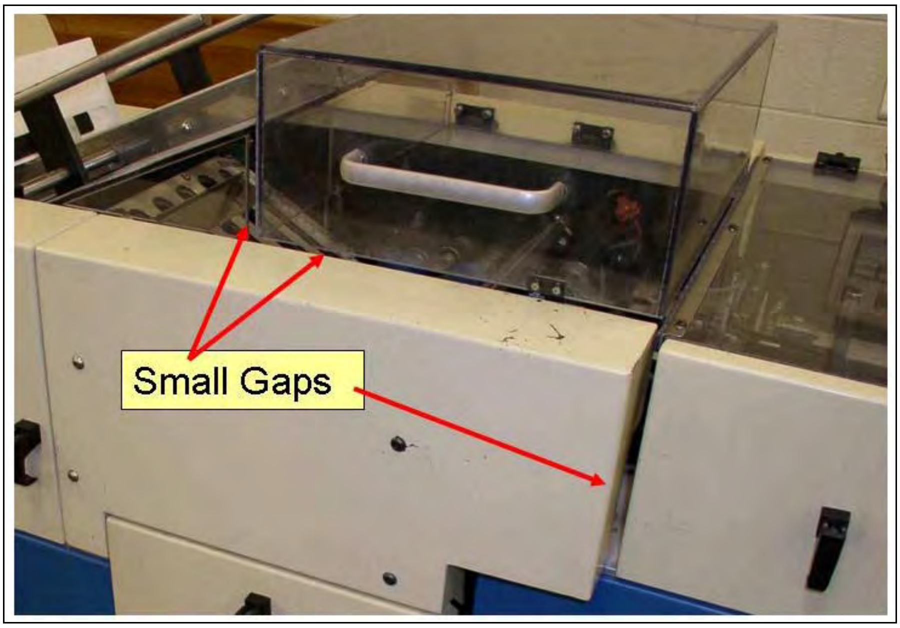


Figure 4.24 - Document feeder with Lexan® guards and covers. Note the small gaps along the covers' edges and between machine panels.

Figure 4.24 shows a document feeder, which is used to insert documents into individual envelopes.

The top section of the machine has multiple Lexan® covers to protect against an employee inadvertently sticking their hand or fingers in the path of the fast-moving components. However, as indicated in the figure, there are a number of small gaps (10-15mm narrow openings) between the guards and machine's casing, as well as between adjacent cabinet sections. The noise level measured one meter from the document feeder, as shown in Figure 4.24, was 94.6 dBA. To improve upon the safety guards, all the small gaps were tightly sealed with flexible hollow tubing, as shown in Figure 4.25. This material was soft enough to conform to the various openings, yet still dense enough to provide significant TL properties.

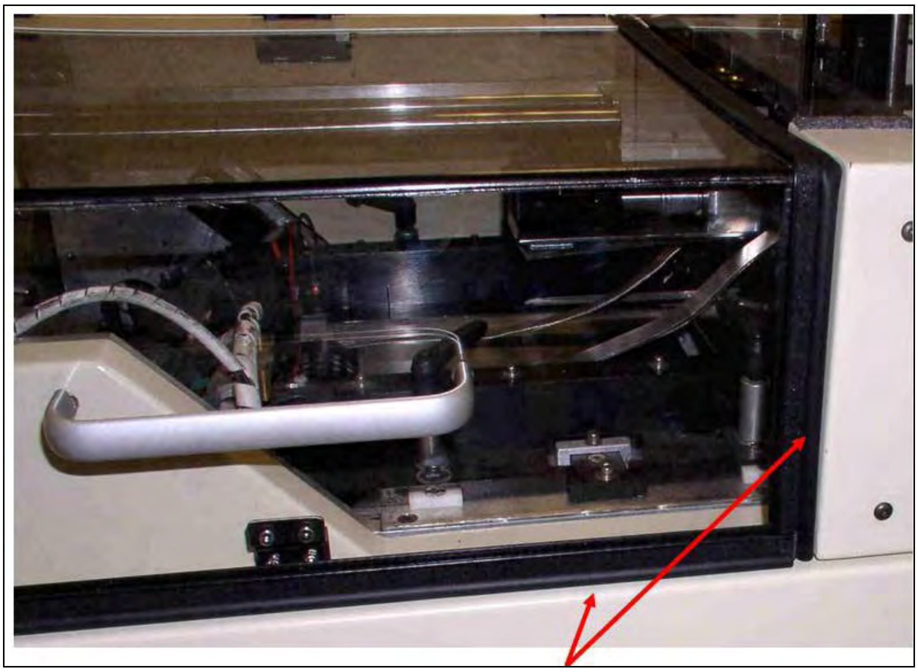


Figure 4.25 – Flexible tubing inserted along all gaps, as indicated by the arrows, provided a tight seal. Note – the tubular material was provided by Trim-Lok, Inc. (www.trimloc.com).

A follow up measurement after treatment was conducted at the same distance in front of the document feeder, and the sound level was 84.2 dBA, which is a noise reduction slightly more than 10 dBA. Figure 4.21 exhibits the before and after A-weighted spectral data.

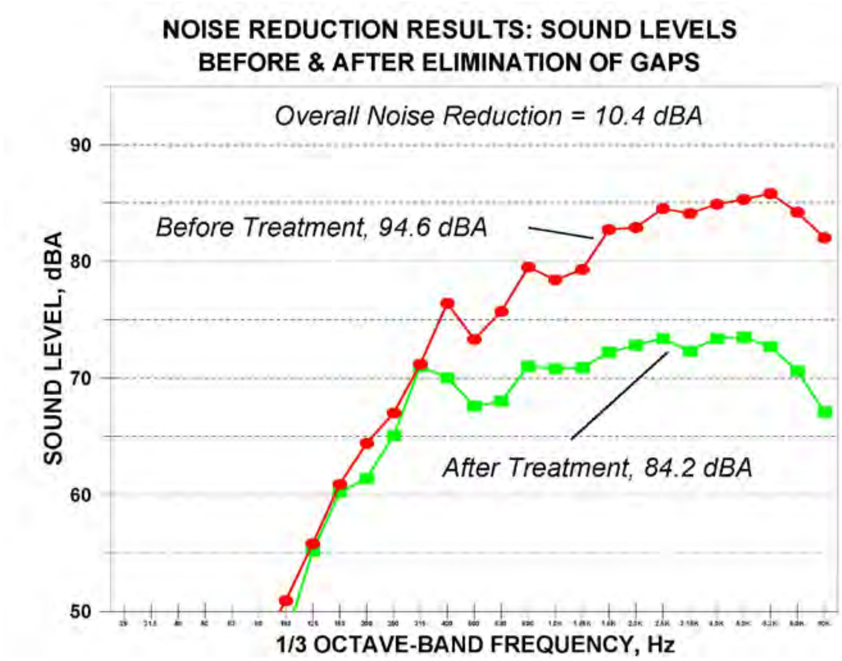


Figure 4.26 – Flexible tubing effectively sealed off the sound flanking paths, and provided a noise reduction just over 10 dBA

The case history above discusses the use of flexible hollow tubing. Some other materials useful for eliminating gaps or openings in safety guards include felt strips, nylon brushes, weather stripping, silicone caulk, flexible vinyl strips, heavy-duty duct tape, etc. When safety guards are movable, to allow operator access, in most cases it is best to attach the sealing material to the edges of the guard, which was the case for the document feeder. In other instances, where the guards do not move or need to be readily opened, the sealing material should be tightly attached to both the guard edges and the machine to provide optimum acoustical sealing.

g) Screens and Barriers

An acoustical barrier is a partial height partition inserted between the noise source and receiver, as depicted in Figure 4.27, which helps block or shield the receiver from the direct sound transmission path.

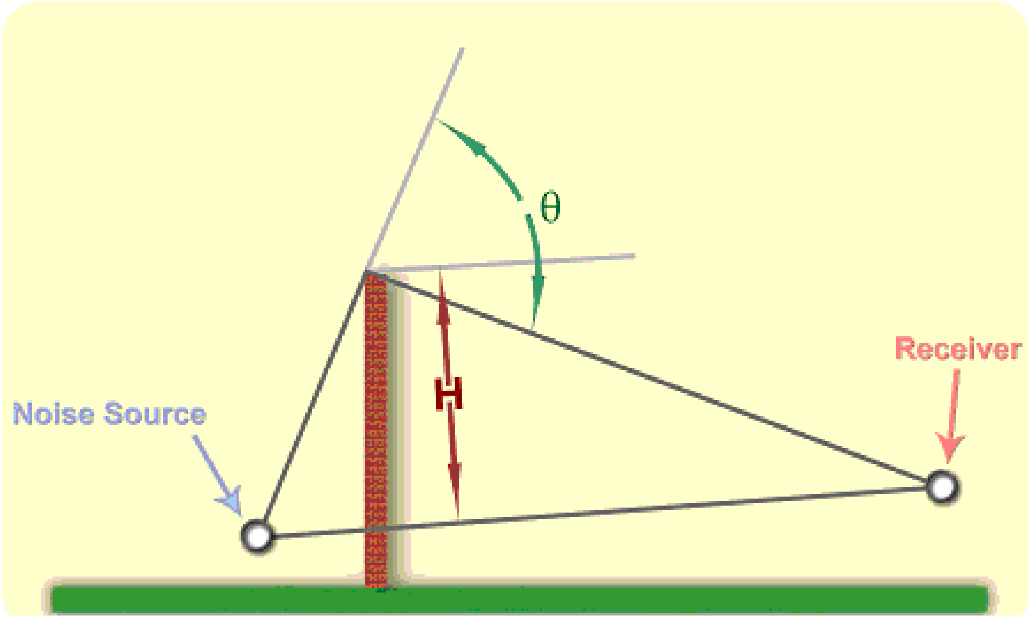


Figure 4.27 - Illustration of a barrier wall inserted between the source and receiver

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),
- 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 4.22.
- 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.

