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Occupational exposure to noise evaluation, prevention and control

ABSTRACT

This book with CD-ROM is intended for occupational hygienists and other occupational health and safety personnel as an introduction to the subject and as a handbook as well. It provides an overview of the evaluation, prevention and control of exposure to noise at the workplace, with a view to preventing noise-induced hearing loss. It starts with the fundamentals of acoustics, including the quantities to be measured and their relation to the psychology of hearing. Further details are given in the following chapters on the physiology and pathophysiology of the ear and hearing. The discussion of the occupational causes of hearing loss and the impossibility to recover from severe damages of the inner ear leads to the important issue of exposure criteria. Since there is agreement that noise reduction at source is the first choice for preventing hearing loss, basic information on noise sources is given in the next chapter. The next two chapters deal with the evaluation of exposure to noise, covering strategy for noise surveys and details on the required instruments, including their use and calibration. In spite of all efforts to reduce noise at the workplace, it is necessary to monitor the indidual‘s hearing by repeated audiometry; this is covered in an extensive chapter, which also deals with the training of audiometric testing personnel and the preparation of the workers to be tested. Legal provisions in many countries require the hazard prevention by control programmes. Principles and measures for engineering noise control, as well as hearing conservation programmes and their management, are presented, always placing control of noise at the source in the center of any preventive strategy. However, the importance of personal measures should not be overlooked and this is covered in a chapter which includes an introduction to the different hearing protectors as well as workers' education and training. Sources of information are given in the last chapter emphasizing the importance of standards for noise control at the design stage and leads to collections of relevant case studies.

Key words:

audiometry, collections of case studies, control programmes, engineering noise control, evaluation, exposure criteria, fundamentals of acoustics, hazard prevention, hearing loss, hearing protectors, industrial hygienists, measurements, measuring instruments, noise control at source, personal measures, physiology of the ear and hearing, programme management, occupational health and safety personnel, standards, strategy for noise surveys, training

L'exposition au bruit en milieu professionnel
Evaluation, prévention et réduction

RÉSUMÉ

Ce livre, accompagné d'un CD-ROM, est destiné aux hygiénistes industriels, aux médecins du travail et aux animateurs en hygiène et sécurité pour lesquels il doit servir aussi bien d'introduction au thème que de manuel de référence. Il offre un aperçu sur l'évaluation de l'exposition au bruit en milieu professionnel, sur les mesures de prévention et de réduction du bruit et a pour but principal de lutter contre les surdités induites par le bruit sur les lieux de travail. Les notions fondamentales de l'acoustique et les grandeurs à mesurer sont présentées ainsi que leur relation avec la sensibilité auditive. Les informations sur la physiologie de l'oreille et les maladies de l'audition conduisent à une discussion sur les causes professionnelles de la perte de l'audition et sur le caractère irrémédiable des troubles cochléaires. Elle soulève la question des limites d'exposition. Partant de la conviction que la réduction du bruit à la source est primordiale pour la prévention de la perte de l'audition, les notions fondamentales concernant les sources de bruit sont présentées.L'évaluation de l'exposition au bruit est abordée et une démarche à suivre pour son mesurage est proposée. Elle est complétée par des informations détaillées concernant les appareils de mesure à utiliser et leur étalonnage. Malgré tous les efforts entrepris pour réduire le bruit sur les lieux de travail, il est nécessaire de surveiller l'ouïe de chaque individu par audiométrie régulière. Cette question est traitée en détail dans un chapitre qui couvre également la formation des techniciens en audiométrie et la préparation des employés à examiner. Dans un grand nombre de pays, des prescriptions légales imposent la prévention des risques par la mise en œuvre de programmes de prévention. Un chapitre présente les principes et moyens techniques de réduction du bruit, de même que les programmes de surveillance médicale et leur organisation, la réduction du bruit à la source restant le centre d'intérêt de toute stratégie préventive. L'importance des mesures de protection des personnes exposées ne devant toutefois pas être oubliée, un chapitre présente les divers protecteurs individuels ainsi que la formation et la sensibilisation des employés. Enfin, le dernier chapitre présente les sources d'information, relatives aux normes sur la réduction du bruit, au stade de la conception et de la construction des machines et équipements et renvoie à diverses études de cas.

Mots clés

animateurs en hygiéne et sécurité, audiométrie, appareils de mesure, exemples de réalisations, déficit auditif, évaluation, de formation, hygiénistes industriels, limites d'exposition, médicins du travail, normes, notions fondamentales de l'acoustique, perte d'audition, physiologie de l'oreille, audition, programmes de réduction, programmes de surveillance médicale, protecteurs individuels, réduction des bruits à la source, études de cas, sources de bruit, conception et construction des machines et équipements

Berufliche Lärmbelastung
Bewertung, Verhütung und Minderung

KURZREFERAT

Dieses Buch mit CD-ROM ist für Arbeitsschutzexperten, Arbeitsmediziner und Fachkräfte für Arbeitssicherheit bestimmt als Einführung in das Thema wie auch als Handbuch. Es bietet eine Übersicht über Bewertung, Verhütung und Minderung der Lärmbelastung am Arbeitsplatz mit dem Ziel, lärmbedingten Hörverlust zu vermeiden. Es beginnt mit den Grundlagen der Akustik einschließlich der zu messenden Größen und ihrer Beziehung zum Hörempfinden. Weitere Details werden in den folgenden Kapiteln zur Physiologie und zu den Erkrankungen von Ohr und Gehör dargestellt. Die Diskussion der beruflichen Ursachen von Hörverlust und die Unmöglichkeit der Erholung von schweren Innenohrschäden führt zu der wichtigen Frage der Belastungsgrenzen. Aufgrund der Überzeugung, daß die Lärmminderung an der Quelle vorrangig für die Verhütung von Hörverlust ist, wird im nächsten Kapitel grundlegend über Geräuschquellen informiert.Die folgenden zwei Kapitel behandeln die Bewertung der Lärm-exposition, wobei sie das Vorgehen bei der Geräuscherfassung und Einzelheiten zu den erforderlichen Meßgeräten, ihren Gebrauch und die Kalibrierung einschließen. Trotz aller Anstrengungen, den Lärm am Arbeitsplatz zu mindern, ist es notwendig, das Gehör des Einzelnen durch wiederholte Audiometrie zu überwachen; dies wird in einem ausführlichen Kapitel dargestellt, das auch die Ausbildung von Audiometristen behandelt sowie die Vorbereitung der zu untersuchenden Beschäftigten. Gesetzliche Vorschriften vieler Länder fordern die Gefahrenverhütung durch Minderungsprogramme. Prinzipien und Mittel der technischen Lärmminderung wie auch Gehörvorsorgeprogramme und ihre Organisation werden dargestellt, wobei die Lärmminderung an der Quelle stets in den Mittelpunkt jeglicher vorbeugenden Strategie gerückt wird. Die Bedeutung personenbezogener Maßnahmen darf jedoch nicht übersehen werden und so folgt ein Kapitel, das eine Einführung zu den verschiedenen Gehörschützern wie auch Schulung und Training der Mitarbeiter umfaßt. Im letzten Kapitel werden Informationsquellen genannt, dabei die Bedeutung der Normen für das lärmarme Konstruieren hervorgehoben und Sammlungen von diesbezüglichen Fallbeispielen mitgeteilt.

Schlagwörter:

Arbeitsmediziner, Audiometrie, Belastungsgrenzen, Bewertung**,** Fachkräfte für Arbeitssicherheit, Gefahrenverhütung, Gehörschützer, Gehörvorsorgeprogramm, Geräuschquelle, Grundlagen der Akustik, Hörverlust, lärmarmes Konstruieren, Lärmminderung an der Quelle, Meßgerät, Minderungsprogramm, Normen, personenbezogene Maßnahmen, Physiologie von Ohr und Gehör, Sammlungen von Fallbeispielen, Schulung, technische Lärmminderung, Training, Vorgehen bei der Geräuscherfassung

BACKGROUND

An international meeting of experts in the field of acoustics was organized by the Office of Occupational Health, World Health Organization, Geneva, 25 -27 September 1995, with the objective of producing a document on the occupational aspects of noise including its effects on humans, particularly hearing loss, its measurement and exposure assessment, and its prevention and control. The meeting was attended by 19 specialists from 16 countries (see list of participants), many of whom contributed new materials for the proposed document.

Work began on this document several years earlier. Ms. Berenice Goelzer from WHO prepared a first draft with contributions from a number of experts in the field of occupational noise, including Professor D. Pupo Noguiera (Brazil), Professor J. Malchaire (Belgium) and Professor Darabont (Romania). In view of other priorities, the project was suspended until 1995, when funds provided under the National Institute for Occupational Safety and Health (NIOSH) Cooperative Agreement for 1994 - 1995 led to the organization of a meeting for the completion, revision and finalization of this document.

The World Health Organization Headquarters and the editors gratefully acknowledge the NIOSH grant and the help and patience of all contributors who attended the meeting in 1995, prepared chapters or clauses, or collaborated by correspondence.

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FOREWORD

Rock, reggae, Rachmaninov – is it sound or noise? The answer depends on your perspective. A natural gas compressor station makes noise from the neighbor's outlook; from the owner's point of view, it makes money. Whatever your perspective, it is undeniably true that we are increasingly surrounded by noise. According to NIOSH, "Noise is one of the most pervasive occupational health problems in America today; approximately thirty million workers are exposed on their jobs to noise levels that are potentially hazardous to their hearing". In developing countries, the situation is usually worse since less effort is expended on noise control.

Elevated noise levels may lead to a number of adverse effects, including elevated blood pressure and sleep interference, and may also interfere with communications in the workplace, thus contributing to the occurrence of accidents. However, the most serious effect is irreversible hearing impairment, resulting from damage to the delicate hearing mechanism of the inner ear. There is no cure for hearing impairment--the only solution is prevention. Fortunately, most occupational noise exposure can be minimized by the use of engineering controls to reduce the generation of noise at its source. This approach, which usually does not require the active participation of workers, is recommended by health and safety professionals around the world. Administrative controls and hearing protective devices can further reduce noise exposure.

The physics of noise, the physiology of hearing, and the evaluation, prevention, and control of noise exposure are complex subjects which deserve thorough treatment.

Occupational Exposure to Noise: Evaluation, Prevention and Control was written and edited by renowned experts in the field. It can be used as a textbook by senior and graduate-level students in occupational health and engineering courses and as a reference book by occupational hygienists, safety specialists, noise engineers, health and safety officials, manufacturers, consultants, audiologists, and plant managers. Although the book is directed towards control of occupational noise, much of it is also applicable to environmental noise. Thus, environmental engineers will also find specific answers to their questions in individual chapters.

Detailed introductions to noise and the physiology of the ear are presented in Chapters 1, 2, and 3. The in-depth discussion of these subjects is applicable both to occupational and environmental noise exposures (as are Chapters 6 and 8). Chapter 4 provides a background on occupational noise exposure limits from the European, American, and international perspectives. A catalogue of industrial noise sources and emission levels is presented in Chapter 5. Chapter 6 will be valuable to occupational and environmental specialists alike, as it describes the components and operation of various sound measuring instruments. Thorough guidance for conducting an industrial noise survey is contained in Chapter 7. The fundamentals of hearing measurement, including equipment and procedures, are presented in Chapter 8. Chapter 9 provides a background to management of noise hazards through prevention and control programmes. Chapter 10 is brimming with practical suggestions for engineering control of industrial noise sources. For situations in which engineering controls are infeasible or inadequate for complete hearing protection, Chapter 11 describes administrative controls and personal protective equipment. And finally, Chapter 12 presents an extensive list of references.

We are convinced that this treatise on evaluation, prevention and control of noise will prove valuable to anyone who is charged with reducing occupational noise exposures and protecting workers' hearing.

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ABBREVIATIONS

AAO	American Academy of Otolaryngology
AAOO	American Academy of Ophthalmology and Otolaryngology
ACGIH	American Conference of Governmental Industrial Hygienists
AIHA	American Industrial Hygiene Association
AMRL	Aerospace Medical Research Laboratory (USA)
ANSI	American National Standards Institute
APV	Assumed Protection Value
AS	Australian Standard
ASHA	American Speech-Language-Hearing Association
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineering
BMA	Bundesministerium für Arbeit und Sozialordnung (*Federal Ministry for Labour and Social Affairs, Germany*)
CAOHC	Council for Accreditation in Occupational Hearing Conservation (USA)
CCOHS	Canadian Center for Occupational Health and Safety
CEN	Comité Européen de Normalisation (*European Committee for Standardization*)
CENELEC	Comité Européen de Normalisation Electrotechnique (*European Committee for Electrotechnical Standardization*)
CHABA	Committee on Hearing and Bioacoustics (USA)
DFT	digital Fourier transform
DHEW	US Department of Health, Education and Welfare
DI	directivity index
EEC	European Economic Community
EN	European Standard
EPA	Environmental Protection Agency (USA)
FFT	fast Fourier transform
FIOH	Finnish Institute for Occupational Health
FIOSH	Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (*Federal Institute for Occupational Safety and Health, Germany*)
FM	frequency modulation
HCP	hearing conservation program
HEG	homogeneous exposure group
HL	hearing loss
HLI	hearing loss index
HML	high-middle-low rating
HTL	hearing threshold level
HSE	Health and Safety Executive, UK
IEC	International Electrotechnical Commission
IL	insertion loss
ILO	International Labour Office / - Organization

INCE	Institute of Noise Control Engineering (USA)
I-INCE	International Institute of Noise Control Engineering
INRETS	Institut National de Recherche sur les Transports et leur Sécurité (*The French National Institute for Transport and Safety Research*)
INRS	Institut National de Recherche et de Sécurité (*National Research and Safety Institute for the prevention of occupational accidents and diseases, France*)
ISO	International Organization for Standardization
ISVR	Institute for Sound and Vibration Research, Southampton, UK
LCL	lower confidence limit
MAF	minimum audible field
MIL-STD	Military Standard (USA)
MSHA	Mine Safety and Health Administration (USA)
NC	noise criterion
NCB	balanced noise criterion
NHCA	National Hearing Conservation Association (USA)
NIHL	noise induced hearing loss
NIOSH	National Institute for Occupational Safety and Health (USA)
NIPTS	noise-induced permanent threshold shift
NR	noise rating
NRB	octave band noise rating
NRC	noise reduction coefficient
NRR	noise reduction rating
OEL	occupational exposure limits
OHC	outer hair cells
OME	otitis media with effusion
OSHA	Occupational Safety and Health Administration (USA)
PEL	permissible exposure level
PIMEX	picture mix exposure
PTS	permanent threshold shift
PWL	sound power level
REAT	real-ear-attenuation-at-threshold
RMS	root mean square
RPM	rotations per minute
SIL	speech interference level
SLM	sound level meter
SNR	single-number rating
SPL	sound pressure level
STS	standard threshold shift
TC	Technical Committee
TL	transmission loss
TLV	threshold limit value
TR	Technical Report
TTS	temporary threshold shift
TTS2	TTS measured 2 minutes after exposure
TWA8	time-weighted average for eight hours
UCL	upper confidence limit
VDI	Verein Deutscher Ingenieure (VDI-Guidelines) (*German Engineering Assoc.*)

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FUNDAMENTALS OF ACOUSTICS

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Fundamental aspects of acoustics are presented, as they relate to the understanding and application of a methodology for the recognition, evaluation and prevention or control of noise as an occupational hazard. Further information can be found in the specialised literature listed at the end of the chapter.

1.1. PHYSICS OF SOUND

To provide the necessary background for the understanding of the topics covered in this document, basic definitions and other aspects related to the physics of sound and noise are presented. Most definitions have been internationally standardised and are listed in standards publications such as IEC 60050-801(1994).

Noise can be defined as "disagreeable or undesired sound" or other disturbance. From the acoustics point of view, **sound** and **noise** constitute the same phenomenon of atmospheric pressure fluctuations about the mean atmospheric pressure; the differentiation is greatly subjective. What is **sound** to one person can very well be noise to somebody else. The recognition of noise as a serious health hazard is a development of modern times. With modern industry the multitude of sources has accelerated noise-induced hearing loss; amplified music also takes its toll. While amplified music may be considered as sound (not noise) and to give pleasure to many, the excessive noise of much of modern industry probably gives pleasure to very few, or none at all.

Sound (or noise) is the result of pressure variations, or oscillations, in an elastic medium (e.g., air, water, solids), generated by a vibrating surface, or turbulent fluid flow. Sound propagates in the form of longitudinal (as opposed to transverse) waves, involving a succession of compressions and rarefactions in the elastic medium, as illustrated by Figure 1.1(a). When a sound wave propagates in air (which is the medium considered in this document), the oscillations in pressure are above and below the ambient atmospheric pressure.