h) Acoustical Insulation or Lagging

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

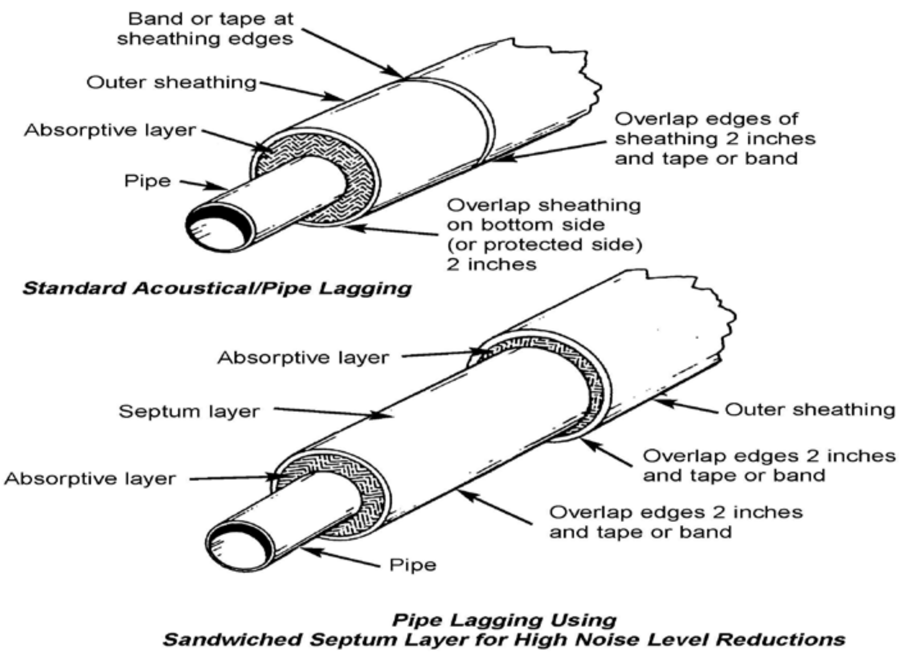
- Noise in the liquid or gaseous medium being transported, which radiates excessive acoustical energy through the pipe wall.
- Vibratory energy transferred to the pipe wall, which may be an efficient radiator of noise, and/or transfer of the vibratory energy to other surface areas capable of radiating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

Pipe lagging consists of wrapping the exterior surface area of a pipe with a sound absorption material (i.e., high-density fibreglass: greater than 32 kg/m^3, or 2 lb/ft^3), then covering the absorptive material with a jacketing material that has high sound transmission loss properties.

Common absorption materials are fibreglass, acoustical foam, or mineral wool. Aluminium (greater than1.4 mm thick), steel (greater than 0.5 mm thick), or dense vinyl are typically used for the outer barrier material. Figure 4.28 depicts two standard configurations for pipes. In effect a tight-fitting cylindrical enclosure is formed around the pipe line.



(Source: The Noise Manual, 5th Edition, AIHA Press)

Figure 4.28 - Standard configurations for single and double-layer pipe insulation

Guidelines for Effective Acoustical Lagging Treatments

Configuration:

1. Provide a layer of resilient absorptive material between pipe surface and outer shell of treatment. A layer of absorptive material should be included; otherwise, there will not be anything to absorb and dissipate the radiated sound energy.

2. Avoid any mechanical coupling between pipe surface and outer shell of treatment, otherwise a transfer of vibratory energy may occur, which in turn enables the outer shell to become a source of sound radiation.

3. Seal all edges and joints airtight. Even extremely small openings (on the order of 0.1% of the total surface area) can significantly degrade the noise reduction achieved. Recall Figure 4.18 for small openings in enclosures - it also applies to the installation of acoustical lagging.

4. Use special materials for high temperature applications. Select a material that will not burn, melt, or decay from exposure to heat and/or moisture.

5. To help absorb low-frequency energy a relatively thick layer of absorption material is required (on the order of 10-15 cm). Recall that low frequencies have relatively long wave lengths when compared to higher frequencies, which makes it difficult to attenuate noise at these lower frequencies.

6. Some means to avoid accumulation of condensation should be included for cold piping. Usually drain taps are sufficient to remove condensation.

Fabrication:

1. For thin-shelled pipes (wall thickness of 6 mm or less) apply a layer of damping material or compound directly on the pipe's outer surface. This damping treatment is not recommended for thicker pipe walls (greater than 6 mm), as the wall thickness is usually sufficient enough to minimize any potential resonant tones.

2. Wrap the pipe with absorptive material.

3. Encapsulate the acoustical absorption material with lightweight metal sheathing.

4. Overlap outside shell edges, compress the acoustical material slightly and bond the joints.

5. Fill in irregular cross sections with loose acoustical material to provide a uniform outer surface.

4.10 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 to minimise exposure times
- Reallocation of noisy tasks to more controllable areas
- Analysis of work flows to minimise interaction between quiet and noisy tasks
- Institute proper use of noise refuge areas or control rooms
- Equipment automation, remote control, and/or remote monitoring
- Introduce 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.

4.10.1 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.

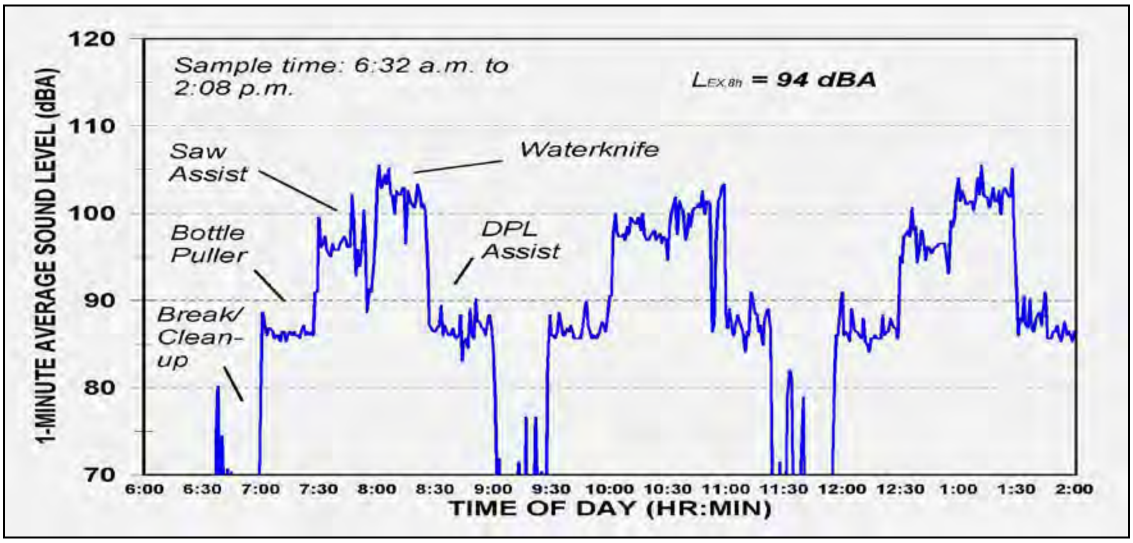


Figure 4.29 - Worker rotation used to distribute the daily noise exposure

For example, Figure 4.29 exhibits a minute-by-minute time-history noise exposure profile for an employee rotating through several work stations. The facility is a glass bottle recycling centre. Before any administrative controls were implemented, each worker performed one or two specific tasks throughout the workday. The employee at the Waterknife station spent the full shift at this location and had an $L_{EX,8h}$ of 105 dBA (Note: $L_{EX,8h}$ is also known as $L_{Aeq,8}$ in some countries), which is an exceptionally high noise exposure. There were two other operators, who split time between the Bottle Puller, Saw Assist and De-palletizer (DPL) Assist stations. Both workers' $L_{EX,8h}$ were approximately 91 dBA. Therefore, a job-rotation schedule was devised and implemented to limit the time spent at the Waterknife. Five separate tasks, lasting 30 minutes each, were set as the rotation schedule.

These assignments were (1) Clean-up/Break, (2) Bottle Puller, (3) Saw Assist, (4) Waterknife, and (5) DPL Assist. This cycle is repeated three times per workday, with an additional 30 minutes of clean-up added to the end of the shift (see Figure 4.23). As a result, the Waterknife operator's $L_{EX,8h}$ is reduced from 105 dBA to 94 dBA, and the two 91 dBA exposures are raised to 94 dBA. Granted the resultant exposure for the Waterknife operator is still above 90 dBA; however, this lower exposure presents a more manageable risk as part of the HCP. As for the elevated $L_{EX,8h}$ for the two other operators, management decided this was acceptable on a temporary basis until engineering controls could be implemented.

Professional judgment is required when designing a job-rotation schedule. It is critical no additional workers be added to the HCP, or the affected workers presently exposed to noise do not have their noise exposure raised to levels where hearing protection is rendered potentially ineffective. Toward this latter goal, if the resultant $L_{EX,8h}$ are kept to 95 dBA or less, practically any hearing protector will be sufficient provided the device fits well and is worn consistently and correctly.

Table 4.1 provides another example of administrative control. The $L_{Aeq,3\ h}$ for each category of performer in an orchestra for a particular program of music has been used to determine the $L_{Aeq,8h}$ for one and for two performances in the one day. For some members the noise exposure would become excessive if they played in two performances so rosters were implemented as part of a noise management plan.

Table 4.1 - Example of the noise exposure for different members of an orchestra for one and two performances of a particular programme

Measured	Position	Performance LAeq,T dB 3h	1 performance gives LAeq,8 Daily	2 performances gives LAeq,8 Daily
1	Conductor	82	78	81
2	Strings	84	80	83
3	Strings	84	80	83
4	Brass	90	86	89
5	Strings	85	81	84
6	Strings/Harp	88	84	87
7	Bass	85	81	84
8	Wood	90	86	89
8a	Horn right	90	86	89
9	Percussion	87	83	86
		Requirement	85	85

(Source: K Mikl)

4.10.2 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 buildup 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 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 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.

Another example can be seen in manufacturing plants. Specifically, when workers service or operate production equipment, 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.

4.10.3 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 4.30, 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 4.30 - 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. 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.

4.10.4 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. As part of an auditory and visual inspection, the following checklist is useful:

1. A check should be made with each operator to identify any machine problems that may be causing excessive time to be spent at the machine.
2. All loose parts should be tightened and/or secured.
3. All machine controls should be checked for proper setting.
4. Air and steam leaks should be identified and fixed as soon as possible.
5. All moving components should be checked for misalignment or worn parts, such as bearings or belt drives.
6. Rotating parts should be checked for shaft alignment and imbalance.
7. All regulators for compressed air or pneumatic cylinders should be checked to ensure excessive impact forces do not occur at each end of its stroke.
8. Compressed air mufflers or pneumatic silencers should be checked to ensure they are in place and not damaged or clogged.
9. The inspector or maintenance surveyor should listen for unusual noises that may indicate component wear or other problems.

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.

4.10.5 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.