1.1.1. Amplitude, Frequency, Wavelength And Velocity

Sound waves which consist of a pure tone only are characterised by:

- the **amplitude of pressure changes**, which can be described by the maximum pressure amplitude, p_M, or the root-mean-square (RMS) amplitude, p_{rms}, and is expressed in Pascal (Pa). Root-mean-square means that the instantaneous sound pressures (which can be positive or negative) are squared, averaged and the square root of the average is taken. The quantity, $p_{rms} = 0.707\ p_M$;

- the **wavelength** (λ), which is the distance travelled by the pressure wave during one cycle;
- the **frequency** (f), which is the number of pressure variation cycles in the medium per unit time, or simply, the number of cycles per second, and is expressed in Hertz (Hz). Noise is usually composed of many frequencies combined together. The relation between wavelength and frequency can be seen in Figure 1.2.
- the **period** (T), which is the time taken for one cycle of a wave to pass a fixed point. It is related to frequency by: $T = 1/f$

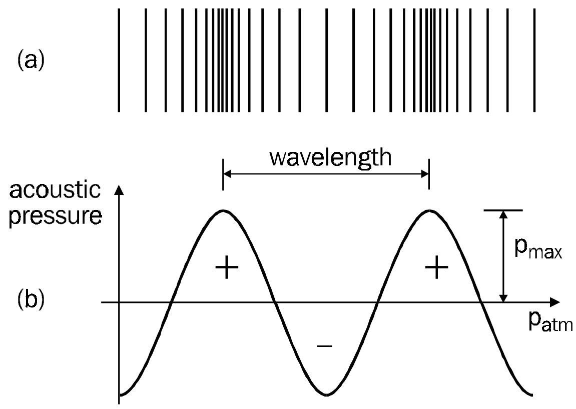


Figure 1.1. Representation of a sound wave.
(a) compressions and rarefactions caused in air by the sound wave.
(b) graphic representation of pressure variations above and below atmospheric pressure.

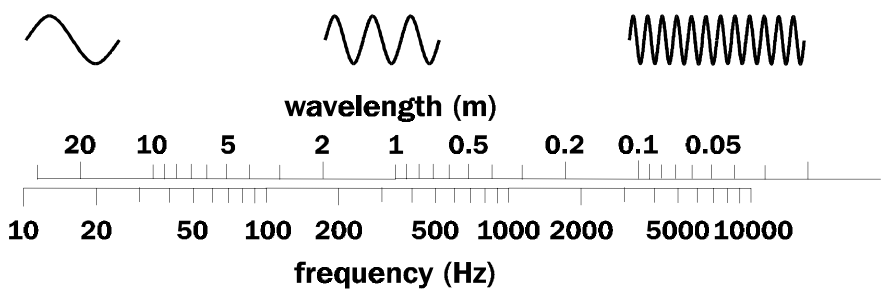


Figure 1.2. Wavelength in air versus frequency under normal conditions (after Harris 1991).

The speed of sound propagation, c, the frequency, f, and the wavelength, λ, are related by the following equation:

$$c = f\lambda$$

- the speed of propagation, c, of sound in air is 343 m/s, at 20°C and 1 atmosphere pressure. At other temperatures (not too different from 20°C), it may be calculated using:

$$c = 332 + 0.6T_c$$

where T_c is the temperature in $°C$. Alternatively the following expression may be used for any temperature and any gas. Alternatively, making use of the equation of state for gases, the speed of sound may be written as:

$$c = \sqrt{\gamma R T_k / M} \qquad (\mathrm{m\ s^{-1}}) \tag{1}$$

where T_k is the temperature in $°K$, R is the universal gas constant which has the value 8.314 J per mole°K, and M is the molecular weight, which for air is 0.029 kg/mole. For air, the ratio of specific heats, γ, is 1.402.

All of the properties just discussed (except the speed of sound) apply only to a pure tone (single frequency) sound which is described by the oscillations in pressure shown in Figure 1.1. However, sounds usually encountered are not pure tones. In general, sounds are complex mixtures of pressure variations that vary with respect to phase, frequency, and amplitude. For such complex sounds, there is no simple mathematical relation between the different characteristics. However, any signal may be considered as a combination of a certain number (possibly infinite) of sinusoidal waves, each of which may be described as outlined above. These sinusoidal components constitute the frequency spectrum of the signal.

To illustrate longitudinal wave generation, as well as to provide a model for the discussion of sound spectra, the example of a vibrating piston at the end of a very long tube filled with air will be used, as illustrated in Figure 1.3

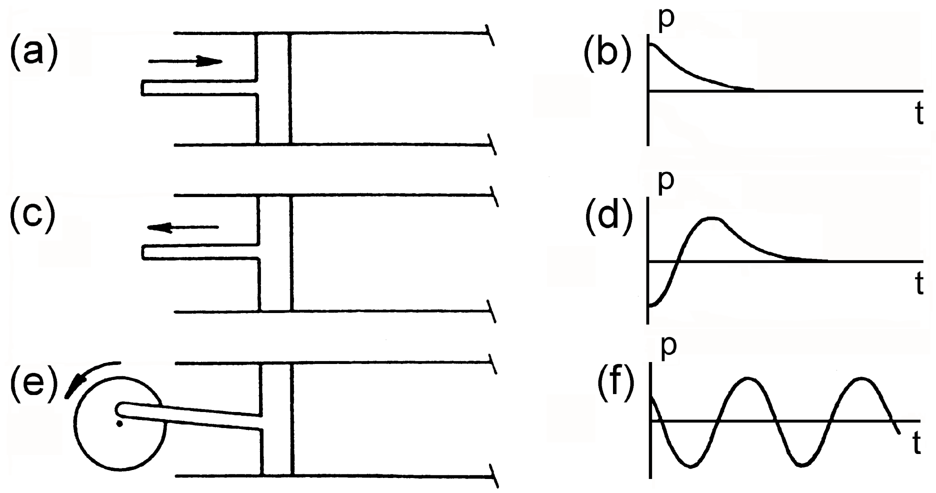


Figure 1.3. Sound generation illustrated. (a) The piston moves right, compressing air as in (b). (c) The piston stops and reverses direction, moving left and decompressing air in front of the piston, as in (d). (e) The piston moves cyclically back and forth, producing alternating compressions and rarefactions, as in (f). In all cases disturbances move to the right with the speed of sound.

Let the piston in Figure 1.3 move forward. Since the air has inertia, only the air immediately next to the face of the piston moves at first; the pressure in the element of air next to the piston increases. The element of air under compression next to the piston will expand forward, displacing the next layer of air and compressing the next elemental volume. A pressure pulse is formed which travels down the tube with the speed of sound, *c*. Let the piston stop and subsequently move backward; a rarefaction is formed next to the surface of the piston which follows the previously formed compression down the tube. If the piston again moves forward, the process is repeated with the net result being a "wave" of positive and negative pressure transmitted along the tube.

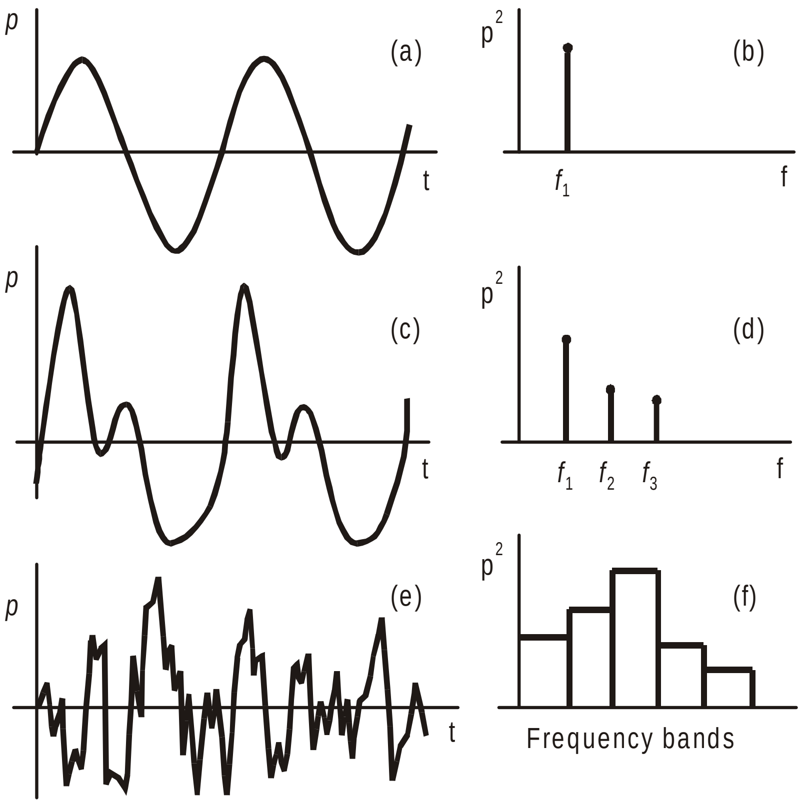


Figure 1.4. Spectral analysis illustrated. (a) Disturbance *p* varies sinusoidally with time *t* at a single frequency f_1, as in (b). (c) Disturbance *p* varies cyclically with time *t* as a combination of three sinusoidal disturbances of fixed relative amplitudes and phases; the associated spectrum has three single-frequency components f_1, f_2 and f_3, as in (d). (e) Disturbance *p* varies erratically with time *t*, with a frequency band spectrum as in (f).

If the piston moves with simple harmonic motion, a sine wave is produced; that is, at any instant the pressure distribution along the tube will have the form of a sine wave, or at any fixed point in the tube the pressure disturbance, displayed as a function of time, will have a sine wave appearance. Such a disturbance is characterised by a single frequency. The motion and corresponding spectrum are illustrated in Figure 1.4a and b.

If the piston moves irregularly but cyclically, for example, so that it produces the waveform shown in Figure 1.4c, the resulting sound field will consist of a combination of sinusoids of several frequencies. The spectral (or frequency) distribution of the energy in this particular sound wave is represented by the frequency spectrum of Figure 1.4d. As the motion is cyclic, the spectrum consists of a set of discrete frequencies.

Although some sound sources have single-frequency components, most sound sources produce a very disordered and random waveform of pressure versus time, as illustrated in Figure

1.4e. Such a wave has no periodic component, but by Fourier analysis it may be shown that the resulting waveform may be represented as a collection of waves of all frequencies. For a random type of wave the sound pressure squared in a band of frequencies is plotted as shown; for example, in the frequency spectrum of Figure 1.4f.

It is customary to refer to spectral density level when the measurement band is one Hz wide, to one third octave or octave band level when the measurement band is one third octave or one octave wide and to spectrum level for measurement bands of other widths.

Two special kinds of spectra are commonly referred to as white random noise and pink random noise. White random noise contains equal energy per hertz and thus has a constant spectral density level. Pink random noise contains equal energy per measurement band and thus has an octave or one-third octave band level which is constant with frequency.

1.1.2. Sound Field Definitions *(see ISO 12001)*

1.1.2.1. Free field

The free field is a region in space where sound may propagate free from any form of obstruction.

1.1.2.2. Near field

The near field of a source is the region close to a source where the sound pressure and acoustic particle velocity are not in phase. In this region the sound field does not decrease by 6 dB each time the distance from the source is increased (as it does in the far field). The near field is limited to a distance from the source equal to about a wavelength of sound or equal to three times the largest dimension of the sound source (whichever is the larger).

1.1.2.3. Far field

The far field of a source begins where the near field ends and extends to infinity. Note that the transition from near to far field is gradual in the transition region. In the far field, the direct field radiated by most machinery sources will decay at the rate of 6 dB each time the distance from the source is doubled. For line sources such as traffic noise, the decay rate varies between 3 and 4 dB.

1.1.2.4. Direct field

The direct field of a sound source is defined as that part of the sound field which has not suffered any reflection from any room surfaces or obstacles.

1.1.2.5. Reverberant field

The reverberant field of a source is defined as that part of the sound field radiated by a source which has experienced at least one reflection from a boundary of the room or enclosure containing the source.

1.1.3. Frequency Analysis

Frequency analysis may be thought of as a process by which a time varying signal in the time domain is transformed to its frequency components in the frequency domain. It can be used for quantification of a noise problem, as both criteria and proposed controls are frequency dependent. In particular, tonal components which are identified by the analysis may be treated somewhat differently than broadband noise. Sometimes frequency analysis is used for noise source identification and in all cases frequency analysis will allow determination of the effectiveness of controls.

There are a number of instruments available for carrying out a frequency analysis of arbitrarily time-varying signals as described in Chapter 6 . To facilitate comparison of measurements between instruments, frequency analysis bands have been standardised. Thus the International Standards Organisation has agreed upon "preferred" frequency bands for sound measurement and analysis.

The widest band used for frequency analysis is the octave band; that is, the upper frequency limit of the band is approximately twice the lower limit. Each octave band is described by its "centre frequency", which is the geometric mean of the upper and lower frequency limits. The preferred octave bands are shown in Table 1.1, in terms of their centre frequencies.

Occasionally, a little more information about the detailed structure of the noise may be required than the octave band will provide. This can be obtained by selecting narrower bands; for example, one-third octave bands. As the name suggests, these are bands of frequency approximately one-third of the width of an octave band. Preferred one-third octave bands of frequency have been agreed upon and are also shown in Table 1.1.

Instruments are available for other forms of band analysis (see Chapter 6). However, they do not enjoy the advantage of standardisation so that the inter-comparison of readings taken on such instruments may be difficult. One way to ameliorate the problem is to present such readings as mean levels per unit frequency. Data presented in this way are referred to as spectral density levels as opposed to band levels. In this case the measured level is reduced by ten times the logarithm to the base ten of the bandwidth. For example, referring to Table 1.1, if the 500 Hz octave band which has a bandwidth of 354 Hz were presented in this way, the measured octave band level would be reduced by $10 \log_{10} (354) = 25.5$ dB to give an estimate of the spectral density level at 500 Hz.

The problem is not entirely alleviated, as the effective bandwidth will depend upon the sharpness of the filter cut-off, which is also not standardised. Generally, the bandwidth is taken as lying between the frequencies, on either side of the pass band, at which the signal is down 3 dB from the signal at the centre of the band.

There are two ways of transforming a signal from the time domain to the frequency domain. The first involves the use of band limited digital or analog filters. The second involves the use of Fourier analysis where the time domain signal is transformed using a Fourier series. This is implemented in practice digitally (referred to as the DFT - digital Fourier Transform) using a very efficient algorithm known as the FFT (fast Fourier Transform). This is discussed further in the literature referenced at the end of the chapter.

1.1.3.1. A convenient property of the one-third octave band centre frequencies

The one-third octave band centre frequency numbers have been chosen so that their logarithms are one-tenth decade numbers. The corresponding frequency pass bands are a compromise; rather than follow a strictly octave sequence which would not repeat, they are adjusted slightly so that they repeat on a logarithmic scale. For example, the sequence 31.5, 40, 50 and 63 has the logarithms 1.5, 1.6, 1.7 and 1.8. The corresponding frequency bands are sometimes referred to as the 15th, 16th, etc., frequency bands.

Table 1.1. Preferred octave and one-third octave frequency bands.

Band number	Octave band center frequency	One-third octave band center frequency	Band limits Lower	Upper
14		25	22	28
15	31.5	31.5	28	35
16		40	35	44
17		50	44	57
18	63	63	57	71
19		80	71	88
20		100	88	113
21	125	125	113	141
22		160	141	176
23		200	176	225
24	250	250	225	283
25		315	283	353
26		400	353	440
27	500	500	440	565
28		630	565	707
29		800	707	880
30	1000	1000	880	1130
31		1250	1130	1414
32		1600	1414	1760
33	2000	2000	1760	2250
34		2500	2250	2825
35		3150	2825	3530
36	4000	4000	3530	4400
37		5000	4400	5650
38		6300	5650	7070
39	8000	8000	7070	8800
40		10000	8800	11300
41		12500	11300	14140
42	16000	16000	14140	17600
43		20000	17600	22500

*NOTE**:** Requirements for filters see IEC 61260; there index numbers are used instead of band numbers. The index numbers are not identical, starting with No.“0" at 1 kHz.*

When logarithmic scales are used in plots, as will frequently be done in this book, it will be well to remember the one-third octave band centre frequencies. For example, the centre frequencies given above will lie respectively at 0.5, 0.6, 0.7 and 0.8 of the distance on the scale between 10 and 100. The latter two numbers in turn will lie at 1.0 and 2.0 on the same logarithmic scale.

1.2. QUANTIFICATION OF SOUND

1.2.1. Sound Power (*W*) and Intensity (*I*) (*see ISO 3744, ISO 9614*)

Sound intensity is a vector quantity determined as the product of sound pressure and the component of particle velocity in the direction of the intensity vector. It is a measure of the rate at which work is done on a conducting medium by an advancing sound wave and thus the rate of power transmission through a surface normal to the intensity vector. It is expressed as watts per square metre (W/m^2).

In a free-field environment, i.e., no reflected sound waves and well away from any sound sources, the sound intensity is related to the root mean square acoustic pressure as follows

$$I = \frac{p_{rms}^2}{\rho c} \tag{2}$$

where ρ is the density of air (kg/m^3), and c is the speed of sound (m/sec). The quantity, ρc is called the "acoustic impedance" and is equal to 414 Ns/m^3 at 20°C and one atmosphere. At higher altitudes it is considerably smaller.

The total sound energy emitted by a source per unit time is the sound power, *W*, which is measured in watts. It is defined as the total sound energy radiated by the source in the specified frequency band over a certain time interval divided by the interval. It is obtained by integrating the sound intensity over an imaginary surface surrounding a source. Thus, in general the power, *W*, radiated by any acoustic source is,

$$W = \int_A \boldsymbol{I} \cdot \boldsymbol{n} \, \mathrm{d}A \tag{3}$$

where the dot multiplication of I with the unit vector, $\boldsymbol{n}$, indicates that it is the intensity component normal to the enclosing surface which is used. Most often, a convenient surface is an encompassing sphere or spherical section, but sometimes other surfaces are chosen, as dictated by the circumstances of the particular case considered. For a sound source producing uniformly spherical waves (or radiating equally in all directions), a spherical surface is most convenient, and in this case the above equation leads to the following expression:

$$W = 4\pi r^2 I \tag{4}$$

where the magnitude of the acoustic intensity, I, is measured at a distance r from the source. In this case the source has been treated as though it radiates uniformly in all directions.

1.2.2. Sound Pressure Level

The range of sound pressures that can be heard by the human ear is very large. The minimum acoustic pressure audible to the young human ear judged to be in good health, and unsullied by too much exposure to excessively loud music, is approximately 20 x 10^{-6} Pa, or 2 x 10^{-10} atmospheres (since 1 atmosphere equals 101.3 x 10^3 Pa). The minimum audible level occurs at about 4,000 Hz and is a physical limit imposed by molecular motion. Lower sound pressure levels would be swamped by thermal noise due to molecular motion in air.

For the normal human ear, pain is experienced at sound pressures of the order of 60 Pa or 6 x 10^{-4} atmospheres. Evidently, acoustic pressures ordinarily are quite small fluctuations about the mean.

A linear scale based on the square of the sound pressure would require 10^{13} unit divisions to cover the range of human experience; however, the human brain is not organised to encompass such a range. The remarkable dynamic range of the ear suggests that some kind of compressed scale should be used. A scale suitable for expressing the square of the sound pressure in units best matched to subjective response is logarithmic rather than linear. Thus the Bel was introduced which is the logarithm of the ratio of two quantities, one of which is a reference quantity.

To avoid a scale which is too compressed over the sensitivity range of the ear, a factor of 10 is introduced, giving rise to the decibel. The level of sound pressure p is then said to be L_p decibels (dB) greater or less than a reference sound pressure p_{ref} according to the following equation:

$$L_p = 10\log_{10}\frac{p_{rms}^2}{p_{ref}^2} = 20\log_{10}\frac{p_{rms}}{p_{ref}} = 20\log_{10}p_{rms} - 20\log_{10}p_{ref} \qquad \text{(dB)} \tag{5}$$

For the purpose of absolute level determination, the sound pressure is expressed in terms of a datum pressure corresponding to the lowest sound pressure which the young normal ear can detect. The result is called the sound pressure level, L_p (or SPL), which has the units of decibels (dB). This is the quantity which is measured with a sound level meter.

The sound pressure is a measured root mean square (r.m.s.) value and the internationally agreed reference pressure p_{ref} = 2 x 10^{-5} N m^{-2} or 20 μPa . When this value for the reference pressure is substituted into the previous equation, the following convenient alternative form is obtained:

$$L_p = 20\log_{10}p_{rms} + 94 \qquad \text{(dB)} \tag{6}$$

where the pressure p is measured in pascals. Some feeling for the relation between subjective loudness and sound pressure level may be gained by reference to Figure 1.5, which illustrates sound pressure levels produced by some noise sources.

1.2.3. Sound Intensity Level

A sound intensity level, L_I, may be defined as follows:

$$L_I = 10\log_{10}\frac{\text{(sound intensity)}}{\text{(ref. sound intensity)}} \qquad \text{(dB)} \tag{7}$$

An internationally agreed reference intensity is 10^{-12} W m^{-2}, in which case the previous equation takes the following form:

$$L_I = 10\log_{10}I + 120 \qquad \text{(dB)} \tag{8}$$

Use of the relationship between acoustic intensity and pressure in the far field of a source gives the following useful result:

$$L_I = L_p + 10 \log_{10} \frac{400}{\rho c} \tag{8a}$$

$$L_I = L_p + 26 - 10 \log_{10}(\rho c) \qquad \text{(dB)} \tag{9}$$

At sea level and 20°C the characteristic impedance, ρc, is 414 kg m^{-2} s^{-1}, so that for both plane and spherical waves,

$$L_I = L_p - 0.2 \qquad \text{(dB)} \tag{10}$$

1.2.4. Sound Power Level

The sound power level, L_w (or PWL), may be defined as follows:

$$L_w = 10 \log_{10} \frac{\text{(sound power)}}{\text{(reference power)}} \qquad \text{(dB)} \tag{11}$$

The internationally agreed reference power is 10^{-12} W. Again, the following convenient form is obtained when the reference sound power is introduced into the above equation:

$$L_w = 10 \log_{10} W + 120 \qquad \text{(dB)} \tag{12}$$

where the power, W, is measured in watts.

For comparison of sound power levels measured at different altitudes a normalization according to equation (8a) should be applied, see ISO 3745.

1.2.5. Combining Sound Pressures

1.2.5.1. Addition of coherent sound pressures

Often, combinations of sounds from many sources contribute to the observed total sound. In general, the phases between sources of sound will be random and such sources are said to be incoherent. However, when sounds of the same frequency are to be combined, the phase between the sounds must be included in the calculation.

For two sounds of the same frequency, characterised by mean square sound pressures $p^2_{1\,rms}$ and $p^2_{2\,rms}$ and phase difference $\beta_1 - \beta_2$, the total mean square sound pressure is given by the following expression (Bies and Hansen, Ch. 1, 1996).

$$p^2_{t\,rms} = p^2_{1\,rms} + p^2_{2\,rms} + 2\,[p_1 p_2]_{rms} \cos(\beta_1 - \beta_2) \tag{13}$$

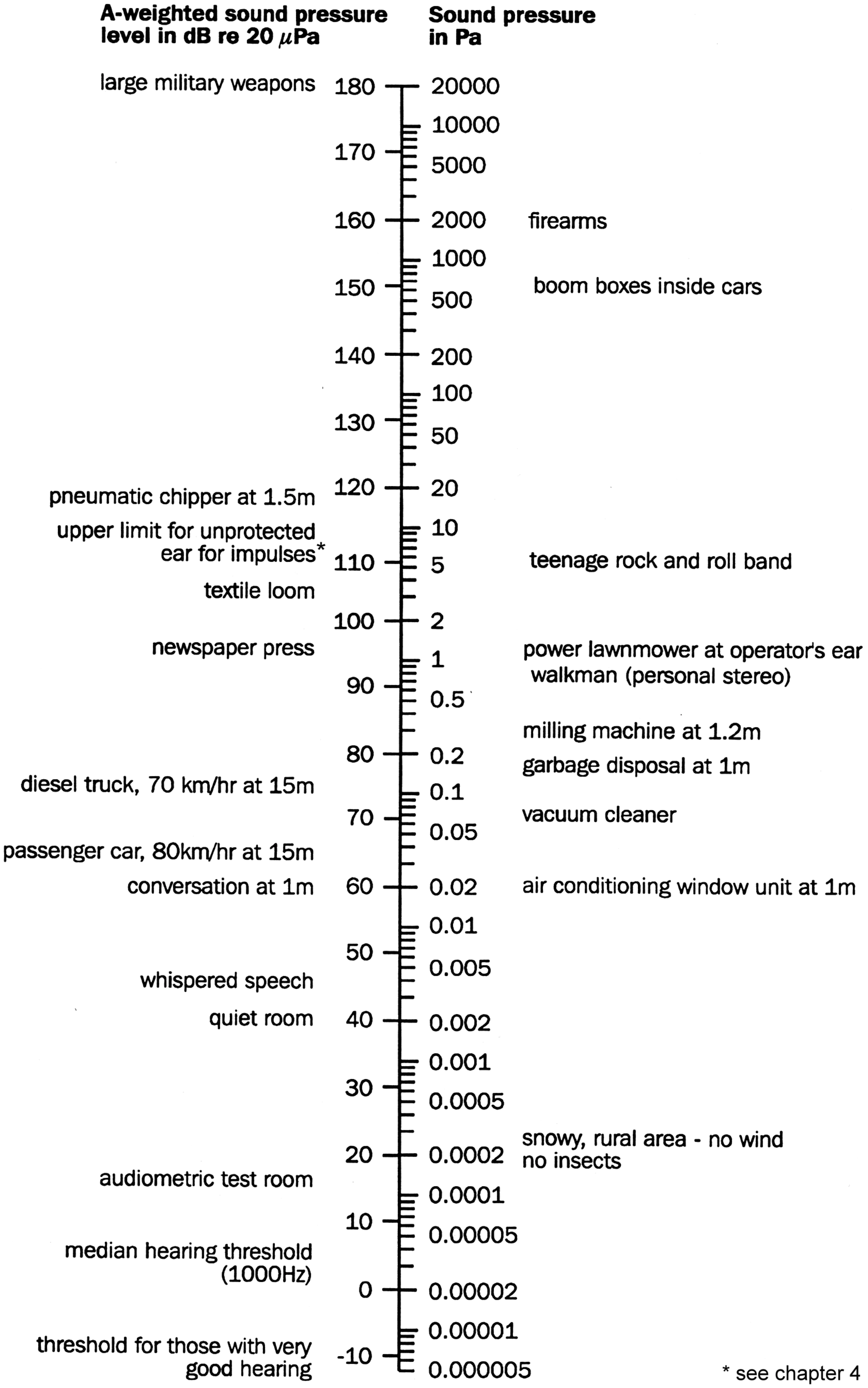


Figure 1.5. Sound levels produced by typical noise sources

When two sounds of slightly different frequencies are added an expression similar to that given by the above equation is obtained but with the phase difference replaced with the frequency difference, Δ, multiplied by time, *t*. In this case the total mean square sound pressure rises and falls cyclically with time and the phenomenon known as beating is observed, as illustrated in Figure 1.6.

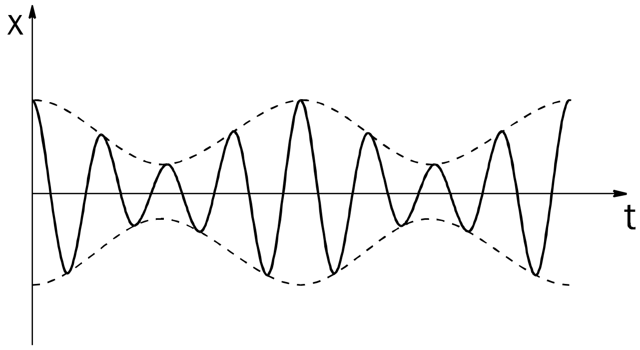


Figure 1.6. Illustration of beating.

1.2.5.2. Addition of incoherent sound pressures (logarithmic addition)

When bands of noise are added and the phases are random, the limiting form of the previous equation reduces to the case of addition of incoherent sounds; that is (Bies and Hansen, Ch. 1, 1996),

$$p_{t\ rms}^2 = p_{1\ rms}^2 + p_{2\ rms}^2 \tag{14}$$

Incoherent sounds add together on a linear energy (pressure squared) basis. A simple procedure which may easily be performed on a standard calculator will be described. The procedure accounts for the addition of sounds on a linear energy basis and their representation on a logarithmic basis. Note that the division by 10 in the exponent is because the process involves the addition of squared pressures.

It should be noted that the addition of two or more levels of sound pressure has a physical significance only if the levels to be added were obtained in the same measuring point.

EXAMPLE
Assume that three sounds of different frequencies (or three incoherent noise sources) are to be combined to obtain a total sound pressure level. Let the three sound pressure levels be (a) 90 dB, (b) 88 dB and (c) 85 dB. The solution is obtained by use of the previous equation.

Solution:
For source (a):

$$p_{1\ rms}^2 = p_{ref}^2 \times 10^{90/10} = p_{ref}^2 \times 10 \times 10^8$$

For source (b):

$$p_{2\ rms}^2 = p_{ref}^2 \times 6.31 \times 10^8$$

For source (c):

$$p_{3\ rms}^2 = p_{ref}^2 \times 3.16 \times 10^8$$

The total mean square sound pressure is,

$$p_{t\ rms}^2 = p_{1\ rms}^2 + p_{2\ rms}^2 + p_{3\ rms}^2 = p_{ref}^2 \times 19.47 \times 10^8$$

The total sound pressure level is,

$$L_{pt} = 10 \log_{10}[p_{t\ rms}^2 / p_{ref}^2] = 10 \log_{10}[19.47 \times 10^8] = 92.9 \text{ dB}$$

Alternatively, in short form,

$$L_{pt} = 10 \log_{10}\left(10^{90/10} + 10^{88/10} + 10^{85/10}\right) = 92.9 \text{ dB}$$

Table 1.2 can be used as an alternative for adding combinations of decibel values. As an example, if two independent noises with levels of 83 and 87 dB are produced at the same time at a given point, the total noise level will be 87 + 1.5 = 88.5 dB, since the amount to be added to the higher level, for a difference of 4 dB between the two levels, is 1.5 dB.

Table 1.2. Table for combining decibel levels.

Difference between the two db levels to be added dB										
0	1	2	3	4	5	6	7	8	9	10
3.0	*2.5*	*2.1*	*1.8*	*1.5*	*1.2*	*1.0*	*0.8*	*0.6*	*0.5*	*0.4*
Amount to be added to the higher level in order to get the total level dB										

As can be seen in these examples, it is only when two noise sources have similar acoustic powers, and are therefore generating similar levels, that their combination leads to an appreciable increase in noise levels above the level of the noisier source. The maximum increase over the level radiated by the noisier source, by the combination of two random noise sources occurs when the sound pressures radiated by each of the two sources are identical, resulting in an increase of 3 dB over the sound pressure level generated by one source. If there is any difference in the original independent levels, the combined level will exceed the higher of the two levels by less than 3 dB. When the difference between the two original levels exceeds 10 dB, the contribution of the less noisy source to the combined noise level is negligible; the sound source with the lower level is practically not heard.

1.2.5.3. Subtraction of sound pressure levels

Sometimes it is necessary to subtract one noise from another; for example, when background noise must be subtracted from total noise to obtain the sound produced by a machine alone. The method used is similar to that described in the addition of levels and will be illustrated with an example.

EXAMPLE

The noise level measured at a particular location in a factory with a noisy machine operating nearby is 92 dB(A). When the machine is turned off, the noise level measured at the same location is 88 dB(A). What is the level due to the machine alone?

Solution

$$L_{pm} = 10 \log_{10}\left(10^{92/10} - 10^{88/10}\right) = 89.8 \text{ dB}(A)$$

For noise-testing purposes, this procedure should be used only when the total noise exceeds the background noise by 3 dB or more. If the difference is less than 3 dB a valid sound test probably cannot be made. Note that here subtraction is between squared pressures.

1.2.5.4. Combining level reductions

Sometimes it is necessary to determine the effect of the placement or removal of constructions such as barriers and reflectors on the sound pressure level at an observation point. The difference between levels before and after an alteration (placement or removal of a construction) is called the insertion loss, *IL*. If the level decreases after the alteration, the *IL* is positive; if the level increases, the *IL* is negative. The problem of assessing the effect of an alteration is complex because the number of possible paths along which sound may travel from the source to the observer may increase or decrease.

In assessing the overall effect of any alteration, the combined effect of all possible propagation paths must be considered. Initially, it is supposed that a reference level L_{pR} may be defined at the point of observation as a level which would or does exist due to straight-line propagation from source to receiver. Insertion loss due to propagation over any other path is then assessed in terms of this reference level. Calculated insertion losses would include spreading due to travel over a longer path, losses due to barriers, reflection losses at reflectors and losses due to source directivity effects (see Section 1.3).

For octave band analysis, it will be assumed that the noise arriving at the point of observation by different paths combines incoherently. Thus the total observed sound level may be determined by adding together logarithmically the contributing levels due to each propagation path.

The problem which will now be addressed is how to combine insertion losses to obtain an overall insertion loss due to an alteration. Either before alteration or after alteration, the sound pressure level at the point of observation due to the *i*th path may be written in terms of the *i*th path insertion loss, IL_i, as (Bies and Hansen, Ch. 1, 1996)

$$L_{pi} = L_{pR} - IL_i \tag{15}$$

In either case, the observed overall noise level due to contributions over *n* paths is

$$L_p = L_{pR} + 10 \log_{10} \sum_{i=1}^{n} 10^{-(IL_i/10)} \tag{16}$$

The effect of an alteration will now be considered, where note is taken that, after alteration, the propagation paths, associated insertion losses and number of paths may differ from those before alteration. Introducing subscripts to indicate cases *A* (before alteration) and *B* (after alteration) the overall insertion loss $(IL = L_{pA} - L_{pB})$ due to the alteration is (Bies and Hansen, Ch. 1, 1996),

$$IL = 10 \log_{10} \sum_{i=1}^{n_A} 10^{-(IL_{Ai}/10)} - 10 \log_{10} \sum_{i=1}^{n_B} 10^{-(IL_{Bi}/10)} \tag{17}$$

EXAMPLE
Initially, the sound pressure level at an observation point is due to straight-line propagation and reflection in the ground plane between the source and receiver. The arrangement is altered by introducing a barrier which prevents both initial propagation paths but introduces four new paths. Compute the insertion loss due to the introduction of the barrier. In situation *A*, before alteration, the sound pressure level at the observation point is L_{pA} and propagation loss over the path reflected in the ground plane is 5 dB. In situation *B*, after alteration, the losses over the four new paths are respectively 4, 6, 7 and 10 dB.