These Directives are: (1) Directive 89/392/EEC (EEC, 1989a), with two amendments 91/368/EEC (EEC, 1991) and 93/44/EEC (EEC, 1993a), (2) Directive 89/106/EEC (EEC, 1989b) and (3) Directive 89/686/EEC (EEC, 1989c), with one amendment 93/95/EEC (EEC, 1993b). The first item listed above (89/392/EEC) is commonly called the Machinery Directive. This Directive was revised in 2006 (2006/42/EC) to include more precise requirements for noise and vibration. The Machinery Directive compels machine manufacturers to include equipment noise control as an essential part of machine safety. As a result, there has been a major emphasis on the design of low-noise equipment since the late 1980s by manufacturers interested in marketing within the EC.

Within the United States, ANSI has published a standard entitled: “Guidelines for the Specification of Noise of New Machinery” (ANSI, 1992, (R2002)). This standard is a useful guide for writing an internal company noise specification. In addition, this standard provides direction for obtaining sound level data from equipment manufacturers. Once obtained from the manufacturer, the data may then be used by plant designers while planning equipment layouts. Because of the various types of distinctive equipment and tools for which this standard has been prepared, there is no single survey protocol appropriate for the measurement of sound level data by manufacturers. As a result, this standard contains reference information on the appropriate sound measurement procedure for testing a variety of stationary equipment types. These survey procedures were prepared by the appropriate trade or professional organization in the United States responsible for a particular type or class of equipment.

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.

Besides selection of the equipment, consideration of noise early in the equipment layout design is essential. The layout designer should exercise caution and take into account the additive effect of multiple noise sources within a room. Relocating equipment on paper during the design phase of a project is much easier than physically moving the equipment later, especially once the equipment is in operation.

Validation of noise criteria requires a cooperative effort between company personnel from departments such as engineering, purchasing, industrial hygiene, environmental, safety, and legal. For example, industrial hygiene, safety and/or environmental personnel may determine the desired noise levels for equipment, as well as conduct sound surveys to qualify equipment. Next, company engineers may write the purchase specification, as well as select quiet types of equipment. The purchasing agent will most likely administer the contract, and rely upon company lawyers for assistance with enforcement. Involvement from all these parties should begin with the inception of the project and continue through funding requests, planning, design, bidding, installation, acceptance, and commissioning.

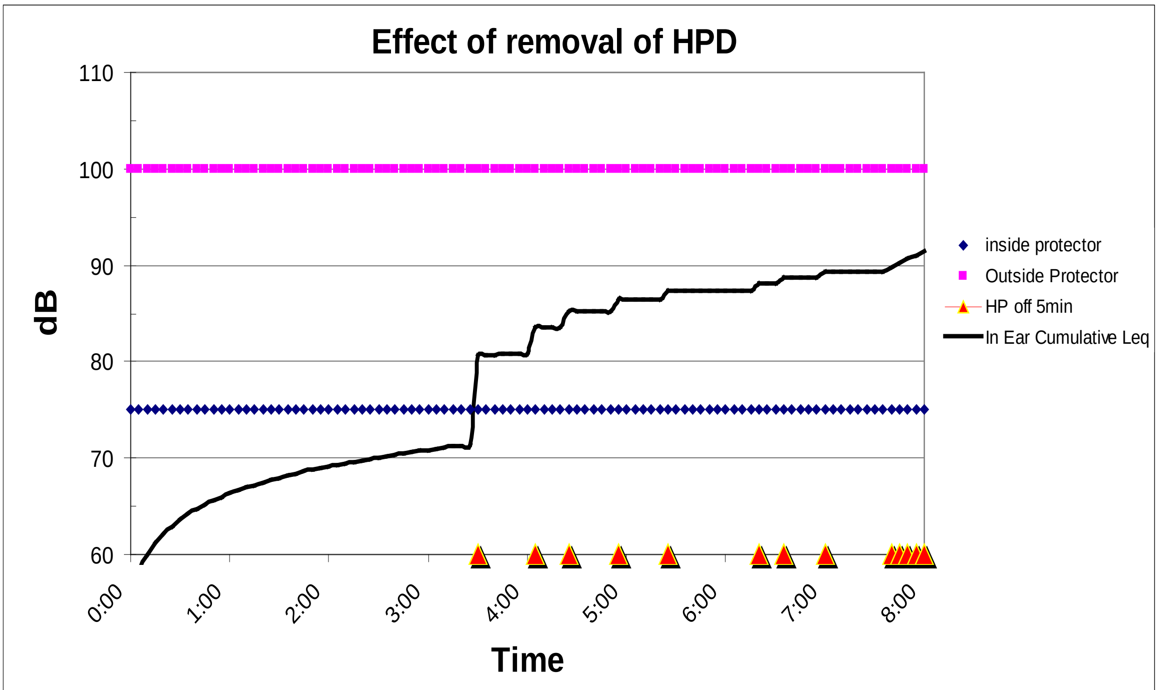
Even the most thorough and concise specification document is of little value unless the onus of compliance is placed on the supplier or manufacturer. Clear contract language should be used to define the means of determining compliance. Company procedures designed to enact guarantees should be consulted 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 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.



(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 non linear 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 goodness 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 Premolded Plugs

Figure 5.3 – Premolded Plugs

Premolded plugs are fabricated from soft, flexible materials; and come in a variety of sizes. These plugs contain anywhere from zero to five flanges. Premolded 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 premolded plugs can work loose during the day, and may need to be periodically repositioned or re-seated by the user. Pre moulded 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. 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 premolded 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 premolded 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.

As you might imagine, 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 tansit 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 performance of hat mounted hearing protectors is less.

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;

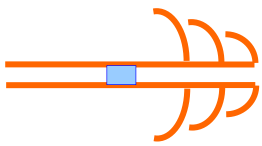
- Radio communication
- Protection against extremely high noise environments
- Devices which turn off and on automatically
- Linear protection to provide good quality transmitted sound for musicians
- Devices with particular frequency response or

- 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**.**

Combat 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 'combat 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'.



(Source: Mikl & Burgess)

Figure 5.7 - Schematic diagram of the principle of the non linear end of combat ear plug. Note the small delay unit in the stem of the plug. Constant sound can be transmitted down the tube to the ear but sharp rise time impulse noise is attenuated by this insert

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

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 coming onto the market for use with iPods and such to screen out traffic noise while the wearer listens to music. These are not as yet certified for use in industrial environments.

Adaptive hearing protection is a relatively new concept that balances speech enhancement with noise suppressions using sophisticated signal processing. Sensear (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 SELECTION

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. Also, unnecessarily high performance HPDs may be a little more uncomfortable and so there is a tendency to remove them.

To achieve worker acceptance a variety of HPDs should be available. 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 SELECTION 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.

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.

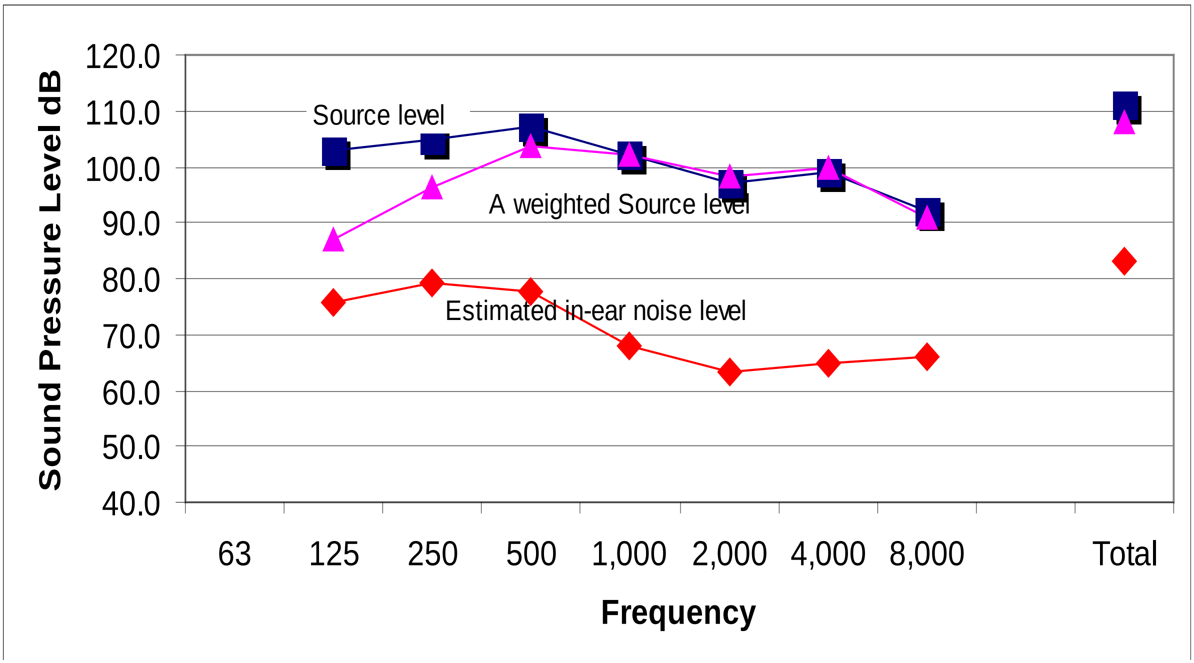
The following example demonstrates hearing protector evaluation using the Octave-band Method.

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)*

line	**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**	**.263**	**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 represents the "effective" exposure under the HPD in dBA.

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.

To estimate the real-world attenuation afforded by HPDs when using the manufacturer's published NRR data and noise exposure, the following derating scheme is recommended: (Note: in the expressions below $L_{Aeq,8}$ may be substituted with $L_{EX,8h}$ or TWA.)

For Single Hearing Protection:

$L_{Aeq,8}$ – [(NRR-7)x0.5] = Estimated $L_{Aeq,8}$ under the protector.

For Dual Hearing Protection (earmuffs worn over earplugs):

$L_{Aeq,8}$ – [(NRR of the better protector-7)x0.5] +5 = Estimated $L_{Aeq,8}$ under the combination of protectors.

As an alternative de-rating scheme, NIOSH (NIOSH, 1998) recommends the following corrections or adjustments in the NRR:

For Earmuffs:	Reduce the NRR by 25%,
For Formable plugs:	Reduce the NRR by 50%, and
For all other plugs:	Reduce the NRR by 70%.

Then take the resultant NRR value and subtract it from the noise exposure or sound level.

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 <u>groups</u> 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} (80^{th} percentile value) – the protection that is possible for most individually trained under to achieve or exceed.
- Method B, NRS_{A80} (80^{th} percentile value) – the protection that is possible for most users to achieve or exceed.
- Method A or Method B, NRS_{A20} (20^{th} percentile value) – the protection that is possible for a few motivated proficient users to achieve or exceed. Note – the 20^{th} 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.