Solution:
Using the preceding equation gives the following result.

$$IL = 10\log_{10}\left[10^{-0/10} + 10^{-5/10}\right] - 10\log_{10}\left[10^{-4/10} + 10^{-6/10} + 10^{-7/10} + 10^{-10/10}\right]$$

$$= 1.2 + 0.2 = 1.4 \text{ dB}$$

1.3. PROPAGATION OF NOISE

1.3.1. Free field

A free field is a homogeneous medium, free from boundaries or reflecting surfaces. Considering the simplest form of a sound source, which would radiate sound equally in all directions from a apparent point, the energy emitted at a given time will diffuse in all directions and, one second later, will be distributed over the surface of a sphere of 340 m radius. This type of propagation is said to be spherical and is illustrated in Figure 1.7.

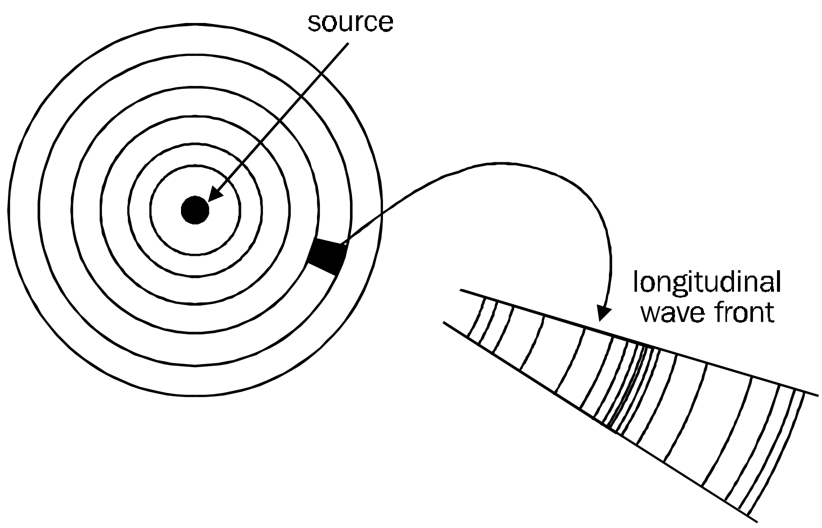


Figure 1.7. A representation of the radiation of sound from a simple source in free field.

In a free field, the intensity and sound pressure at a given point, at a distance r (in meters) from the source, is expressed by the following equation:

$$p^2 = \rho c I = \frac{\rho c W}{4\pi r^2} \tag{18}$$

where ρ and c are the air density and speed of sound respectively.

In terms of sound pressure the preceding equation can be written as:

$$L_p = L_w + 10\log_{10}\left(\frac{\rho c}{400}\right) - 10\log_{10}(4\pi r^2) \tag{19}$$

which is often approximated as:

$$L_p = L_w - 10\log_{10}(4\pi r^2) \tag{20}$$

Measurements of source sound power, L_w, can be complicated in practice (see Bies and Hansen, 1996, Ch. 6). However, if the sound pressure level, L_m, is measured at some reference distance, r_m, from the noise source (usually greater than 1 metre to avoid source near field effects which complicate the sound field close to a source), then the sound pressure level at some other distance, r, may be estimated using:

$$L_p = L_m - 20\log_{10}\left(\frac{r}{r_m}\right) \tag{21}$$

From the preceding expression it can be seen that in free field conditions, the noise level decreases by 6 dB each time the distance between the source and the observer doubles. However, true free-field conditions are rarely encountered in practice, so in general the equation relating sound pressure level and sound power level must be modified to account for the presence of reflecting surfaces. This is done by introducing a directivity factor, Q which may also be used to characterise the directional sound radiation properties of a source.

1.3.2. Directivity

Provided that measurements are made at a sufficient distance from a source to avoid near field effects (usually greater than 1 meter), the sound pressure will decrease with spreading at the rate of 6 dB per doubling of distance and a directivity factor, Q, may be defined which describes the field in a unique way as a function solely of direction.

A simple point source radiates uniformly in all directions. In general, however, the radiation of sound from a typical source is directional, being greater in some directions than in others. The directional properties of a sound source may be quantified by the introduction of a directivity factor describing the angular dependence of the sound intensity. For example, if the sound intensity I is dependent upon direction, then the mean intensity, I_{av}, averaged over an encompassing spherical surface is introduced and,

$$I_{av} = \frac{W}{4\pi r^2} \tag{22}$$

The directivity factor, Q, is defined in terms of the intensity I_θ in direction (θ, ψ) and the mean intensity (Bies and Hansen, Ch. 5, 1996):

$$Q_\theta = \frac{I_\theta}{I_{av}} \tag{23}$$

The directivity index is defined as (Bies and Hansen, Ch. 5, 1996),

$$DI = 10\log_{10} Q_\theta \tag{24}$$

1.3.2.1. Reflection effects

The presence of a reflecting surface near to a source will affect the sound radiated and the apparent directional properties of the source. Similarly, the presence of a reflecting surface near to a receiver will affect the sound received by the receiver. In general, a reflecting surface will affect not only the directional properties of a source but also the total power radiated by the source (Bies, 1961). As the problem can be quite complicated the simplifying assumption is often made and will be made here, that the source is of constant power output which means that its output sound power is not affected by reflecting surfaces (see Bies and Hansen, 1996 for a more detailed discussion).

For a simple source near to a reflecting surface outdoors (Bies and Hansen, Ch. 5, 1996),

$$W = I\,\frac{4\pi r^2}{Q} = p_{rms}^2\,\frac{4\pi r^2}{\rho c Q} \tag{25a,b}$$

which may be written in terms of levels as

$$L_p = L_w + 10\log_{10}\left(\frac{Q}{4\pi r^2}\right) = L_w + 10\log_{10}\left(\frac{1}{4\pi r^2}\right) + DI \tag{26a,b}$$

For a uniformly radiating source, the intensity I is independent of angle in the restricted region of propagation, and the directivity factor Q takes the value listed in Table 1.3. For example, the value of Q for the case of a simple source next to a reflecting wall is 2, showing that all of the sound power is radiated into the half-space defined by the wall.

Table 1.3. Directivity factors for a simple source near reflecting surfaces.

Situation	Directivity factor, Q	Directivity Index, *DI (dB)*
free space	1	0
centred in a large flat surface	2	3
centred at the edge formed by the junction of two large flat surfaces	4	6
at the corner formed by the junction of three large flat surfaces	8	9

1.3.3. Reverberant fields

Whenever sound waves encounter an obstacle, such as when a noise source is placed within boundaries, part of the acoustic energy is reflected, part is absorbed and part is transmitted. The relative amounts of acoustic energy reflected, absorbed and transmitted greatly depend on the nature of the obstacle. Different surfaces have different ways of reflecting, absorbing and transmitting an incident sound wave. A hard, compact, smooth surface will reflect much more, and absorb much less, acoustic energy than a porous, soft surface.

If the boundary surfaces of a room consist of a material which reflects the incident sound, the sound produced by a source inside the room - the direct sound - rebounds from one boundary to another, giving origin to the reflected sound. The higher the proportion of the incident sound reflected, the higher the contribution of the reflected sound to the total sound in the closed space. This "built-up" noise will continue even after the noise source has been turned off. This phenomenon is called reverberation and the space where it happens is called a reverberant sound field, where the noise level is dependent not only on the acoustic power radiated, but also on the size of the room and the acoustic absorption properties of the boundaries.

As the surfaces become less reflective, and more absorbing of noise, the reflected noise becomes less and the situation tends to a "free field" condition where the only significant sound is the direct sound. By covering the boundaries of a limited space with materials which have a very high absorption coefficient, it is possible to arrive at characteristics of sound propagation similar to free field conditions. Such a space is called an anechoic chamber, and such chambers are used for acoustical research and sound power measurements.

In practice, there is always some absorption at each reflection and therefore most work spaces may be considered as semi-reverberant.

The phenomenon of reverberation has little effect in the area very close to the source, where the direct sound dominates. However, far from the source, and unless the walls are very absorbing, the noise level will be greatly influenced by the reflected, or indirect, sound. The sound pressure level in a room may be considered as a combination of the direct field (sound radiated directly from the source before undergoing a reflection) and the reverberant field (sound which has been reflected from a surface at least once) and for a room for which one dimension is not more than about five times the other two, the sound pressure level generated at distance r from a source producing a sound power level of L_w may be calculated using (Bies and Hansen, Ch. 7, 1996),

$$L_p = L_w + 10\log_{10}\left(\frac{Q}{4\pi r^2} + \frac{4(1-\bar{\alpha})}{S\bar{\alpha}}\right) \tag{27}$$

where $\bar{\alpha}$ is the average absorption coefficient of all surfaces in the room.

These principles are of great importance for noise control and will be further discussed in more detail in Chapter 5 and 10.

1.4. PSYCHO-ACOUSTICS

For the study of occupational exposure to noise and for the establishment of noise criteria, not only the physical characteristics of noise should be considered, but also the way the human ear responds to it.

The response of the human ear to sound or noise depends both on the sound frequency and the sound pressure level. Given sufficient sound pressure level, a healthy, young, normal human ear is able to detect sounds with frequencies from 20 Hz to 20,000 Hz. Sound characterised by frequencies between 1 and 20 Hz is called infrasound and is not considered damaging at levels below 120 dB. Sound characterised by frequencies in excess of 20,000 Hz is called ultrasound and is not considered damaging at levels below 105 dB. Sound which is most damaging to the range of hearing necessary to understand speech is between 500 Hz and 2000 Hz.

1.4.1. Threshold of hearing

The threshold of hearing is defined as the level of a sound at which, under specified conditions, a person gives 50% correct detection responses on repeated trials, and is indicated by the bottom line in Figure 1.8.

1.4.2. Loudness

At the threshold of hearing, a noise is just "loud" enough to be detected by the human ear. Above that threshold, the degree of loudness is a subjective interpretation of sound pressure level or intensity of the sound.

The concept of loudness is very important for the evaluation of exposure to noise. The human ear has different sensitivities to different frequencies, being least sensitive to extremely high and extremely low frequencies. For example, a pure-tone of 1000 Hz with intensity level of 40 dB would impress the human ear as being louder than a pure-tone of 80 Hz with 50 dB, and a 1000 Hz tone at 70 dB would give the same subjective impression of loudness as a 50 Hz tone at 85 dB.

In the mid-frequency range at sound pressures greater than about 2×10^{-3} Pa (40 dB re 20 μPa SPL), Table 1.4 summarises the subjective perception of noise level changes and shows that a reduction in sound energy (pressure squared) of 50% results in a reduction of 3 dB and is just perceptible to the normal ear.

Table 1.4. Subjective effect of changes in sound pressure level.

Change in sound level (dB)	Change in power		Change in apparent loudness
	Decrease	Increase	
3	1/2	2	just perceptible
5	1/3	3	clearly noticeable
10	1/10	10	half or twice as loud
20	1/100	100	much quieter or louder

The loudness level of a sound is determined by adjusting the sound pressure level of a comparison pure tone of specified frequency until it is judged by normal hearing observers to be equal in loudness. Loudness level is expressed in **phons**, which have the same numerical value as the sound pressure level at 1000 Hz. Attempts have been made to introduce the **sone** as the unit of loudness designed to give scale numbers approximately proportional to the loudness, but it has not been used in the practice of noise evaluation and control.

To rate the loudness of sounds, "equal-loudness contours" have been determined. Since these contours involve subjective reactions, the curves have been determined through psycho-acoustical experiments. One example of such curves is presented in Figure 1.8. It shows that the curves tend to become more flattened with an increase in the loudness level.

The units used to label the equal-loudness contours in the figure are called phons. The lines in figure 1.8 are constructed so that all tones of the same number of phons sound equally loud. The phon scale is chosen so that, at 1 kHz, the number of phons equals the sound pressure level. For example, according to the figure a 31.5 Hz tone of 50 phons sounds equally as loud as a 1000 Hz tone of 50 phons, even though the sound pressure level of the lower-frequency sound is 30 dB higher. Humans are quite "deaf" at low frequencies. The bottom line in Figure 1.8 represents the average threshold of hearing, or minimum audible field (*MAF*).

1.4.3. Pitch

Pitch is the subjective response to frequency. Low frequencies are identified as "low-pitched", while high frequencies are identified as "high-pitched". As few sounds of ordinary experience are of a single frequency (for example, the quality of the sound of a musical instrument is determined by the presence of many frequencies other than the fundamental frequency), it is of interest to consider what determines the pitch of a complex note. If a sound is characterised by a series of integrally related frequencies (for example, the second lowest is twice the frequency of the lowest, the third lowest is three times the lowest, etc.), then the lowest frequency determines the pitch.

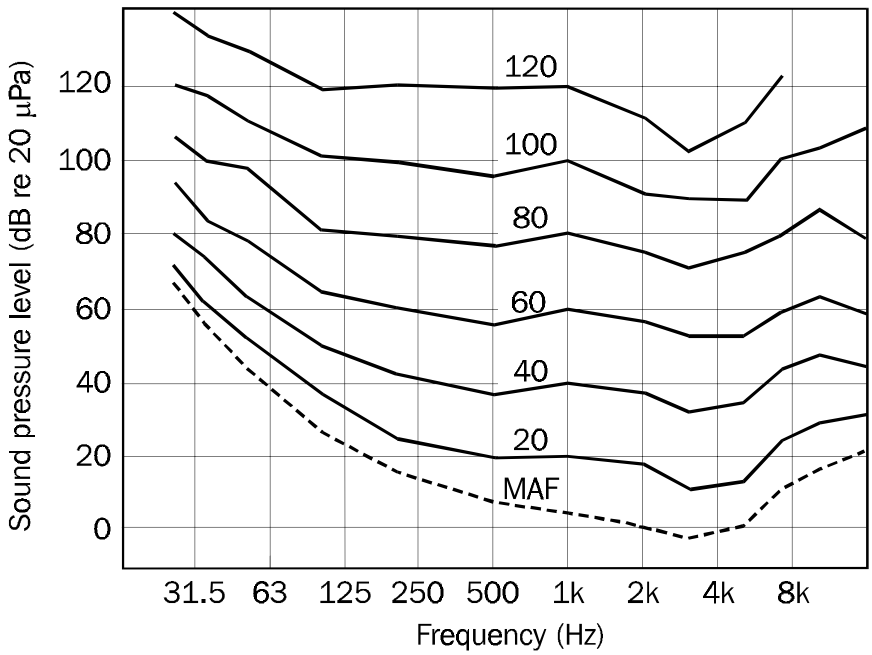


Figure 1.8. Loudness level (equal-loudness) contours, internationally standardised for pure tones heard under standard conditions (ISO 226). Equal loudness contours are determined relative to the reference level at 1000 Hz. All levels are determined in the absence of the subject, after subject level adjustment. MAF means minimum audible field.

Furthermore, even if the lowest frequency is removed, say by filtering, the pitch remains the same; the ear supplies the missing fundamental frequency. However, if not only the fundamental is removed, but also the odd multiples of the fundamental as well, say by filtering, then the sense of pitch will jump an octave. The pitch will now be determined by the lowest frequency, which was formerly the second lowest. Clearly, the presence or absence of the higher frequencies is important in determining the subjective sense of pitch.

Sense of pitch is also related to level. For example, if the apparent pitch of sounds at 60 dB re 20 μPa is taken as a reference, then sounds of a level well above 60 dB and frequency below 500 Hz tend to be judged flat, while sounds above 500 Hz tend to be judged sharp.

1.4.4. Masking

Masking is the phenomenon of one sound interfering with the perception of another sound. For example, the interference of traffic noise with the use of a public telephone on a busy street corner is probably well known to everyone.

Masking is a very important phenomenon and it has two important implications:

- speech interference, by which communications can be impaired because of high levels of ambient noise;
- utilisation of masking as a control of annoying low level noise, which can be "covered" by music for example.

In general, it has been shown that low frequency sounds can effectively "mask" high frequency sounds even if they are of a slightly lower level. This has implications for warning sounds which should be pitched at lower frequencies than the dominant background noise, but not at such a low frequency that the frequency response of the ear causes audibility problems. Generally frequencies between about 200 and 500 Hz are heard most easily in the presence of typical industrial background noise, but in some situations even lower frequencies are needed. If the warning sounds are modulated in both frequency and level, they are even easier to detect.

Other definitions of masking are used in audiometry and these are discussed in Chapter 8 of this document.

1.4.5. Frequency Weighting

As mentioned in the previous section, the human ear is not equally sensitive to sound at different frequencies. To adequately evaluate human exposure to noise, the sound measuring system must account for this difference in sensitivities over the audible range. For this purpose, frequency weighting networks, which are really "frequency weighting filters" have been developed.

These networks "weight" the contributions of the different frequencies to the **over-all sound level**, so that sound pressure levels are reduced or increased as a function of frequency before being combined together to give an overall level. Thus, whenever the weighting networks are used in a sound measuring system, the various frequencies which constitute the sound contribute differently to the evaluated over-all sound level, in accordance with the given frequency's contribution to the subjective loudness of sound, or noise.

The two internationally standardised weighting networks in common use are the "A" and "C", which have been built to correlate to the frequency response of the human ear for different sound levels. Their characteristics are specified in IEC 60651.

Figure 1.9 and Table 1.5 describe the attenuation provided by the A, and C networks (IEC 60651).

The "A" network modifies the frequency response to follow approximately the equal loudness curve of 40 phons, while the "C" network approximately follows the equal loudness curve of 100 phons, respectively. A "B" network is also mentioned in some texts but it is no longer used in noise evaluations.

The popularity of the A network has grown in the course of time. It is a useful simple means of describing interior noise environments from the point of view of habitability, community disturbance, and also **hearing damage**, even though the C network better describes the loudness of industrial noise which contributes significantly to hearing damage. Its great attraction lies in its direct use in measures of **total noise exposure** (Burns and Robinson, 1970).

When frequency weighting networks are used, the measured noise levels are designated specifically, for example, by dB(A) or dB(C). Alternatively, the terminology A-weighted sound level in dB or C-weighted sound level in dB are often preferred. If the noise level is measured without a "frequency-weighting" network, then the sound levels corresponding to all frequencies contribute to the total as they actually occur. This physical measurement without modification is not particularly useful for exposure evaluation and is referred to as the linear (or unweighted) sound pressure level.

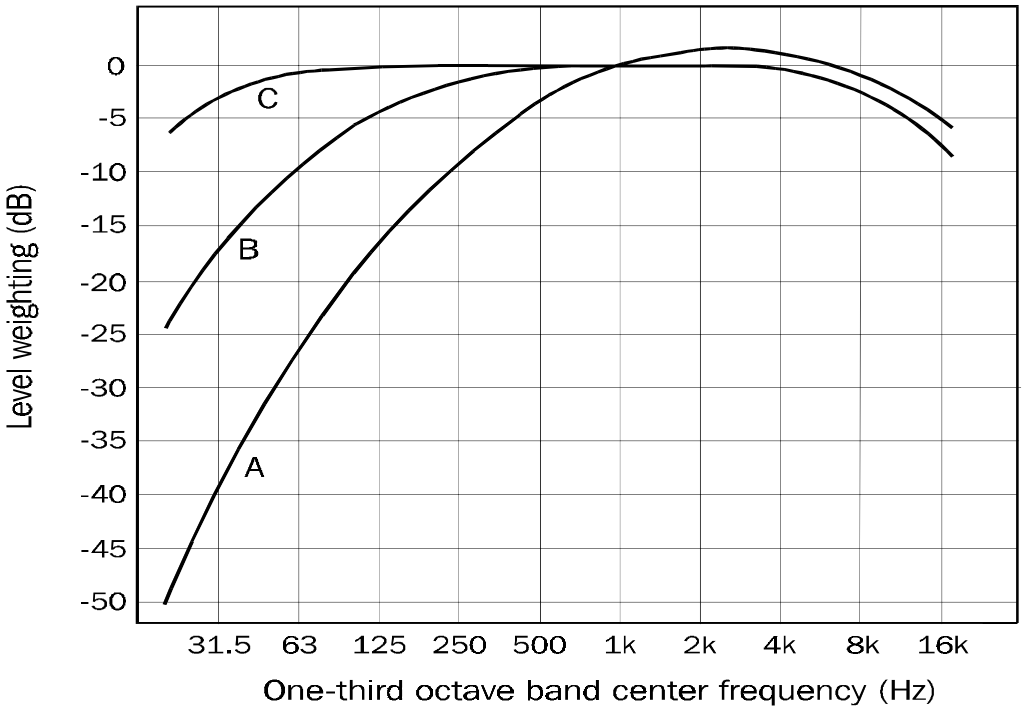


Figure 1.9. Frequency weighting characteristics for A and C networks.

1.5. NOISE EVALUATION INDICES AND BASIS FOR CRITERIA

To properly evaluate noise exposure, both the type and level of the noise must be characterised. The type of noise is characterised by its frequency spectrum and its variation as a function of time. The level is characterised by a particular type of measurement which is dependent on the purpose of the measurement (either to evaluate exposure or to determine the optimum approach for noise control).

Table 1.5. Frequency weighting characteristics for A and C networks (*).

Frequency Hz	Weighting, dB	
	A	C
31.5	- 39	- 3
63	- 26	- 1
125	- 16	0
250	- 9	0
500	- 3	0
1,000	0	0
2,000	1	0
4,000	1	- 1
8,000	- 1	- 3

*This is a simplified table, for illustration purposes. The full characteristics for the A, B and C weighting networks of the sound level meter have been specified by the IEC (IEC 60651).

1.5.1. Types of Noise (*see ISO 12001*)

Noise may be classified as steady, non-steady or impulsive, depending upon the temporal variations in sound pressure level. The various types of noise and instrumentation required for their measurement are illustrated in Table 1.6.

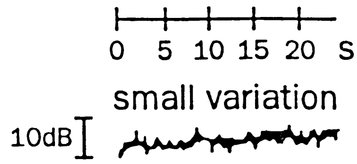
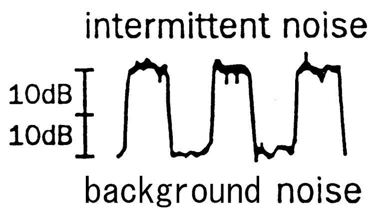
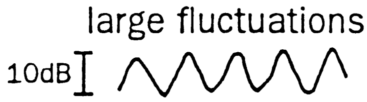
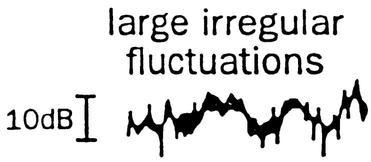
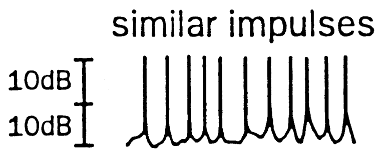
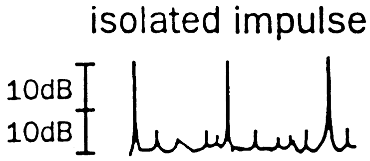
Steady noise is a noise with negligibly small fluctuations of sound pressure level within the period of observation. If a slightly more precise single-number description is needed, assessment by NR (Noise Rating) curves may be used.

A noise is called **non-steady** when its sound pressure levels shift significantly during the period of observation. This type of noise can be divided into intermittent noise and fluctuating noise.

Fluctuating noise is a noise for which the level changes continuously and to a great extent during the period of observation.

Tonal noise may be either continuous or fluctuating and is characterised by one or two single frequencies. This type of noise is much more annoying than broadband noise characterised by energy at many different frequencies and of the same sound pressure level as the tonal noise.

Table 1.6. Noise types and their measurement.

	Characteristics	Type of Source
	Constant continuous sound	Pumps, electric motors, gearboxes, conveyers
	Constant but intermittent sound	Air compressor, automatic machineryduring a work cycle
	Periodically fluctuating sound	Mass production, surface grinding
	Fluctuating non-periodic sound	Manual work, grinding, welding, component assembly
	Repeated impulses	Automatic press, pneumatic drill, riveting
	Single impulse	Hammer blow, material handling, punch press, gunshot, artillery fire

Noise characteristics classified according to the way they vary with time. Constant noise remains within 5 dB for a long time. Constant noise which starts and stops is called intermittent. Fluctuating noise varies significantly but has a constant long term average ($L_{\mathrm{Aeq,T}}$). Impulse noise lasts for less than one second.

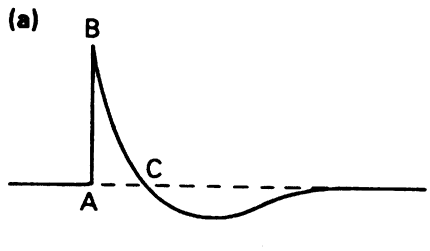
Type of Measurement	Type of Instrument	Remarks
Direct reading of A-weighted value	Sound level meter	Octave or 1/3 octave analysis if noise is excessive
dB value and exposure time or L_{Aeq}	Sound level meter, Integrating sound level meter	Octave or 1/3 octave analysis if noise is excessive
dB value, L_{Aeq} or noise exposure	Sound level meter Integrating sound level meter	Octave or 1/3 octave analysis if noise is excessive
L_{Aeq} or noise exposure Statistical analysis	Noise exposure meter, Integrating sound level meter	Long term measurement usually required
L_{Aeq} or noise exposure & Check "Peak" value	Integrating sound level meter with "Peak" hold and "C-weighting"	Difficult to assess. More harmful to hearing than it sounds
L_{Aeq} and "Peak" value	Integrating sound level meter with "Peak" hold and "C-weighting"	Difficult to assess. Very harmful to hearing especially close

Intermittent noise is noise for which the level drops to the level of the background noise several times during the period of observation. The time during which the level remains at a constant value different from that of the ambient background noise must be one second or more. This type of noise can be described by

- the ambient noise level
- the level of the intermittent noise
- the average duration of the on and off period.

In general, however, both levels are varying more or less with time and the intermittence rate is changing, so that this type of noise is usually assimilated to a fluctuating noise as described below, and the same indices are used.

Impulsive noise consists of one or more bursts of sound energy, each of a duration less than about 1s . Impulses are usually classified as type A and type B as described in Figure 1.10, according to the time history of instantaneous sound pressure (ISO 10843) . Type A characterises typically gun shot types of impulses, while type B is the one most often found in industry (e.g., punch press impulses). The characteristics of these impulses are the peak pressure value, the rise time and the duration (as defined in Figure 1.10) of the peak.



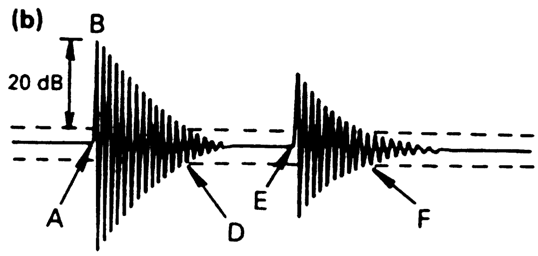


Figure 1.10. Idealised waveforms of impulse noises. Peak level = pressure difference AB; rise time = time difference AB; A duration = time difference AC; B duration = time difference AD (+ EF when a reflection is present).

(a) explosive generated noise.

(b) impact generated noise.

1.5.2. A-weighted Level

The noise level in dB, measured using the filter specified as the A network (see figure 1.9) is referred to as the "A-weighted level" and expressed as dB(A). This measure has been widely used to evaluate occupational exposure because of its good correlation with hearing damage even though the "C" weighting better describes the loudness of industrial noise.

1.5.3. Equivalent Continuous Sound Level (*see ISO 1999*)

Very often industrial noise fluctuates. This can be easily observed as the oscillations in the visual display of a sound level meter in a noisy environment. The equivalent continuous sound level (L_{eq}) is the steady sound pressure level which, over a given period of time, has the same total energy as the actual fluctuating noise. The A-weighted equivalent continuous sound level is denoted L_{Aeq}. If the level is normalised to an 8-hour workday, it is denoted $L_{Aeq,8h}$. If it is over a time period of T hours, then it is denoted $L_{Aeq,T}$, and is defined as follows:

$$L_{Aeq,T} = 10\log_{10}\left(\frac{1}{T}\int_0^T\left(\frac{p_A(t)}{p_0}\right)^2 \mathrm{d}t\right) \tag{28}$$

where $p_A(t)$ is the time varying A-weighted sound pressure and p_0 is the reference pressure (20μ Pa). A similar expression can be used to define $L_{Ceq,T}$, the equivalent continuous C-weighted level.

The preferred method of measurement is to use an integrating sound level meter averaging over the entire time interval, but sometimes it is convenient to split the time interval into a number (M) of sub-intervals, T_i, for which values of $L_{Aeq,Ti}$ are measured. In this case, $L_{Aeq,T}$ is determined using,

$$L_{Aeq,T} = 10\log_{10}\left(\frac{1}{T}\sum_{i=1}^{M} T_i \times 10^{(L_{Aeq,T_i})/10}\right) \qquad \text{dB} \tag{29}$$

1.5.4. A-weighted Sound Exposure

Sound exposure may be quantified using the A-weighted sound exposure, $E_{A,T}$, defined as the time integral of the squared, instantaneous A-weighted sound pressure, $p_A^2(t)$ (pa^2) over a particular time period, $T = t_2 - t_1$ (hours). The units are pascal-squared-hours (Pa^2.h) and the defining equation is,

$$E_{A,T} = \int_{t_1}^{t_2} p_A^2(t)\,\mathrm{d}t \tag{30}$$

The relationship between the A-weighted sound exposure and the A-weighted equivalent continuous sound level, $L_{Aeq,T}$, is

$$E_{A,T} = 4T \times 10^{(L_{Aeq,T} - 100)/10} \tag{31}$$

A noise exposure level normalised to a nominal 8-hour working day may be calculated from $E_{A,8h}$ using

$$L_{Aeq,8h} = 10\log_{10}\left(\frac{E_{A,8h}}{3.2 \times 10^{-9}}\right) \tag{32}$$

1.5.5. Noise Rating Systems

These are curves which were often used in the past to assess steady industrial or community noise. They are currently used in some cases by machinery manufacturers to specify machinery noise levels.

The Noise Rating (*NR*) of any noise characterised in octave band levels may also be calculated algebraically. More often the family of curves is used rather than the direct algebraic calculation. In this case, the octave band spectrum of the noise is plotted on the family of curves given in Figure 1.11. The NR index is the value of that curve which lies just above the spectrum of the measured noise. For normal levels of background noise, the NR index is equal to the value of the A-weighted sound pressure level in decibels minus 5. This relationship should be used as a guide only and not as a general rule.

The NR approach actually tries to take into account the difference in frequency weighting made by the ear, at different intensity levels. NR values are especially useful when specifying noise in a given environment for control purposes.

NR curves are similar to the NC (Noise criterion) curves proposed by Beranek (Beranek, 1957). However, these latter curves are intended primarily for rating air conditioning noise and have been largely superseded by Balanced Noise Criterion (NCB) curves, Fig. 1.12**.**

Balanced Noise Criterion Curves are used to specify acceptable noise levels in occupied spaces. More detailed information on NCB curves may be found in the standard ANSI S12.2-1995 and in the proposals for its revision by Schomer (1999). The designation number of an NCB curve is equal to the Speech Interference Level (SIL) of a noise with the same octave band levels as the NCB curve. The SIL of a noise is the arithmetic average of the 500 Hz, 1 kHz, 2 kHz and 4 kHz octave band levels.