Worked 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 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 SLC_{80} method

$L_{Aeq,8h}$ dB(A)	Class	SLC_{80}
Less than 90	1	10-13
90 to less than 95	2	14-17
95 to less than100	3	18-21
100 to less than105	4	22-25
105 to less than 110	5	>26
110 or greater	requires specialist advice	

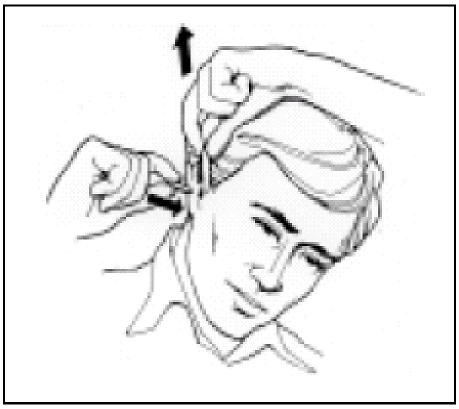
If the noise environment is narrow band in character with significant tonality or has significant high or low frequency components or exhibits other complexities, then the octave-band method should be used.

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.

5.4.1 Foam Earplugs

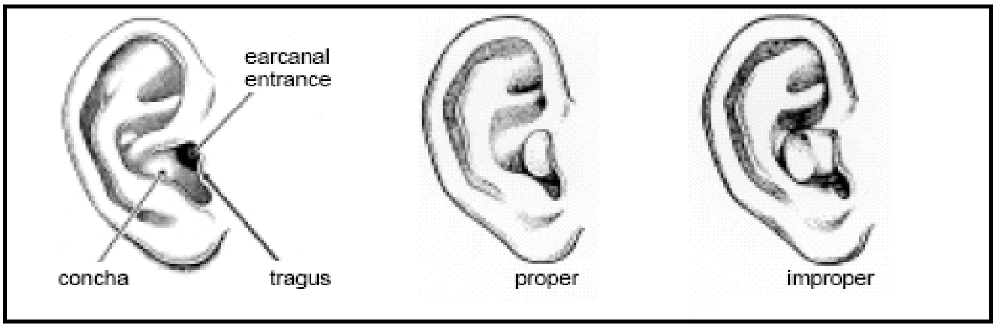
Most foam plugs are designed to be rolled down by the user and inserted into the ear canal. After insertion the plug slowly expands and conforms to the individual ear canal shape. The following roll-down procedure is described in EARLOG[19] (Berger, 1988): "to insert foam earplugs roll them down between 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 5.11 - Pinna Pull Insertion Technique



(Source: *Illustration provided courtesy of Aearo Technologies)*

Figure 5.12 – 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.

5.4.2 Premolded Earplugs

Premolded 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 premolded 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 <u>increase</u> 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.

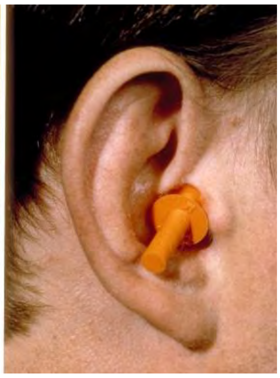
Examples of Visual Checks for Proper HPD Use

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.

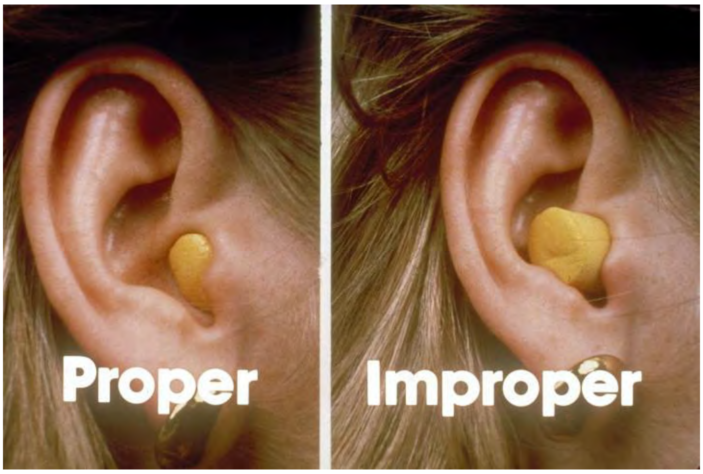


Improper Insertion: the end flange sticks out past the tragus.

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.

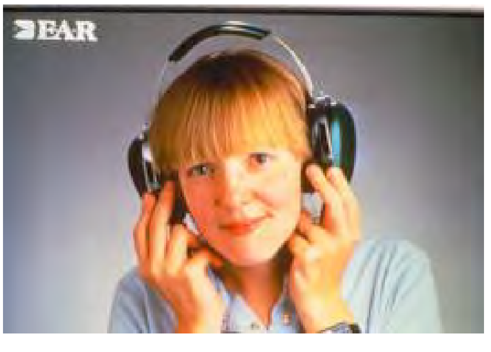


The EAR Classic foam plug shown in the left photo is a proper insertion, as the end of the plug is just past the tragus.

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 wearer can perform to fit check their HPDs. 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

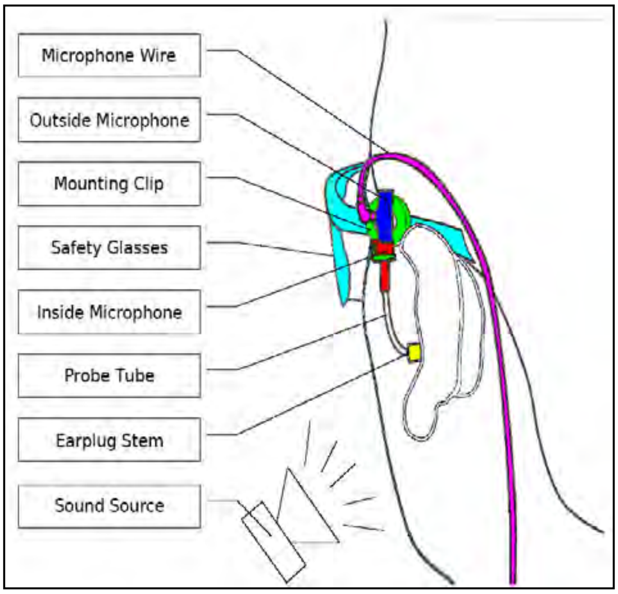
Even with appropriate focus on noise control, reliance on HPDs as the last line of defence against occupational noise exposure is inevitable. As discussed earlier, one critical failure in this process has historically been the fact the labelled protection values on HPD are not reliable predictors of 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.

If it is important to estimate how well HPDs work for individual users, they must be tested on individual users. New and emerging technologies make this possible. 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.

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 5.13 – 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).*

(Source: Courtesy of Michael & Associates)

Figure 5.14 – FitCheck Equipment

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.

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. 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 5.15 – Example of Warning Signage

5.8 TRAINING AND MAINTENANCE

5.8.1 Training

HPD wearers should be trained in the proper use and care of their protectors during initial fitting, at the time of their annual hearing test, and whenever observed to be improperly wearing HPDs.

5.8.2 Maintenance

Earplugs, primarily re-useable premolded and custom plugs, should be routinely inspected to ensure no damage or physical changes have occurred to the device over time that would inhibit the ability to obtain an airtight seal. 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. All plugs may be cleaned with a mild soap and water, when needed.

Earmuffs should be checked regularly because impressions, cracking, and hardening of cushions can cause air leaks affecting the attenuation. Replacement cushions are available from the manufacturer although it may be more cost-effective to replace the aged ear muffs rather than keeping stocks of replacement cushions. 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. Thus 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 they can provide guidance on what is applicable for their particular workplace. Those exposed to the noise must also understand the hazard and the safety systems that are installed immediately 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 have personnel with the capacity 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.

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) Explain 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 For Protecting Hearing

a) Explain the importance of protecting hearing including the difficulties experienced by people with hearing impairments and the limitations of hearing aids, i.e. without sounding alarmist or using scare tactics, discuss the social isolation and psychological problems associated with mild and severe hearing loss.

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.

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 and check each individual can use their selected protectors.

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 sections of AS/NZS 1269, other 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; ie 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 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. 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 ie 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

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 otoscerosis. 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.

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. It is this type of hearing loss that the cochlea implant can be used to improve hearing as the implant provides direct stimulation to the hair cells

- **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. Hearing impaired people often say, “I hear you talking, but I can’t understand what you are saying.”

- **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 overlaying 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 complicated because it is not linear.

- **Impulse/Impact Noise**

  Both impulse and impact noises are short duration bursts of acoustic energy. Impulse noise results from an explosive action, such as gunfire, and impact noise occurs when two hard surfaces strike together, such as a hammer on metal. Regardless of the distinctions, both impact and impulse noise can cause “acoustic trauma” resulting in significant hearing loss, tinnitus, and a sensation of fullness in the ear. 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.

  A single high level impulse noise can be more damaging than a continuous noise of the same level or a series of impulses as the sharp rise time of the signal does not allow time for the “acoustic reflex” or “auditory reflex” or to come into operation. 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.

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 levels for humans have been 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 workshifts 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.

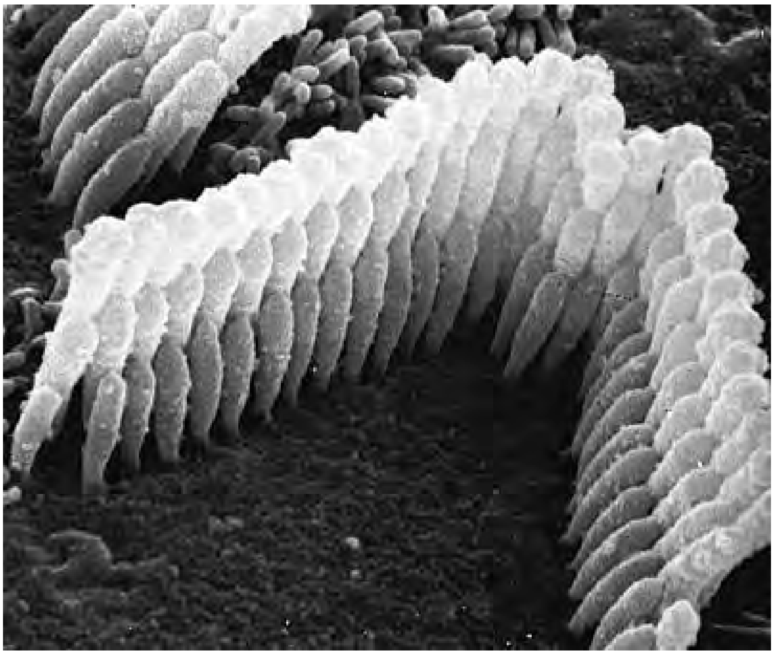
- **Temporary and Permanent Threshold Shifts**

  A temporary threshold shift (TTS) is a hearing loss 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.