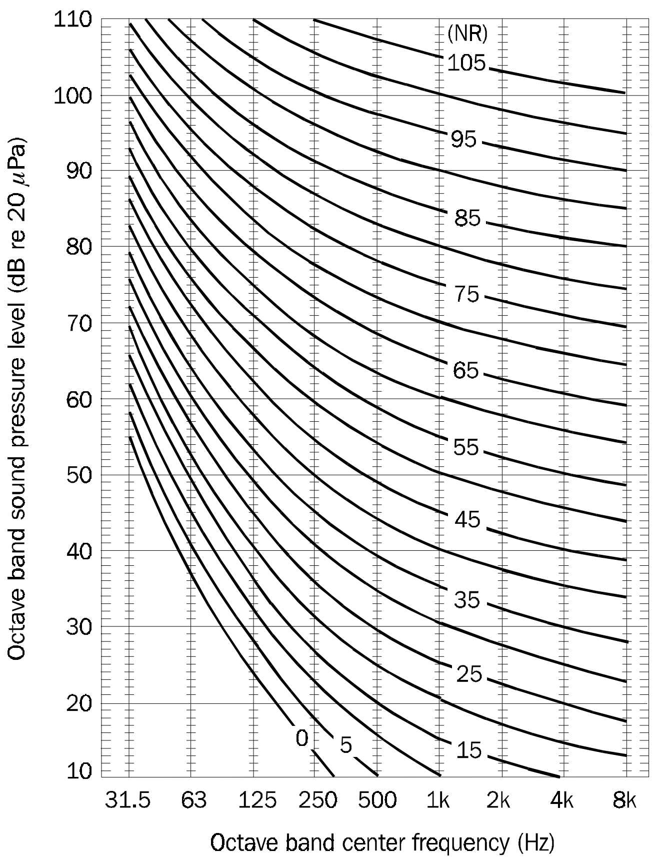


Figure 1.11. Noise rating (NR) curves

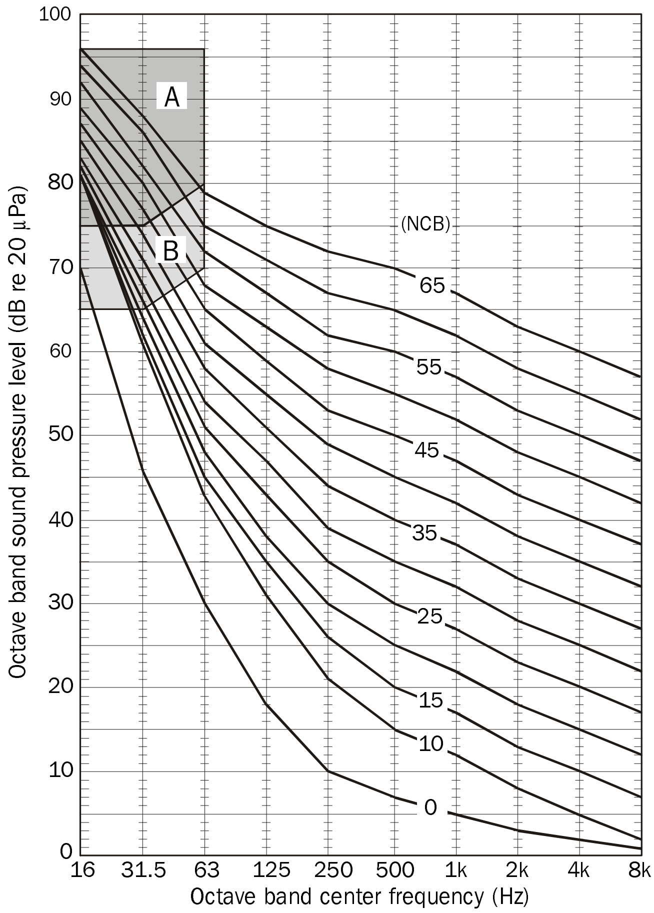


Figure 1.12. Balanced Noise Criterion (NCB) curves. Region A represents exceedance of criteria for readily noticeable vibrations and Region B represents exceedance of criteria for moderately (but not readily) noticeable vibrations.

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INTERNATIONAL STANDARDS

Titles of the following standards related to or referred to in this chapter one will find together with information on availability in chapter 12:

ISO 226, ISO 1999, ISO 2533, ISO 3744, ISO 9614, ISO 12001, ISO 10843,
IEC 60651, IEC 60804, IEC 60942, IEC 61043, IEC 61260.

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2

THE ANATOMY AND PHYSIOLOGY OF THE EAR AND HEARING

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2.1. INTRODUCTION

Hearing is one of the major senses and like vision is important for distant warning and communication. It can be used to alert, to communicate pleasure and fear. It is a conscious appreciation of vibration perceived as sound. In order to do this, the appropriate signal must reach the higher parts of the brain. The function of the ear is to convert physical vibration into an encoded nervous impulse. It can be thought of as a biological microphone. Like a microphone the ear is stimulated by vibration: in the microphone the vibration is transduced into an electrical signal, in the ear into a nervous impulse which in turn is then processed by the central auditory pathways of the brain. The mechanism to achieve this is complex. This chapter will deal mainly with the ear, first its structure and then its function, for it is the ear that is mainly at risk from hazardous sounds.

The ears are paired organs, one on each side of the head with the sense organ itself, which is technically known as the cochlea, deeply buried within the temporal bones. Part of the ear is concerned with conducting sound to the cochlea, the cochlea is concerned with transducing vibration. The transduction is performed by delicate hair cells which, when stimulated, initiate a nervous impulse. Because they are living, they are bathed in body fluid which provides them with energy, nutrients and oxygen. Most sound is transmitted by a vibration of air. Vibration is poorly transmitted at the interface between two media which differ greatly in characteristic impedance (product of density of the medium and speed of sound within it, ρc), as for example air and water. The ear has evolved a complex mechanism to overcome this impedance mis-match, known as the sound conducting mechanism. The sound conducting mechanism is divided into two parts, an outer and the middle ear, an outer part which catches sound and the middle ear which is an impedance matching device. Let us look at these parts in detail (see Figure 2.1).

2.2. SOUND CONDUCTING MECHANISMS

2.2.1. The Outer Ear

The outer ear transmits sound to the tympanic membrane. The pinna, that part which protrudes from the side of the skull, made of cartilage covered by skin, collects sound and channels it into the ear canal. The pinna is angled so that it catches sounds that come from in front more than those from behind and so is already helpful in localizing sound. Because of the relative size of the head and the wavelength of audible sound, this effect only applies at higher frequencies. In the middle frequencies the head itself casts a sound shadow and in the lower frequencies phase of arrival of a sound between the ears helps localize a sound. The ear canal is about 4 centimetres long and consists of an outer and inner part. The outer portion is lined with hairy skin containing sweat glands and oily sebaceous glands which together form ear wax. Hairs grow in the outer part of the ear canal and they and the wax serve as a protective barrier and a disinfectant. Very quickly however, the skin of the ear canal becomes thin and simple and is attached firmly to the bone of the deeper ear canal, a hard cavity which absorbs little sound but directs it to the drum head (eardrum or tympanic membrane) at its base. The outer layer of the drumhead itself is formed of skin in continuity with that of the ear canal.

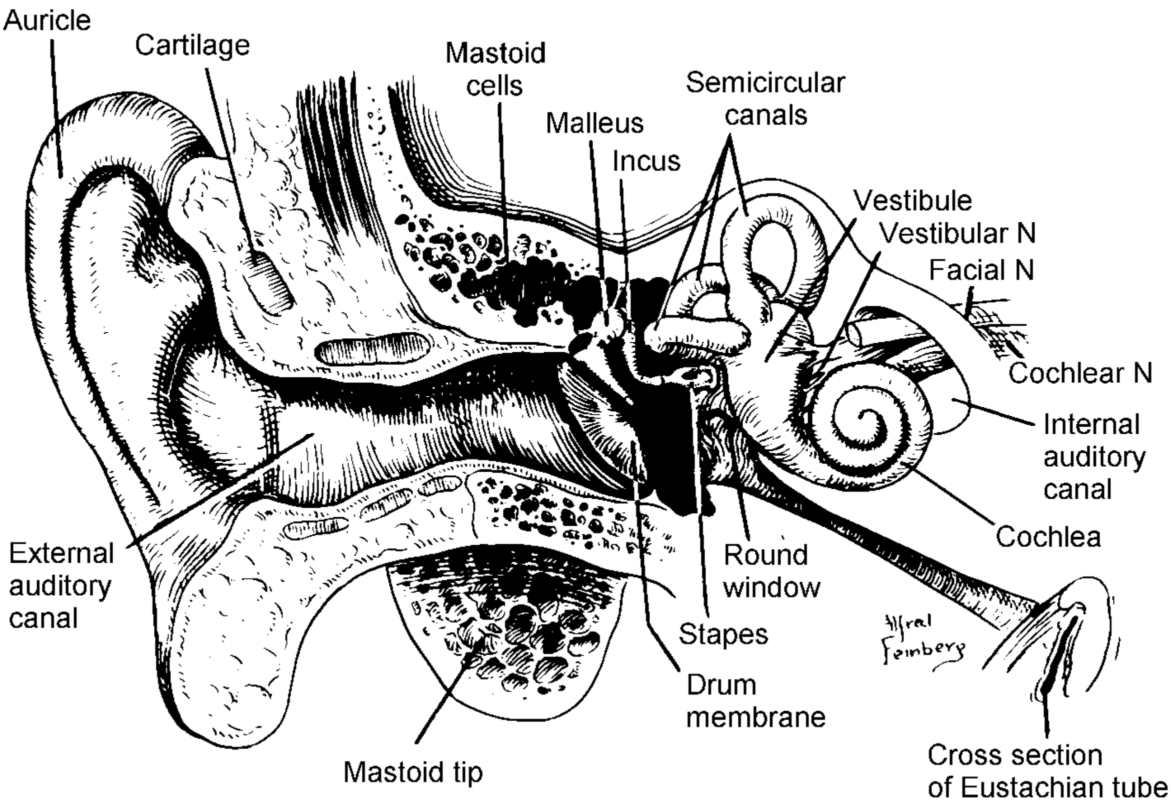

Figure 2.1. The pinna and external auditory canal form the outer ear, which is separated from the middle ear by the tympanic membrane. The middle ear houses three ossicles, the malleus, incus and stapes and is connected to the back of the nose by the Eustachian tube. Together they form the sound conducting mechanism. The inner ear consists of the cochlea which transduces vibration to a nervous impulse and the vestibular labyrinth which houses the organ of balance. (from Hallowell and Silverman, 1970)

In life, skin sheds and is continuously renewing. Ear canal skin grows like a fingernail fromthe depths to the exterior so that the skin is shed into the waxy secretions in the outer part and falls out. This is the reason for not using cotton buds to clean the ear canal because very frequently they merely push the shed skin and wax deep into the canal, impacting it and obstructing hearing. The ear canal has a slight bend where the outer cartilaginous part joins the bony thin skinned inner portion, so that the outer part runs somewhat backwards and the inner part somewhat forwards. This bend is yet another part of the protective mechanism of the ear, stopping foreign objects from reaching the tympanic membrane. However it means that to inspect the tympanic membrane from the outside, one must pull the ear upwards and backwards. The tympanic membrane separates the ear canal from the middle ear and is the first part of the sound transducing mechanism. Shaped somewhat like a loudspeaker cone (which is an ideal shape for transmitting sound between solids and air), it is a simple membrane covered by a very thin layer of skin on the outside, a thin lining membrane of the respiratory epithelium tract on the inner surface and with a stiffening fibrous middle layer. The whole membrane is less than a 1/10th of millimetre thick. It covers a round opening about 1 centimetre in diameter into the middle ear cavity. Although the tympanic membrane is often called the ear drum, technically the whole middle ear space is the ear drum and the tympanic membrane the drum skin.

2.2.2. The Middle Ear

The middle ear is an air filled space connected to the back of the nose by a long, thin tube called the Eustachian tube. The middle ear space houses three little bones, the hammer, anvil and stirrup (malleus, incus and stapes) which conduct sound from the tympanic membrane to the inner ear. The outer wall of the middle ear is the tympanic membrane, the inner wall is the cochlea. The upper limit of the middle ear forms the bone beneath the middle lobe of the brain and the floor of the middle ear covers the beginning of the great vein that drains blood from the head, the jugular bulb. At the front end of the middle ear lies the opening of the Eustachian tube and at its posterior end is a passageway to a group of air cells within the temporal bone known as the mastoid air cells. One can think of the middle ear space shaped rather like a frying pan on its side with a handle pointing downwards and forwards (the Eustachian tube) but with a hole in the back wall leading to a piece of spongy bone with many air cells, the mastoid air cells. The middle ear is an extension of the respiratory air spaces of the nose and the sinuses and is lined with respiratory membrane, thick near the Eustachian tube and thin as it passes into the mastoid. It has the ability to secret mucus. The Eustachian tube is bony as it leaves the ear but as it nears the back end of the nose, in the nasopharynx, consists of cartilage and muscle. Contracture of muscle actively opens the tube and allows the air pressure in the middle ear and the nose to equalize.

Sound is conducted from the tympanic membrane to the inner ear by three bones, the malleus, incus and stapes. The malleus is shaped like a club; its handle is embedded in the tympanic membrane, running from its centre upwards. The head of the club lies in a cavity of the middle ear above the tympanic membrane (the attic) where it is suspended by a ligament from the bone that forms the covering of the brain. Here the head articulates with the incus which is cone shaped, with the base of the cone articulating with the head of the malleus, also in the attic. The incus runs backwards from the malleus and has sticking down from it a very little thin projection known as its long process which hangs freely in the middle ear. It has a right angle bend at its tip which is attached to the stapes(stirrup), the third bone shaped with an arch and a foot plate. The foot plate covers the oval window, an opening into the vestibule of the inner ear or cochlea, with which it articulates by the stapedio-vestibular joint.

2.3. THE SOUND TRANSDUCING MECHANISM

2.3.1. The Inner Ear

2.3.1.1. Structure

The bony cochlea is so called because it is shaped like a snail shell It has two and a half turns and houses the organ of hearing known as the membranous labyrinth surrounded by fluid called the perilymph. The cochlea has a volume of about 0.2 of a millilitre. In this space lie up to 30,000 hair cells which transduce vibration into nervous impulses and about 19,000 nerve fibres which transmit the signals to and from the brain. It is easiest to think of the membranous labyrinth by imagining the cochlea to be straightened out as a bony tube closed at the apex and open at the base with the round and oval windows and a connection to the vestibular labyrinth (see Figure 2.2). It is in continuity with the vestibular labyrinth or organ of balance which in technical terms acts as both a linear and angular accelerometer, thus enabling the brain to know the position of the head in relationship to gravity and its surroundings. The organ of balance will not be dealt with any further.

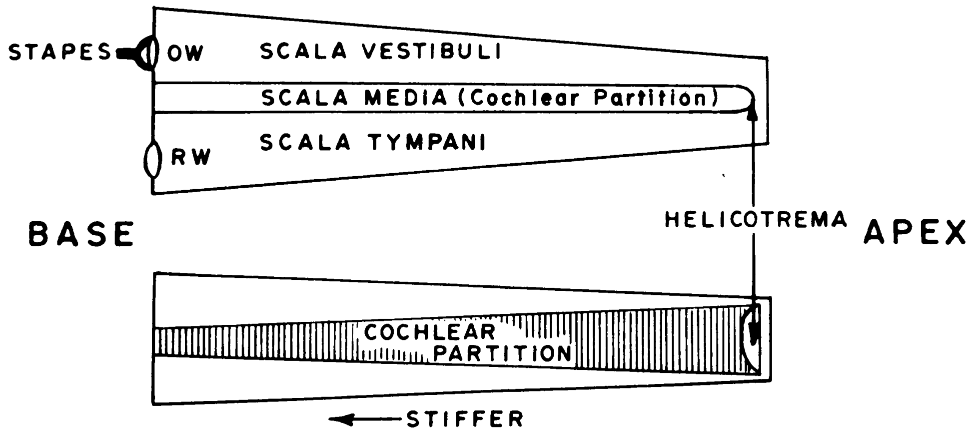

Figure 2.2. The cochlea is a bony tube, filled with perilymph in which floats the endolymph filled membranous labyrinth. This separates the scala vestibuli from the scala media. (from Hallowell and Silverman, 1970)

Vibration of the foot plate of the stapes vibrates the perilymph in the bony cochlea. This fluid is essentially incompressible. Therefore, there has to be a counter opening in the labyrinth to allow fluid space to expand when the stapes foot plate moves inwards and in turn to move inwards when the stapes foot plate moves outwards. The counter opening is provided by the round window membrane which lies beneath the oval window in the inner wall of the middle ear. It is covered by a fibrous membrane which moves synchronously but in opposite phase with the foot plate in the oval window.

The membranous labyrinth is separated into three sections, by a membranous sac of triangular cross section which run the length of the cochlea. The two outer sections are the scala vestibuli which is connected to the oval window, and the scala tympani which is connected to the round window. The sections are filled with perilymph; they connect at the apex by a small opening known as the helicotrema which serves as a pressure equalizing mechanism at frequencies well below the audible range. They also connect at the vestibular end with the fluid surrounding the brain, through a small channel known as the perilymphatic aqueduct. The membranous labyrinth, also known as the cochlear duct, is filled with different fluid called endolymph. On one side it is separated from the scala vestibuli by Reissner's membrane, and on the opposite side from the scala tympani by the basilar membrane (see Figure 2.3). The basilar membrane is composed of a great number of taut, radially parallel fibres sealed between a gelatinous material of very weak shear strength. These fibres are resonant at progressively lower frequencies as one progresses from the basal to the apical ends of the cochlea. Four rows of hair cells lie on top of the basilar membrane, together with supporting cells. A single inner row is medial, closest to the central core of the cochlea. It has an abundant nerve supply carrying messages to the brain. The three outer rows, which receive mainly an afferent nerve supply, are separated from the inner row by tunnel cells forming a stiff structure of triangular cross section known as the tunnel of Corti (see Figure 2.3). Any natural displacement of the cochlear partition results in a rocking motion of the tunnel of Corti and consequently a lateral displacement of the inner hair cells.

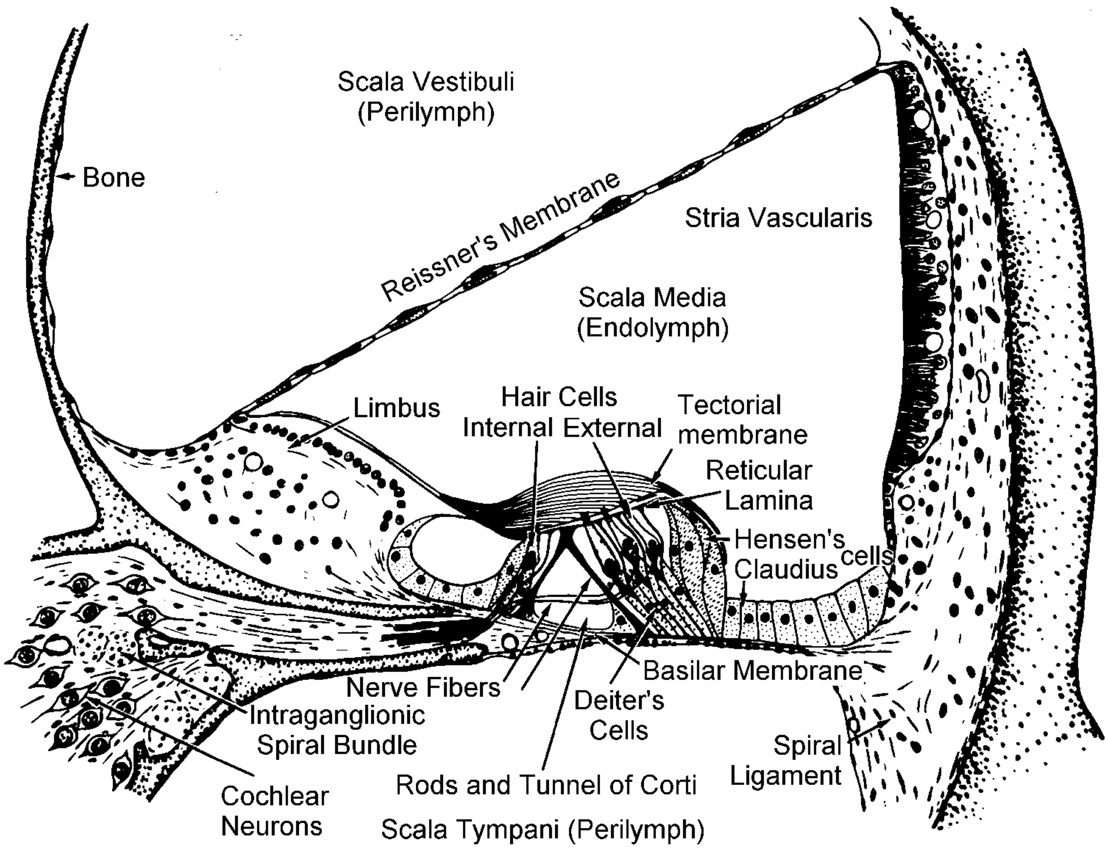

Figure 2.3. A cross section of one turn of the cochlea showing details of the membranous labyrinth. (from Hallowell and Silverman, 1970)

The hair cells derive their name from the presence at their free ends of stereocilia which are tiny little stiff hair like structures of the order of a few micrometers long (Figure 2.4). The stereocilia of the hair cells are arranged in rows in a very narrow cleft called the subtectorial space formed by the presence above the hair cells of the radially stiff tectorial membrane. The cilia of the outer hair cells are firmly attached to the tectorial membrane while the cilia of the inner hair cells are either free standing are loosely attached to the tectorial membrane.

In summary then, anatomically, the ear consists of a sound conducting mechanism and a sound transducing mechanism. The sound conducting mechanism has two parts, the outer ear consisting of the pinna and ear canal, and the middle ear consisting of the tympanic membrane. The middle ear air space is connected to the nose by the Eustachian tube and to the mastoid air cells housing the ossicular chain, the malleus, stapes and incus. The inner ear, or cochlea, transduces vibration transmitted to the perilymph via the ossicular chain into a nervous impulse which is then taken to the brain where it is perceived as sound.

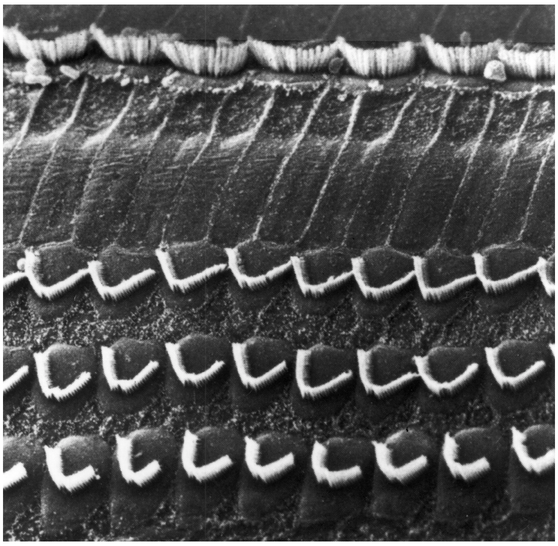

Figure 2.4. A surface view looking down on the top of the hair cells; note the three rows of outer hair cells and the one row of inner cells.

2.3.1.2. Function

Transduction of vibration in the audible range to a nervous impulse is performed by the inner hair cells; when the basilar membrane is rocked by a travelling wave, the cilia of the inner hair cells are bent in relation to the body of the cell, ion passages are opened or closed in the body of the cell and the afferent nerve ending which is attached to the hair cell base is stimulated.

As mentioned earlier, the basilar membrane responds resonantly to highest frequencies at the basal end nearest the oval window and to progressively lower frequencies as one progresses toward the apical end. At the apical end the basilar membrane responds resonantly to the lowest frequencies of sound. A disturbance introduced at the oval window is transmitted as a wave which travels along the basilar membrane with the remarkable property that as each frequency component of the travelling wave reaches its place of resonance it stops and travels no further. The cochlea is thus a remarkably efficient frequency analyser.

The cochlea has an abundant nerve supply both of fibres taking impulses from the cochlea to the brain (afferent pathways) and fibres bringing impulses from the brain to the cochlea (efferent fibres). When stimulated the inner hair cells trigger afferent nervous impulses to the brain. Like virtually all neural-mechanisms there is an active feedback loop. The copious nerve supply to the outer hair cells is overwhelmingly efferent, although the full function of the efferent pathways is not yet fully understood. It has been suggested that the purpose of the active feedback system which has been described is to maintain the lateral displacement of the stereocilia in the sub tectorial space within some acceptable limits.

2.4. THE PHYSIOLOGY OF HEARING (How does this all work?)

2.4.1. The Outer and Middle Ears

Let us deal first with the sound conducting mechanism. The range of audible sound is approximately 10 octaves from somewhere between 16 and 32 Hz (cycles per second) to somewhere between 16,000 and 20,000 Hz. The sensitivity is low at the extremes but becomes much more sensitive above 128 Hz up to about 4,000 Hz when it again becomes rapidly less sensitive. The range of maximum sensitivity and audibility diminishes with age.

The head itself acts as a natural barrier between the two ears and thus a sound source at one side will produce a more intense stimulus of the ear nearest to it and incidentally the sound will also arrive there sooner, thus helping to provide a mechanism for sound localization based on intensity and time of arrival differences of sound. High frequency hearing is more necessary than low frequency hearing for this purpose and this explains why sound localization becomes difficult with a high frequency hearing loss. The head in humans is large in comparison to the size of the pinna so the role of the pinna is less than in some other mammals. Nonetheless, its crinkled shape catches higher frequency sounds and funnels them into the ear canal. It also blocks some higher frequency sound from behind, helping to identify whether the sound comes from the front or the back.

The ear canal acts as a resonating tube and actually amplifies sounds at between 3000 and 4,000 Hz adding to the sensitivity (and susceptibility to damage) of the ear at these frequencies.

The ear is very sensitive and responds to sounds of very low intensity, to vibrations which are hardly greater than the natural random movement of molecules of air. To do this the air pressure on both sides of the tympanic membrane must be equal. Anyone who has their ear blocked even by the small pressure change of a rapid elevator ride knows the truth of this. The Eustachian tube provides the means of the pressure equalization. It does this by opening for short periods, with every 3rd or 4th swallow; if it were open all the time one would hear one's own every breath.

Because the lining membrane of the middle ear is a respiratory membrane, it can absorb some gases, so if the Eustachian tube is closed for too long it absorbs carbon dioxide and oxygen from the air in the middle ear, thus producing a negative pressure. This may produce pain (as experienced if the Eustachian tube is not unblocked during descent of an aeroplane). The middle ear cavity itself is quite small and the mastoid air cells act as an air reservoir cushioning the effects of pressure change. If negative pressure lasts too long, fluid is secreted by the middle ear, producing a conductive hearing loss.

The outer and middle ears serve to amplify the sound signal. The pinna presents a fairly large surface area and funnels sound to the smaller tympanic membrane; in turn the surface of the tympanic membrane is itself much larger than that of the stapes foot plate, so there is a hydraulic amplification: a small movement over a large area is converted to a larger movement of a smaller area. In addition, the ossicular chain is a system of levers which serve to amplify the sound. The outer and middle ears amplify sound on its passage from the exterior to the inner ear by about 30 dB.

2.4.2. The Inner Ear

The function of the inner ear is to transduce vibration into nervous impulses. While doing so, it also produces a frequency (or pitch) and intensity (or loudness) analysis of the sound. Nerve fibres can fire at a rate of just under 200 times per second. Sound level information is conveyed to the brain by the rate of nerve firing, for example, by a group of nerves each firing at a rate at less than 200 pulses per second. They can also fire in locked phase with acoustic signals up to about 5 kHz. At frequencies below 5 kHz, groups of nerve fibres firing in lock phase with an acoustic signal convey information about frequency to the brain. Above about 5 kHz frequency information conveyed to the brain is based upon the place of stimulation on the basilar membrane. As an aside, music translated up into the frequency range above 5 kHz does not sound musical.

As mentioned above each place along the length of the basilar membrane has its own characteristic frequency, with the highest frequency response at the basal end and lowest frequency response at the apical end. Also any sound introduced at the oval window by motion of the stapes is transmitted along the basilar membrane as a travelling wave until all of its frequency components reach their respective places of resonance where they stop and travel no further. For example, a 1 kHz tone induces resonance at about the middle of the basilar membrane. Any frequency components lower than 1 kHz must travel more than half the length of the basilar membrane, whereas high frequency components, greater than 1 kHz must travel less than half the length of the basilar membrane. Evidently the brain must suppress high frequency information in favour of low frequency information as the travelling wave on the basilar membrane passes through places of high frequency resonant response. An explanation is thus provided for the observation that low frequency sounds, for example traffic noise, are very effective in masking high frequency sounds, for example the fricatives of speech, making telephones near busy streets difficult to use.

How does the brain cope with intensity? The physiological range of intensity of the normal ear is huge. As a matter of interest it is the same as that of the eye when the responses of the cones and rods are considered together; thus the visual analogue is appropriate. It is as wide as seeing a candle flicker on a dark night at a hundred meters to looking indirectly into a bright sun. The range is so great that only the logarithmic response characteristic of variable rate processes and thus favoured by anatomical systems, is capable of encompassing it. The normal range of human hearing is from 0 to 100 dB(A), before sound becomes uncomfortably loud.

Mounted on the basilar membrane close to the end nearest the central core of the cochlea are a single row of inner hair cells followed by three rows of outer hair cells which are separated from the single row of inner hair cells by a stiff structure of triangular cross section known as the tunnel of Corti. Any natural displacement of the cochlear partition results in a rocking motion of the tunnel of Corti and consequently a lateral displacement of the inner hair cells.

The ear has evolved a very intriguing mechanism to cope with the large range in sound intensity encountered in the environment. Only the inner hair cells initiate nervous impulses which are heard as sound. They are not particularly sensitive but they are rugged and they are placed at the inner edge of the basilar membrane which is relatively immobile . The point where the basilar membrane vibrates most is about its middle so that the inner hair cells are spared the most violent vibration of very intense sound. The question then arises, how do the inner hair cells respond to slight or moderate amounts of stimulation? Here the outer hair cells play a major role. When they are stimulated by the travelling wave they respond actively and physically contract. They have muscle proteins in their wall and literally shorten. Because they are attached both to the Reissner's membrane and the basilar membrane, this produces an additional shear movement of the membranous labyrinth, which amplifies the travelling wave at the point of maximal stimulation. This amplified movement is transmitted to the inner hair cells which then respond. If the amount of movement of the basilar membrane is slight, the amount of outer hair cell contracture adds significantly to the basilar cell movement; if the amount of movement is large the contracture adds nothing to the already great displacement of the membranous labyrinth.

If the outer hair cells are damaged they no longer contract in response to slight sounds and the inner hair cells are not stimulated. This produces a hearing loss for low intensity sound. If the sound is more intense, the inner hair cells are stimulated directly and they respond normally so that the ability to hear louder sounds remain unimpaired. This is a common phenomenon known as loudness recruitment. The inner hair cells are much "tougher" than outer hair cells and much less likely to be damaged by ageing, noise or most ototoxic drugs, so ageing, noise and ototoxic drugs usually only produce hearing loss but not deafness. It was noted earlier that the ear is most sensitive to sounds between approximately 3000 and 4000 Hz, in part because of the amplifying mechanism of the ear canal. Thus, the most intense stimulus is produced at these frequencies and the outer hair cells which respond to these frequencies are most at risk from damage. Prolonged exposure to loud sounds damages these hair cells and thus explains the hearing loss from noise which occurs first at 3 to 4 kHz.

2.5. CENTRAL AUDITORY PROCESSING

The nervous impulses are carried along the 8th (statico-acoustic nerve) from the cochlea to the brain stem. Here the nerve fibres reach nuclei where they relay with other nerve fibres. The fibres from each auditory nerve split, some passing to one side of the brain, others remaining on the same side. Thus, as auditory stimuli pass up each side of the brain from both ears, unilateral hearing loss cannot be caused by a brain lesion. The fibres pass up the hind brain to the mid brain and the cerebral cortex. There are many central functions, some of which will be examined but most of which lie outside the scope of this chapter.

2.5.1. The Ability to Block Out Unwanted Sounds.

In a crowded noisy room a young person with normal hearing can tune in and out conversations at will. This is known technically as the cocktail party effect. The brain quite automatically adjusts time of arrival and intensity differences of sound from different signal sources so that the one which is wanted passes to the cortex and all others which do not meet these criteria are suppressed by feedback loops. This requires both good high frequency peripheral hearing, two ears and an additional central mechanism. Even in the presence of normal bilateral peripheral hearing, the elderly lose part of the central mechanism and find it difficult to listen in crowded rooms. This is compounded if there is some hearing loss.

2.5.2. Spatial Localization.

A normal human can localize quite accurately the source of the sound. One knows from what direction the sound is coming; one knows where to turn one's head to look for a speaker; as one knows where to look for an aeroplane or a bird. There are specific neurones which deal with this in the mid brain.

2.5.3. On and Off Sounds

Hearing has an alerting function especially to warning signals of all kinds. There are brain cells which respond only to the onset of a sound and others which respond only to the switching off of the sound, i.e. a change. Think only of being in an air conditioned room when the air conditioner turns on, one notices it. After a while it blends into the background and is ignored. When it switches off, again one notices it for a short time and then too the absence of sound blends into the background. These cells allow the ear to respond to acoustic change - one adjusts to constant sound - change is immediately noticeable. This is true too with machinery and a trained ear notices change.

2.5.4. Interaction of Sound Stimuli with Other Parts of the Brain

Sound stimuli produce interaction with other parts of the brain to provide appropriate responses. Thus, a warning signal will produce an immediate general reaction leading to escape, a quickening of the heart rate, a tensing of the muscle and a readiness to move. A baby's cry will alert the mother in a way it does not alert others. The sound of martial music may lead to bracing movement of those to whom it is being played and induce fear and cowering in the hearts and minds of those at whom it is being played. Certain sounds can evoke anger, others pleasure. The point is that the sensations produced by hearing are blended into the body mechanism in the central nervous system to make them part of the whole milieu in which we live.

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3

THE PATHOPHYSIOLOGY OF THE EAR

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Things can go wrong with all parts of the ear, the outer, the middle and the inner. In the following sections, the various parts of the ear will be dealt with systematically.

3.1. THE PINNA OR AURICLE

The pinna can be traumatized, either from direct blows or by extremes of temperature. A hard blow on the ear may produce a haemorrhage between the cartilage and its overlying membrane producing what is known as a cauliflower ear. Immediate treatment by drainage of the blood clot produces good cosmetic results. The pinna too may be the subject of frostbite, a particular problem for workers in extreme climates as for example in the natural resource industries or mining in the Arctic or sub-Arctic in winter. The ears should be kept covered in cold weather. The management of frostbite is beyond this text but a warning sign, numbness of the ear, should alert one to warm and cover the ear.

3.2. THE EXTERNAL CANAL

3.2.1. External Otitis

The ear canal is subject to all afflictions of skin, one of the most common of which is infection. The skin is delicate, readily abraded and thus easily inflamed. This may happen when in hot humid conditions, particularly when swimming in infected water producing what is known as swimmer's ear. The infection can be bacterial or fungal, a particular risk in warm, damp conditions.