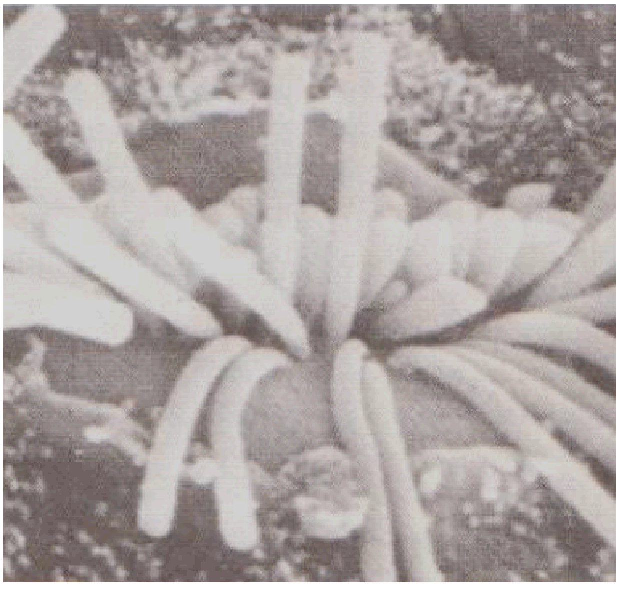
Intense blasts can cause such extreme vibration that the eardrum may perforate and/or haemorrhage, the ossicles can fracture, and in severe cases, the organ of Corti can be torn off the basilar membrane and eventually deteriorate. Hearing loss from this extensive damage would be profound and affect multiple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

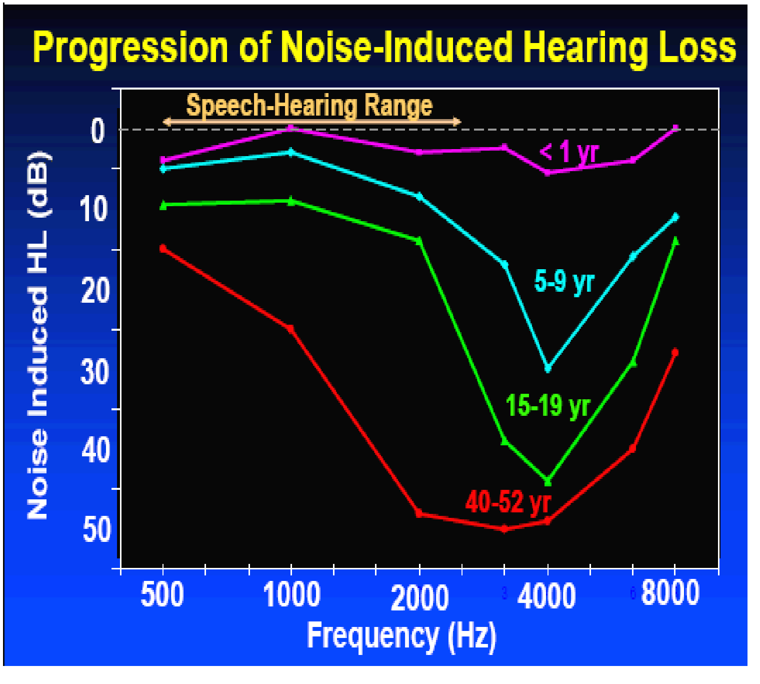
NIHL from continuous, long-term exposure is more likely to be contained within the cochlea, more specifically there will be structural damage to the outer hair cells. The more severe the hearing loss, the more likely the damage extends to the inner hair cells and supporting cells. Figures 7.1 and 7.2 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 stereocilla. 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 4k notch” or “a 4k 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.

It is important to note here that the ‘noise notch’ occurs just at that part of the frequency range which is most important for understanding speech.

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 affects 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. The primary assessment may be by a trained Audiometrist.

Competent audiometric programmes 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. There is opportunity to teach employees about hearing and hearing protection during one-on-one sessions with workers to review hearing test results and to select and fit hearing protection devices. They should understand audiometric results in order to identify abnormal audiograms and those with significant changes in hearing. The need for medical referrals based on the audiometric thresholds and medical information should be recognised. Follow-up actions need to be managed and rigorous, 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 the primary goal.

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. The effectiveness of a HCP is measured by its ability to prevent occupational hearing loss.

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 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), The 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 25oHz 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.

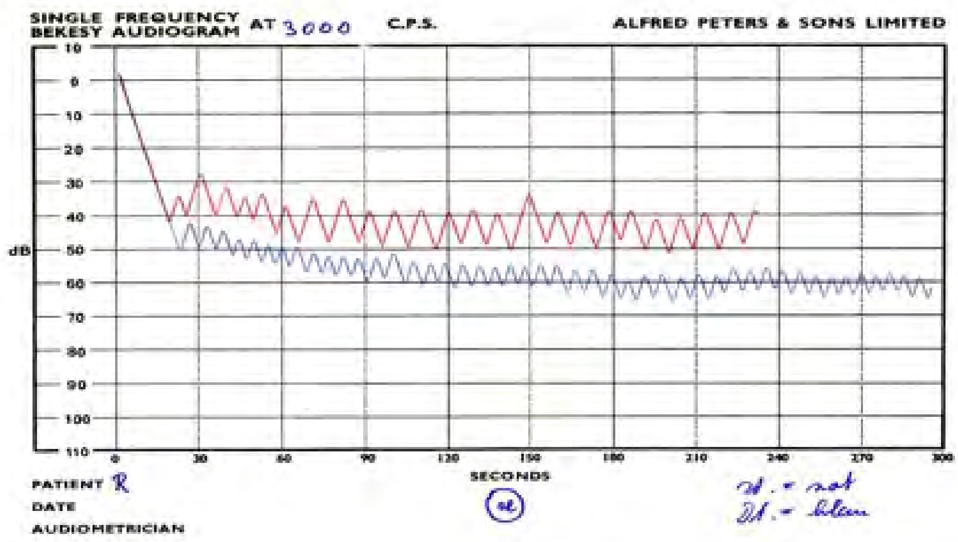


Figure 7.7 - Example of Bekesy threshold tracing at 3000 Hz

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.

g) Other Methods for Hearing Assessment

Otoacoustic emission (OAE) is a sound which is generated from within the inner ear. Studies have shown that OAEs disappear after the inner ear has been damaged and so can be used as a measure of inner ear health. There are two general types of otoacoustic emissions: Spontaneous Otoacoustic Emissions and Evoked Otoacoustic Emissions. The click-evoked OAE is a non-invasive test for hearing defects and is now widely used for newborn babies and for children who are too young to cooperate in conventional hearing tests. The test may well become more common for general audiometric screening.

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 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. 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 COHC 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.

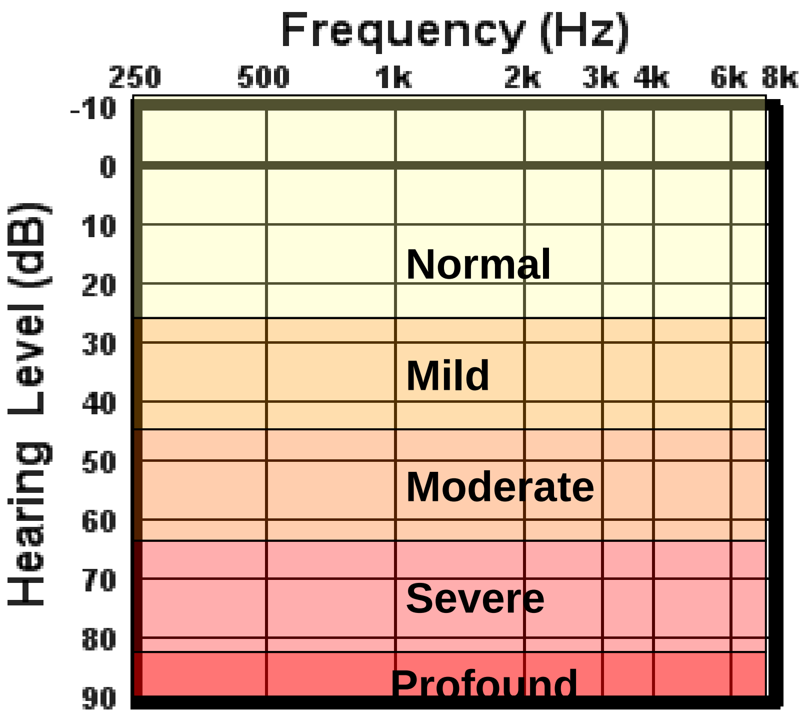
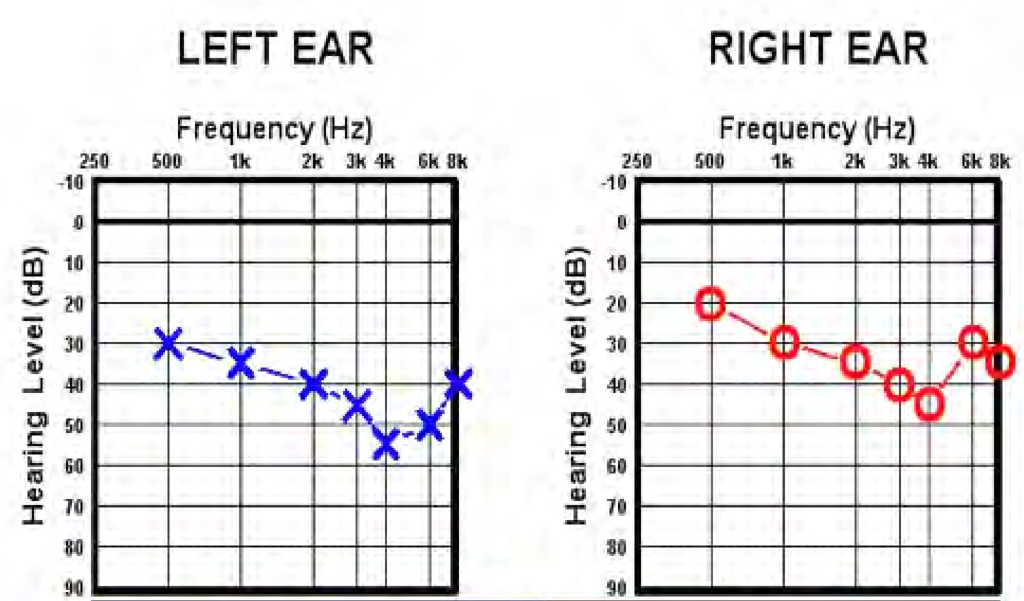


Figure 7.9 - Audiogram illustrating regions of hearing sensitivity

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.



Left							Right						
500	1k	2k	3k	4k	6k	8k	500	1k	2k	3k	4k	6k	8k
30	35	40	45	55	50	40	20	30	35	40	45	30	35

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.

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.

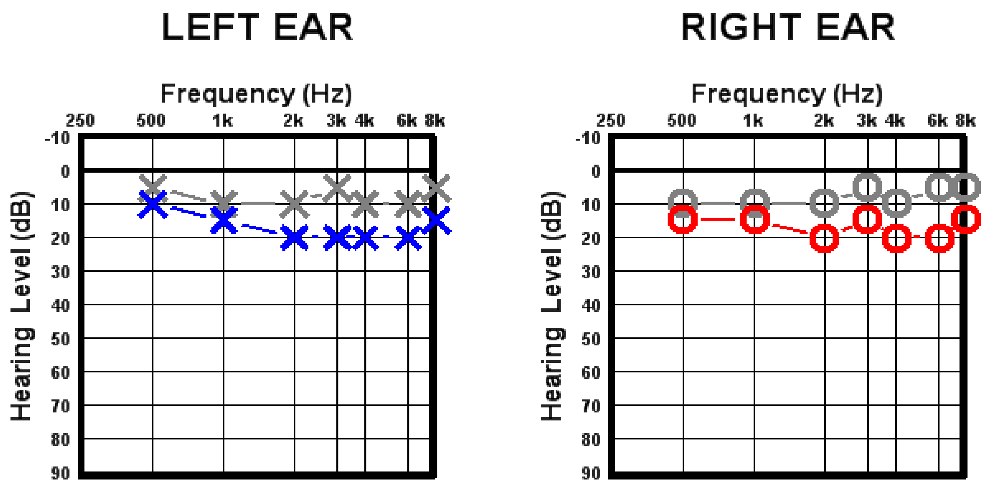
Employees with hearing loss identified on the baseline test should be notified and referred to the employee’s personal physician and/or audiologist to further investigate the cause of hearing loss and possible treatment options. These cases should be reviewed

- ***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.

- ***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 that they are 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.

Based on extensive research by NIOSH and more than 30 years of experience by the author in the subject, the following are the recommended minimum requirements an HCP needed 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 two 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.

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 NOISE SURVEYS

Noise surveys are carried out for a number of different reasons and objectives. Noise surveys may be necessary for many other purposes than hearing loss prevention, such as evaluating communications interference, recognition of emergency alarms and warning signals, evaluating rest areas, etc, but these are beyond the scope of this practice. Noise surveys relevant to this guideline are conducted to:

- Identify employees who need to be included in the hearing HCP,
- Determine area and equipment noise levels, and generate noise contour maps,
- Collect acoustical data for noise control engineering purposes,
- Identify all hearing protection required areas, and
- Enable the selection of the appropriate hearing protection devices.

9.1.1 Instrumentation

Instruments used in noise surveys must meet internationally recognized performance standards and be properly maintained and calibrated.

9.1.2 Survey of the Area and Equipment Noise Levels

The first step of a detailed survey is an Area and Equipment Survey. The purpose of the area and equipment sound level survey is to document all machines and components operating at 80 dBA or above, identify areas and tasks where hearing protection is required, plan for noise exposure assessments, and initiate a priority list of noise sources potentially suitable for noise control treatment.

Area and equipment sound levels should be revalidated at least every two years, after new equipment is installed, or when process changes occur that may affect the area or equipment sound levels. To the extent practical, noise surveys should address intermittent process cycles and reasonably anticipated abnormal operating conditions (e.g., steam leaks, worn motor bearings, misaligned couplings, etc.). Note – the biennial revalidation process may only necessitate a walk-through and/or preliminary sound survey, as described above, and comparison of the results to the current detailed sound survey data. If the sound levels differ by 3 dBA or more, either higher or lower, then the detailed survey should be updated.

Surveys should evaluate and document sound levels at each machine and in each work area above 80 dBA. This should include documenting the conditions at the time of survey. Measurements should be collected during typical operating conditions and be supplemented when practical to evaluate intermittent and abnormal conditions.

Measurement results may be presented graphically, as a noise contour map, or in tabular form, whichever best communicates the nature of the potential for exposure. Persons performing area and equipment surveys require appropriate training and need to have demonstrated competency in performing such surveys.

9.1.3 Noise Exposure Survey

The second step of a detailed noise assessment is a Noise Exposure Survey. Noise exposure surveys provide data to enable the programme administrator to make informed decisions regarding actual employee exposures, thus guiding management of the HCP. A noise exposure determination shall be made for all employees who work in areas having sound levels of 80 dBA or higher or who operate equipment generating sound levels at or above 80 dBA.

After the initial noise exposure survey, re-evaluations should be conducted at least every two years if biennial revalidation of the area and equipment data concludes the sound levels have changed by 3 dBA or more. However, checking is also necessary whenever new equipment is added, old equipment removed or shut down, or process or work practice changes occur that alter the area noise environment or worker exposure to the environment.

One method for determining worker noise exposure is through use of personal noise dosimeters. For HCP purposes the dosimeter shall 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 and no threshold level. Note that some jurisdictions may also require monitoring using different thresholds or exchange rates. Where applicable, such monitoring should be in addition to the health-based monitoring described in this Guideline. In such cases it would be preferable to use equipment that can collect all data simultaneously to assess against both standards.

An alternative is to estimate the individual noise exposure based on the noise levels measured at the individual's ear plus data on the time of exposure to each noise source. Then the daily noise exposure can be determined.

Representative noise exposure may be used where similar exposure groups are identified that have the same job function or activity, and are exposed to similar kinds of noise. Noise exposure profiling may be used to determine noise exposure for certain very well-defined situations, where permissible under applicable regulations.

All noise exposure data shall be normalized to an 8-hour average for purposes of comparison to the HCP inclusion criteria under this practice (8 hours at 85 dBA being defined as 100% of daily allowable dose or comparable permissible exposure limit). Care must be exercised to avoid confusion of the average derived using the criteria described in this practice versus criteria used under various other measurement systems.

The noise survey report and all data shall be maintained for the time required under local legislation. This may be as long as forty (40) years or for the duration of employment plus 30 years for each impacted employee.

9.2 NOISE CONTROL

Engineering noise controls shall be used as the preferred means to prevent hearing loss through reduction in area and equipment noise. Where practical engineering controls are inadequate to reduce average noise exposures to less than 85 dBA, administrative controls and personal protective equipment shall be used to achieve adequate protection. The principal goal of noise controls is to reduce all $L_{Aeq,8}$ noise exposures below 85 dBA. When determining the feasibility of a noise control option, it is important to consider the interaction between the exposed workers and the noise sources of concern. Noise sources should be prioritized for implementation of feasible engineering noise controls based on the highest rank order of their contribution to actual worker noise exposures.

9.2.1 Engineering Noise Control Options

Reducing excessive equipment noise may be accomplished by treating the source, sound transmission path, receiver, or any combination of these options. Note that engineering controls for the receiver do not include personal protective equipment. This refers to engineered provisions that eliminate the need for the receiver to be in the area where the noise is present or that isolate the receiver from the ambient noise environment.

9.2.2 Administrative Noise Control Options

Administrative controls involve changes to employee work routines that affect their daily noise exposure in a positive manner. When designing administrative controls it is important to consider the fact that 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. However, rotating employees in this manner will at least double the number of employees exposed. This option should only be implemented if the resultant noise exposures for all of the affected workers would be such that none would be at risk of noise-induced hearing loss. Where administrative controls are used, training and supervision need to be sufficient to ensure the controls are sustainable.

9.2.3 Personal Protective Equipment (Hearing Protection Devices)

Hearing protection devices (HPDs) consist of earplugs and earmuffs, and are used to reduce the level of sound reaching the inner ear. HPDs shall be used in designated high-noise areas until feasible engineering noise control measures effectively reduce workplace noise exposures below 85 dBA or where other controls have not yet proven feasible.

Selection of Hearing Protection Devices:

The type of HPDs to be used in each work environment will be made by persons qualified to assess the suitability and effectiveness of such equipment. HPDs must reduce worker noise exposure below 85 dBA.

There is no “best” type of HPD. The most effective device is that which is actually worn and worn properly. Thus, it is important to consider employee comfort and practicality of use in the actual work environment. It is recommended more than one type of HPD be provided in order to fit all employees and to suit all tasks and conditions. However, although the employee may select the type of HPD they prefer, it is imperative the selection of size and fit be completed by qualified persons.

Devices used must be sufficient to control actual exposures to below an average of 85 dBA, based on expected real-world attenuation predicted for the type of device. To estimate the real-world attenuation afforded by HPDs, it is recommended a scientifically acceptable derating scheme be used to estimate the “protected” level or $L_{Aeq,8}$ under the protector. It is important to keep in mind derating the manufacturer’s attenuation rating may not be applicable for determining regulatory compliance; and therefore, may need to be performed as a separate calculation.

Special equipment may be necessary where communication in the noise environment is critical. Selection of HPDs must take into consideration the need for communication in the noise environment. As a minimum, all values for the $L_{Aeq,8}$ under the protector must be reduced below 85 dBA. However, to ensure optimum protection and communication capabilities it is recommended the $L_{Aeq,8}$ under the protector be kept between 75-80 dBA. Having the $L_{Aeq,8}$ under the protector less than 70 dBA poses a risk of overprotection, which can lead to miscommunication or failure to recognize emergency alarms and warning signals.

All hearing protectors need to be fitted when initially dispensed. Even wearers of foam earplugs should have their ear canals inspected to ensure there are no physical problems that might prevent a good seal from being achieved. Wearers of ear muffs should be examined to ensure the wearer’s physical features do not preclude an adequate seal and that the headband size is appropriate.

HPDs are required to be worn in all areas with sound levels 85 dBA or greater, regardless of the time that the individual is expected to be exposed. Because the adequacy of single protection reaches of real-world attenuation limit when exposures exceed 105 dBA, dual hearing protection (muffs and plugs) is required when sound levels are greater than 105 dBA (Berger 1996).

HPDs must be readily available at locations or stations where people are expected to enter into a high-noise area. All areas of 85 dBA or more shall be posted as “hearing protection required” areas. Equipment or areas of 105 dBA or more must be posted as “dual hearing protection required” areas. Temporary high noise areas should be appropriately posted to the extent reasonably practicable.

9.3 HCP TRAINING

9.3.1 Employee Training

Employees 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 noise induced hearing loss. Teaching employees the value of good hearing is critical to the overall success of the HCP. The emphasis is that noise-induced hearing loss is 100% preventable. The intent of training should be not only to inform employees about what is necessary to protect their hearing, but also to generate life-long interest in hearing health and shape positive attitudes and behaviors. Training should promote prevention of hearing loss, such as use of HPDs, for hazardous noise both on and off the job.

Those responsible for presenting training need to be properly qualified to present the training. In addition, the trainer should have specific knowledge about the workplace noise exposures and information on the noise control programme. Finally, all training must be documented and the effectiveness of the training should be assessed and documented.

9.3.2 Management Training

In addition to the employee training content, management has additional need for education to deliver an effective HCP, thereby, minimizing worker's compensation costs, reducing safety risks, and realizing all the other benefits of hearing loss prevention. The content of management training should be adapted to fit the role of the manager in ensuring the effectiveness of the HCP.

9.4 AUDIOMETRIC MONITORING

Valid audiometric monitoring allows the assessment of HCP effectiveness. Unless barred by law, participation in audiometric testing should be a condition of employment for employees exposed to hazardous noise.

All employees identified as having an 8-hour average noise exposure equal to or greater than 85 dBA shall receive:

- A baseline audiogram upon initial exposure,
- Annual audiometric monitoring exams for the duration of their employment in which exposure continues to be above 85 dBA, and
- Termination audiometric exam upon cessation of employment or cessation of exposure to hazardous noise.

Audiometric monitoring shall be conducted by qualified personnel using standardized, calibrated audiometric equipment and procedures. Results of audiometric testing must be evaluated, or "professionally reviewed" by a qualified audiologist or physician (referred to as the "professional supervisor") to identify recommended and required employee and employer follow-up actions, revise baselines, determine work-relatedness, and to manage the audiometric database. Local and country requirements shall be met in addition to any internal company policies.

Where allowed by law, employees whose exposure is only incidental may be excluded from annual audiometric testing. Such employees still require training. For purposes of this guideline, incidental exposure is defined as exposure that does not exceed an $L_{Aeq,8}$ of 85 dBA on more than 5% of the employee's workdays in any one year.

Any threshold shift in the audiogram should be investigated and checked. If there is a real threshold shift then the noise management in the workplace should be reassessed. If this is shown to be adequate the employee should be counselled and further investigations undertaken to check why the hearing loss is occurring. Once the reason has been uncovered action should be taken to prevent further hearing loss.

9.5 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.

9.6 RECORDKEEPING

Good records are essential to an effective HCP. Recordkeeping is required in all components of the HCP. Records which must be retained include:

- Noise measurements, including determinations of noise-free areas,
- Noise exposure assessments, including notices to exposed employees,
- Employees included in the HCP,
- Audiometric testing and medical history records, including notifications to employees,
- All HPDs available to and individually used by employees,
- Training records for employees and management,
- Noise control studies, including projects undertaken to reduce exposure,
- Local HCP programme and policy documents,
- Determination of hearing protection device effectiveness,
- Audits of HCP, and
- Calibration of instruments.

9.7 INTERVENTION STRATEGIES FOR PREVENTION OF NIHL

STS is intended to be the trigger point for intervention, subsequently preventing an eventual permanent hearing shift. However, using other metrics, more sensitive to the initial signs of NIHL combined with applying early intervention strategies can be more effective in preventing NIHL.

9.7.1 Identification of Employees at Risk For Hearing Loss

Analysis of the audiometric database can reveal specific employees who have the potential to develop an threshold shift.

By comparing threshold shift rates of specific departments and/or job positions, those with the highest STS rates can be identified and targeted for additional intervention.

Employees with extreme high noise exposures, such as greater than or equal to 105 dBA $L_{Aeq,8}$ requiring dual HPD may be targeted for additional intervention strategies.

9.8 PROACTIVE INTERVENTION STRATEGIES

9.8.1 "Buy Quiet" Programme

Reducing the employee noise exposures can be accomplished by implementing a "Buy Quiet" programme, in which all new equipment or production procedures must adhere to a company defined noise exposure limit, less than 85 dBA $L_{Aeq,8}$. Company procedures can be established requiring management approval before equipment or procedures are installed. Any new buildings or procedures should be designed with noise exposure limits in mind.

9.8.2 Engineering Solutions

Reducing the employee noise exposures may be accomplished by examining the source of the noise and implementing engineering solutions to reduce the noise at the source.

Other options which should be considered are to reduce the noise between the source and the employee or provide a noise reduction enclosure around the employee.

9.8.3 HPD Refit/Retrain For At Risk Employees

Employees who are identified as being "at risk" or most likely to develop threshold shift because of an early NIHL indicator, can be given additional training and individual attention.

The employee can be counselled on hearing loss prevention, and the HPD fit should be verified and documented. These employees could be checked for proper HPD fit periodically throughout the year, rather than on an annual basis.

9.8.4 Audiometric Testing Schedule

The audiometric test schedule can be adjusted to test high risk employees more frequently. For example, employees exposed over 105 dBA $L_{Aeq,8}$, may benefit from testing every 6 months. In addition, employees who have experienced an STS, can be retested on "rested ears" (no noise exposure at least 14 hours prior to the test) the day after the annual test showing the STS. The more immediate the follow-up, the better the chance is to identify temporary threshold shift due to excessive noise exposure.

9.8.5 Special Events For Hearing Awareness and Appreciation

Heightening the awareness of hearing and noise issues can foster a hearing healthy environment. There are national events focused on hearing as well as public health campaigns with educational materials and resources, such as International Noise Awareness Day, Better Hearing Month, etc.

9.8.6 Field Audits of HPD Use

Periodic personal protective equipment checks can be conducted randomly throughout the year, with an emphasis on proper hearing protection fit and use. HPDs should also be checked for wear, damage, and need for replacement.

9.8.7 Training Courses For Management

Additional training for managers and others responsible for enforcement of HCP policies is helpful to explain the rationale behind the company rules. Enhancing the knowledge of noise and hearing loss prevention increases motivation for administering an effective HCP.

9.8.8 HPD For Off The Job Exposure

Employees should be encouraged to use HPDs away from work when exposed to hazardous noise in recreational activities.

By including non-occupational noise exposure information in the employee training and providing HPDs for use away from work, the employee may be more willing and able to practice hearing loss prevention for all hazardous exposures, both at work and outside the workplace.

9.9 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. 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. A side effect of annoyance is stress that can affect some health conditions. Economic effects will also trigger complaints; increased noise in a previously quiet community can change the value of property.

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.

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. Consequently, companies that operate multiple facilities can face significantly different environmental noise challenges at various locations.

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 local 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. 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 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.

Measures of Environmental Noise

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 the level exceeded for 10% of the time, L_{A10}, to represent the noise from the source and the level exceeded for 90% of the time , L_{A90}, to represent the background noise. 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 is used in special circumstances related to impulsive noise. 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., which is used throughout much of Europe.

In different countries there are some variations in the times used for the day, evening and night to reflect the social traditions of the region.

10.1 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 recognised 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 directive covers the effects of transportation and industrial noise on the environment, and requires Member States to:

- Determine environmental noise exposure by requiring sound emissions noise contour mapping,
- Inform the public on environmental noise and its effects,
- Develop local action plans to reduce noise where applicable,
- Preserve areas with acceptable noise quality, and
- Continue to collect noise data for future policy.

The directive applies to:

- Agglomerations or areas with populations more than 100,000 persons, and
- Transportation: major roads with traffic exceeding 3,000,000 vehicles per year, railways with more than 30,000 train passages per year, and municipal airports with more than 50,000 flights per year.

The directive lays down several deadlines, many of which are still pending, to completely phase in the rule by 2012.

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).*

10.2 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), 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 about 770 people per square kilometre. 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 Leq 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:

Ld = 57.6

The Nighttime Average is:

Ld = 53.9

L_{dn} = 61.1 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 nighttime 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.

10.3 OTHER APPROACHES TO ENVIRONMENTAL CRITERIA

To overcome the limitations of the use of a time averaged level like Ldn or Lden, many jurisdictions have developed environmental noise legislation that specified noise levels that should not exceed at various times during the day. A ten or fifteen minute average of the noise level is then compared with the noise level considered to be suitable for the type of area and time of day. An excess of 5 dB may be accepted but any greater excess requires action to reduce the overall noise impact. An example of these noise limits is provided in Table 10.1.

Table 10.1 – Example of Legislated Environmental Noise Limits

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 ie 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.

(Source: Mikl & Burgess – *Based on the principles of AS 1055*)

10.4 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 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.

10.5 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 (SPL)* 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 SPLs at different locations from the source. For sound radiating from a point source in a free field, the SPL per octave band at a given distance may be calculated from:

$$L_p = L_w - A_{total} - 10.9 \quad \text{dB}$$

where,

L_p = the octave-band sound pressure level, 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:

$$A_{total} = A_{div} + A_{air} + A_{env} + A_{misc} \quad \text{dB}$$

where,

A_{div} is the attenuation due to geometrical divergence,

A_{air} is the air absorption,

A_{env} is the sound reduction due to the 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 usually 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.

10.5.1 Geometrical Divergence

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:

$A_{div} = 20 \log r/r_0$ 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, which equates to a 20-dB decrease for each tenfold increase of distance. 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 3-dB decrease per doubling of distance.

10.5.2 Air Attenuation or Atmospheric Absorption

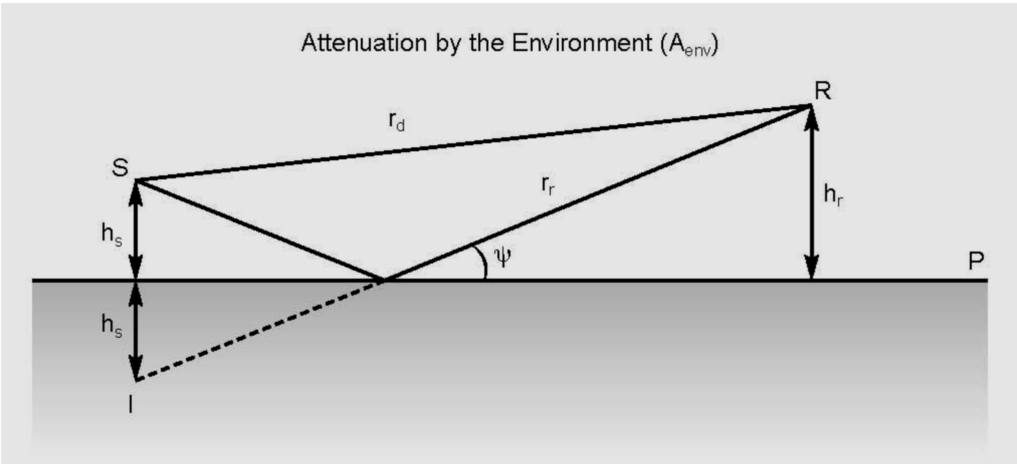
Sound energy decreases in a quiet calm atmosphere by two mechanisms: (1) heat conduction and viscosity in the air, and (2) relaxation of air molecules as they vibrate (Kurze and Beranek, 1988). The atmospheric absorption losses depend on frequency, temperature and relative humidity. Of these three factors, relative humidity is the dominant variable, followed by the frequency and then the temperature.

10.5.3 Attenuation Due to Environmental Effects

In addition to divergence and air absorption, sound propagating from a source is also attenuated by the environment, such as the ground, wind and temperature gradients. Figure 10.1 illustrates the propagation path from source to receiver. 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^o 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.
- *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.



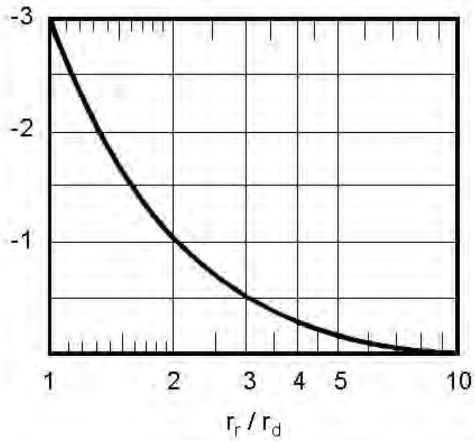
(Source: From Piercy and Daigle - *Used with permission*)

Figure 10.1 - Paths for propagation from source S to receiver R. The direct ray is r_d, and the ray reflected from the plane P (which effectively comes from image source I) is r_r, whose length is measured from plane P to R.

Table 10.2

Values of environmental attenuation A_{env} in decibels for short-range propagation [r < 100 m (300 ft)].*

***Hard ground** (asphalt, concrete)*

$(r_r - r_d) \ll$ all λ	$(r_r - r_d) \gg$ all λ
– 6.0	

***Soft ground** (grass, vegetation), h_r = 1.8 m*

Source Height (m)	*Distance (m)*	*Frequency (Hz)*					
		125	*250*	*500*	*1000*	*2000*	*4000*
0.01	10	- 5.7	- 5.0	- 3.6	- 1.4	1.1	4.1
	20	- 5.6	- 4.6	- 1.8	1.9	5.1	8.5
	40	- 5.5	- 3.9	- 1.4	6.7	10.1	13.7
	60	- 5.4	- 3.3	4.2	9.8	13.2	16.9
	80	- 5.4	- 2.7	6.8	12.2	15.5	19.3
	100	- 5.3	- 2.2	9.2	14.0	17.4	21.1
0.3	10	-5.4	- 4.3	- 0.9	5.9	- 2.5	- 1.9
	20	- 5.4	- 4.0	- 0.1	6.3	- 0.1	- 3.0
	40	- 5.4	- 3.4	2.9	10.2	4.1	- 2.9
	60	- 5.3	- 2.8	5.8	13.1	7.1	- 0.4
	80	- 5.2	- 2.2	8.4	15.3	9.3	1.7
	100	- 5.2	- 1.7	10.8	17.1	11.1	3.4
1.2	10	- 4.0	2.0	0.1	- 3.0	- 3.0	- 3.0
	20	- 4.8	- 1.9	7.5	- 2.7	- 3.0	- 3.0
	40	- 4.9	- 2.1	6.9	0.5	- 3.0	- 3.0
	60	- 4.9	- 1.6	9.1	2.9	- 3.0	- 3.0
	80	- 4.8	-1.0	11.6	4.8	- 2.8	- 3.0
	100	- 4.8	- 0.5	13.8	6.4	- 1.5	- 3.0

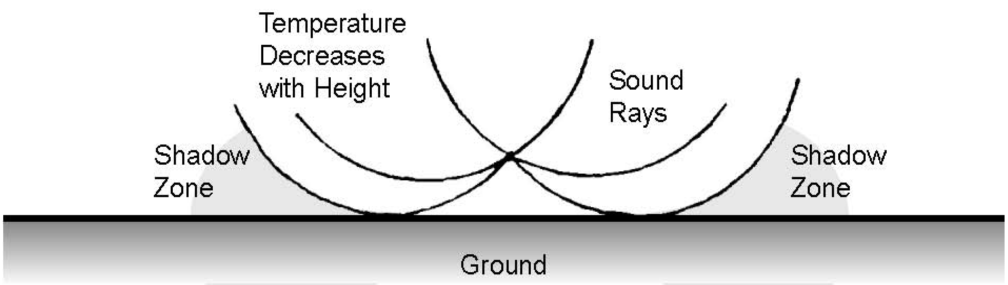
(Source: From Piercy and Daigle (1991) – *Used with permission*)

* Note: Refer to Figure 10.1 for illustration of r_d and r_r which are the paths for sound wave propagation from source to reviewer.

10.5.4 Effects of Wind and Temperature

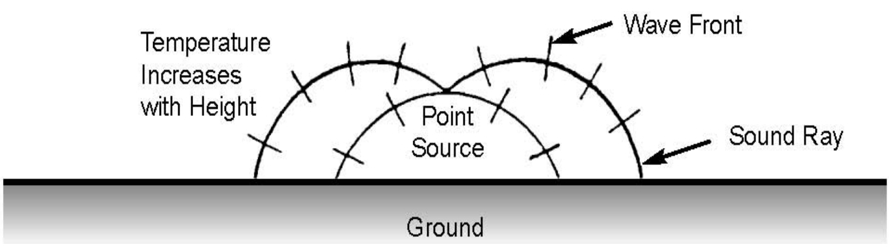
Sound wave propagation follows a predictable model in a still environment. However, sound will not conform to any predictable pattern in windy conditions. As temperature changes occur, there is a corresponding change in the speed of sound.

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 10.2. 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 10.2 - Wave Propagation During Daytime

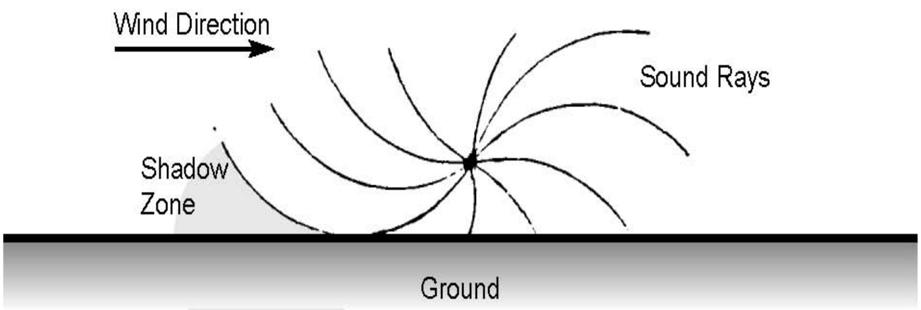


(Source: The Noise Manual, 5th Edition – *Courtesy AIHA Press)*

Figure 10.3 - Wave Propagation During Daytime

Figure 10.3 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.

Figure 10.4 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 10.4 - 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.

10.5.5 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 10.3

The attenuation due to propagation through foliage, such as trees and bushes.

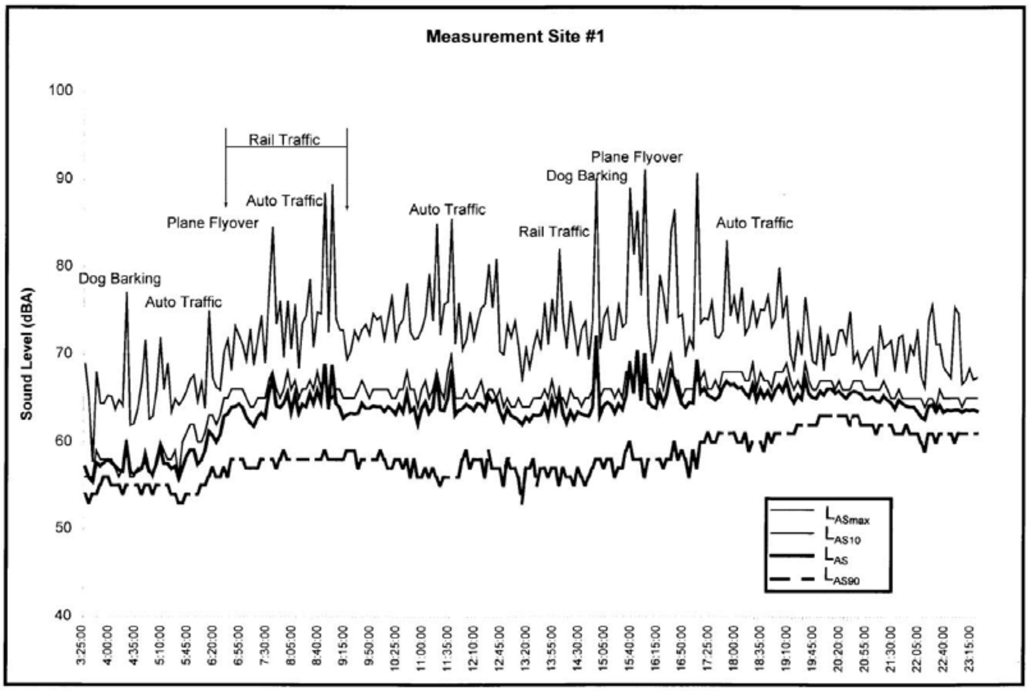
	Octave-Band Center Frequency (Hz)							
	31.5	63	125	500	1000	2000	4000	8000
A_{misc} (dB/m)	0.02	0.02	0.03	0.04	0.05	0.06	0.08	0.12

(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 10.3 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).

10.6 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 10.5 – Example Time-History Log

10.7 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 discernable 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.

Berger (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.

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.

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

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.

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.

EC (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.

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.

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.

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.

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.

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.

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.

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 Labeling 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.

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.

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., Gatley, W. S., and Eversen, H. A., (1980). *Noise Control for Engineers*, McGraw-Hill Book Co., New York, NY.

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.

NIOSH (1998). “*Criteria for a Recommended Standard*,” Occupational Noise Exposure, Revised Criteria,” DHHS (NIOSH) Pub. No. 98-126, Cincinnati, OH.

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.

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.

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). <u>A Practical Guide to Noise and Vibration Control for HVAC Systems</u>, 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.