The use of ear muffs particularly in hot weather may produce hot, very humid conditions in the ear canal leaving it susceptible to infection, and similarly insertion and removal of ear plugs may produce inflammation. Although this is surprisingly rare; it does occur particularly in those working with toxic chemicals. These people should take care to wash their hands before inserting or removing ear plugs or preferably use ear muffs. The soft seal of a muff should be kept clean and if reusable plugs are used, they should also be regularly washed. Inflamed or infected ear canals should be treated by a physician.

3.2.2. Obstructing Wax.

One of the more common conditions found is obstruction of the ear canal by a mass of wax. Wax is a mixture of dead skin, oily secretions and sweat and it has varying consistencies from soft to almost rock hard. It normally is extruded on its own but if it is not, it needs careful removal. Contrary to popular belief, wax is not soluble in oil but does disintegrate in water. Gently flushing the ear with water, as for example in a shower, goes a long way towards clearing the ear of wax, or softening it for a physician or nurse to remove. Methods for removal of wax are beyond the scope of this document.

3.2.3. Exostosis

Sometimes there are bony narrowings of the ear canal known as exostoses which are often found in people who have swum a great deal in cold water. They sometimes look like white pearls and are frequently mistaken for cysts. Their only importance is that they may obstruct the view of the tympanic membrane and may be mistaken for pathology. For fuller details of diseases of the pinna and external auditory canal, the reader should consult standard texts or atlases such as Hawke et al (1990).

3.3. THE TYMPANIC MEMBRANE

Perforations of the tympanic membrane may occur as a result of disease or trauma. They usually occur in the pars tensa and may be central or marginal. A central perforation is one which does not reach the edge (annulus) and is usually harmless; a marginal perforation on the other hand which reaches the edge of the membrane and is congruent with the ear canal. This allows the skin of the ear canal to grow into the middle ear space where it desquamates without the debris being able to fall out and may lead to severe disease. Attic perforations are considered as dangerous as marginal perforations. These matters will be dealt with further under the pathology of the tympanic membrane and middle ear.

Traumatic perforations of the tympanic membrane are not infrequent and may occur as a result of a foreign body being pushed through the membrane, as for example a pencil, hair clip or cotton applicator. Industrially, sparks from welding or brazing may fall into the ear canal and burn a hole in the membrane and finally, intense explosion, such as nearby shells or bombs, particularly in a confined space or accidental exposure to mining and quarrying blasts may perforate the membrane. If the explosion is severe enough , there may be disruption of the ossicular chain, and even a sensory neural hearing loss as well (see for example, Cudennec, 1986; Borchgrevink, 1991). Traumatic perforation of all types usually heal on their own; if they do not, surgical grafting may be necessary.

Wormald and Browning (1996), give an excellent, simple, logical, well illustrated guide to diseases of the tympanic membrane and middle ear.

3.4. THE MIDDLE EAR

3.4.1. Acute Otitis Media

The most common causes of disease of the middle ear are respiratory infections producing acute or chronic otitis media. The middle ear, being part of the respiratory tract, is subjected to the same infections as the nose and sinuses and is frequently involved when they become inflamed. The most common is acute otitis media, inflammation of the lining membrane of the middle ear, including the tympanic membrane. If the infection is severe, the middle ear lining, including the tympanic membrane, swells. This produces intense pain and if the swelling is too great then the blood vessels in the ear drum are compressed, local tissue necrosis and the ear drum bursts, letting out pus and relieving the pain. Usually the hole is small and heals quite quickly. It is customary to prescribe an antibiotic although it should be said that about 80%of all acute otitis media resolve spontaneously without treatment.

3.4.2. Chronic Serous Otitis Media

Otitis media with effusion, OME, is probably the most common form of sub-acute ear disease found in the developed world. It occurs following otitis media, when the fluid in the ear, formed by the infection, does not drain spontaneously. The tympanic membrane is intact but the middle ear is fluid filled. This puts it at risk for further infection and certainly worsens hearing by about 30 dB. This is most frequently found in children and can interfere with language acquisition and learning.

3.4.3. Chronic Otitis Media

Sometimes the infection does not settle down and a chronic perforation occurs. This may produce a conductive hearing loss because there is not enough area of the tympanic membrane to catch sound. This type of perforation is usually central, and the middle ear lining becomes thickened and chronically inflamed. The ear is at risk for further acute infections, particularly if dirty water enters the ear. The hearing is also reduced, with a conductive loss of about 20 to 50 dB. The perforation usually happens in childhood and is often associated with a malfunction of the Eustachian tube.

3.4.4. Chronic Otitis Media with Cholesteatoma

In the presence of marginal perforations skin from the ear canal can migrate into the middle ear and space and into the attic surrounding the ossicles and into the mastoid. This skin sheds its surface cells which remain in the middle ear space, looking like white pearly material. If this gets wet or infected it swells and can produce a great deal of damage in the ear and surrounding structures such as the brain and the facial nerve, the nerve that supplies the muscles of the face, because it runs through the ear. Its diagnosis and management are outside the scope of this document.

3.5. INDUSTRIALLY RELATED PROBLEMS OF THE EXTERNAL AND MIDDLE EAR

3.5.1. Trauma

3.5.1.1. Direct blows

Blows to the pinna may produce haematoma described previously. Wearing of dirty ear plugs may produce external otitis. Insertion and removal of ear plugs with dirty hands may produce contact dermatitis of the ear canals. Hard blows to the side of the head may produce perforation of the tympanic membrane, which usually heals spontaneously. All have been described above.

Severe blows to the head may fracture the temporal bone and dislocate and fracture the ossicular chain. This may produce a significant amount of conductive hearing loss although it is usually accompanied also by a sensori-neural loss.

3.5.1.2. Foreign bodies

These may fall into the ear as for example sparks when welding and hot objects may hit the tympanic membrane burning holes in it. These are difficult to close permanently by operation. The writer has seen unfortunate individuals who have fallen into vats containing chemicals, producing chemical external otitis or in whom hot liquids which they had been carrying on their shoulder have spilled into the ear, burning the ear (Frenkiel and Alberti, 1977). The tympanic membrane may also be directly perforated by sharp object stabs in the ear, or by explosions as already described.

3.5.1.3. Barotrauma

Divers are subject to middle ear haemorrhage and blockage if they cannot clear their ears when descending or ascending. If this occurs, a physicians' opinion should be sought. Care should be taken not to dive with a cold, for this reduces Eustachian tube function and thereby the ability to equalize middle ear pressure.

3.6. THE INNER EAR

At birth the inner ear is fully developed. The cochlea is adult sized and has its total complement of hair cells, supporting cells and nerve fibres. The tissues respond like those elsewhere in the body to trauma and infection by producing an inflammatory response. However, unlike most other tissue in the body, if the damage is severe enough to destroy a mammalian hair cell or nerve fibre, it does not regenerate. One is born with the full complement of hair cells and nerve fibres. Through life they are gradually diminished as a result of a variety of processes including infection, trauma and ageing. By contrast, avian auditory hair cells retain the capacity to regenerate if destroyed by, for example, acoustic trauma; there is much research worldwide to elucidate the mechanism in the hope that it may be applied to the mammalian ear.

3.6.1. Infection

Certain viral infections have a predilection for the ear and wreak havoc with its structure. Pregnant women may contract Rubella (German Measles) and the virus may destroy the developing cochlea leading to a child born deaf, as part of the rubella syndrome. In post-natal life both measles and particularly mumps may infect the inner ear destroying the cochlea, producing total deafness in that ear. This is usually unilateral and almost always happens in childhood. It can be completely prevented by appropriate vaccination. It may occur in as many as one in a hundred children who develop mumps, leaving them with a unilateral hearing loss. If this occurs early it may produce noticeable symptoms, often only being discovered in later in life when the telephone is first used and held to the deaf ear.

3.6.2. Bacterial Infections

Meningitis commonly affects the inner ear because the perilymph, the fluid surrounding the membranous labyrinth is in direct continuity with the cerebral spinal fluid. Meningitis produces an acute inflammatory response of the meninges (the membrane surrounding the brain)and may also produce a similar response in the cochlea destroying it completely. Of those who survive meningitis up to five percent may be deaf (Fortnum and Davis, 1993). This too can usually be prevented by a vaccination. It has become a major problem in the central African and West Asian countries which form part of the meningitis belt (Moore and Broome, 1994).

3.6.3. Immunological Diseases

The inner ear is subject to certain diseases, one of the most common of which is Meniere's disease or syndrome. The disease is characterized by episodes of loss of hearing, a sense of fullness in the ear, ringing, nausea and vomiting. To begin with, the hearing loss is transient but ultimately it becomes permanent. The dizziness lasts for two or three hours at a time and the whole episode with repeated attacks may last for a month or six weeks only to recur again several months later. The pathophysiology is almost certainly an immune reaction. This gives rise to an inflammatory response producing too much fluid within the membranous labyrinth which distends and ultimately may rupture. When there is inter-mingling of endolymph and perilymph, hearing loss occurs. If the ruptured membrane heals, the hearing may recover. In time fifteen percent of patients develop the disease in both ears. After many years it ultimately burns out. It rarely leaves the person deaf but it does produce a severe hearing loss. For further details see standard texts or monographs such as Nadol (1989) or Oosterveld (1983).

3.6.4. Sudden Hearing Loss

A sudden inner ear hearing loss, defined as a loss which develops in a matter of seconds to two or three days, is quite common. The person will often notice an increased buzzing in the ear and a loss of hearing and associated with a distortion of sounds. Treatment varies widely throughout the world, ranging from nil to aggressive in hospital management with a variety of medications. The results seem to be similar: more than one-third recover completely, one-third recover somewhat and one-third do not recover. It may be associated with an episode of acute vertigo. The cause of this type of loss is unknown although it is sometimes attributed to excessive pressure change as for example hard nose blowing which may rupture Reissner's membrane or the round window membrane. This is probably conjecture.

For more information about diseases of the inner ear, the reader should consult the standard textbook of Otology in use in their country.

3.6.5. Tinnitus

Ringing in the ears is an extremely common phenomenon found at some time or another in up to one-third of the adult population; twelve percent have it sufficiently severely for them to seek a medical opinion about it. The noises in the ear are of many types, ranging from hearing one's own pulse to buzzes, clanging, clicking, whistling, humming and ringing of which the most common types are buzzing and ringing. Usually tinnitus cannot be heard by the outside observer and is known as subjective tinnitus. It is irritating but usually harmless. People with tinnitus are often worried that it is a precursor of some serious disorder such as stroke, hypertension or brain tumour. The prevalence of tinnitus in these conditions is no greater than the population at large, so they can be reassured. It is more common in the presence of hearing loss and may be precipitated by an acute traumatic episode such as an explosion or a head injury. Transient tinnitus is a fairly common finding in response to loud sound, often occurring in those who go to a noisy disco. It is also a common finding in occupational hearing loss, found somewhat more frequently in those exposed to impact than to steady state noise. It should be considered as a warning of excessive sound exposure and appropriate precautions taken.

Occasionally the noises may be heard by another person in which case they are known as objective tinnitus. This is caused either by a vascular malformation in which case the sound is a pulsatile one which may be heard by an outside observer through a stethoscope applied to the head or it is due to muscleclonus, usually of the palate in which case there is an audible clicking sound. For further reading about tinnitus in general, the reader is referred to conference proceedings edited by Feldmann (1987) and by Aran and Dauman(1991).

3.7. OCCUPATIONAL CAUSES OF INNER EAR HEARING LOSS

3.7.1. Noise

Excessive exposure to noise is probably the most common cause of preventable hearing loss on a global basis. In general terms, prolonged exposure to sound in excess of 85 dB(A) is potentially hazardous although the important factor is the total amount of sound exposure i.e., both the level and length of exposure are important and the two interrelate (see for example Robinson, 1987, Dobie, 1993). Chapter 4 in this document deals with safe levels of sound exposure both in terms of loudness and duration. Here we will deal with the damage that excessive sound may cause to the inner ear. After exposure to a typical hazardous industrial sound, perhaps in the low nineties (dB(A)) for an 8-hour work day, the ear fatigues and develops a temporary threshold shift (TTS). The hair cells become exhausted from the excessive metabolic stress placed upon them and hearing becomes less acute. This is usually transient and after appropriate rest, recovery ensues. Workers notice this with their car radios: when they leave work they turn the volume up and by the next morning the radio is too loud; those going to discos cannot hear while they are in the disco and cannot hear when they come out but by the next morning their ears too have recovered.

The pathophysiology of noise damage to the ear has been extensively studied in man and animals and much is now known of the mechanism whereby excessive sound exposure damages the ear. Low levels of damaging sound exposure produces TTS, as described in the preceding paragraph. If TTS occurs day after day, the recovery becomes less complete and a permanent threshold shift (PTS) occurs because with persistent exposure to such sounds some hair cells do not recover. First to fail permanently are the outer hair cells (OHCs) in the basilar part of the cochlea, in the area which responds to 4 kHz and the adjacent areas of 3 and 6 kHz. This is where the ear is most sensitive, in part because of the harmonic amplification of the ear canal and in part because of an absolute sensitivity. Once hair cells degenerate they do not recover and a permanent hearing loss develops. Classically therefore, following noise exposure, hearing loss is shown as an audiometric notch, usually maximal at 4 kHz but may also be based anywhere between 3 and 6 kHz. With higher noise exposure for longer periods, the loss extends into adjacent frequencies. If the sound is sufficiently intense, it produces a much more severe TTS which may go on to a more rapidly produced PTS. There is a critical point where moderate TTS changes to longer term TTS which correlates well with anatomical damage to the OHCs, a process of damage and scarring or repair. The threshold for TTS is somewhere between 78 and 85 dB and the point where it changes from mid-term to long-term is about 140 dB. The spectrum of the sound and the length of exposure are critical.

Cilia of the OHCs are attached to each other near their tip by linking filaments and each cilium has a little rootlet which passes through the ciliary plate (see Figure 3.1).

If the mechanical disturbance produced by sound is sufficient to fracture the rootlet, or to

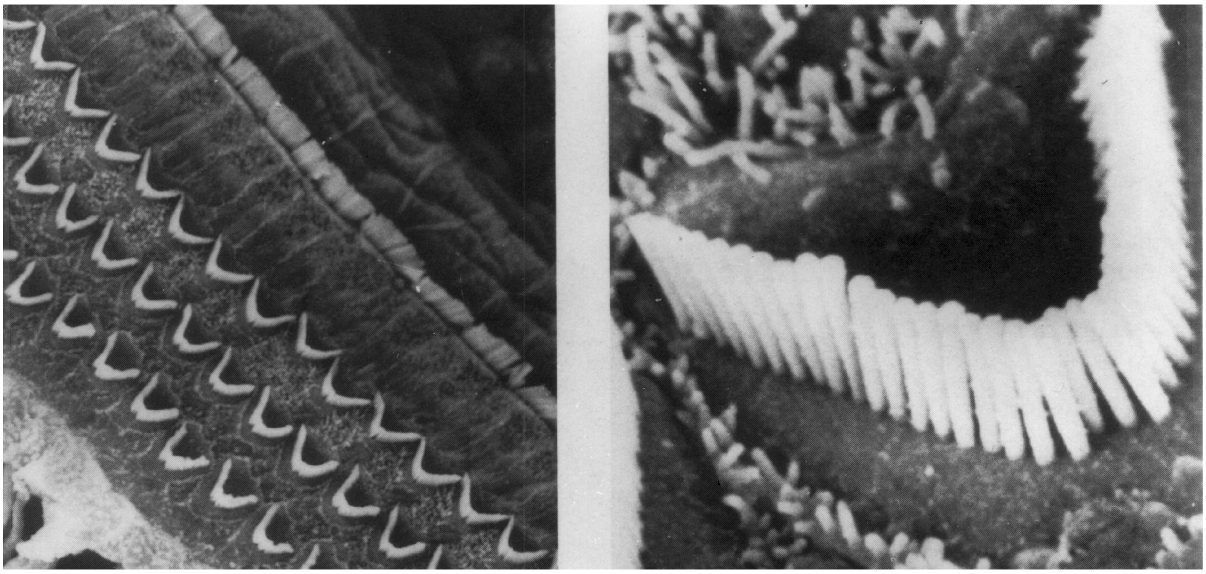

**Figure 3.1. (a) Surface of the normal organ of Corti, guinea-pig, X 1100.
(b) Close up view of the stereocilia of OHC, X 11000 (from Gao et al, with permission).**

disturb the linkages, which frequently are concurrent, the result is a floppy cilium. These either partially recover or are totally destroyed and replaced by phalangeal scarring. By contrast, moderate sound excursion produces much less (and temporary) distortion of the cilia and they recover (see Figure 3.2).

Noise characteristically damages the OHCs of the basilar turn. If sound is intense enough, there is physical disruption of the cochlea and other structures may also be damaged, such as the stria vascularis and the supporting cells. Some time after hair cell death there is also neural degeneration of the first order neurones. Very intense sound has been shown to produce damage to the vestibular epithelium of guinea-pigs but has not been convincingly demonstrated in man.

Figure 3.2(a). Changes in stereocilia, guinea pig, (X 1700) after 30 minutes exposure at 110 dB. Note slight bending and separation at the tips of the stereocilia. The ear had a 25 -30 dB TTS.

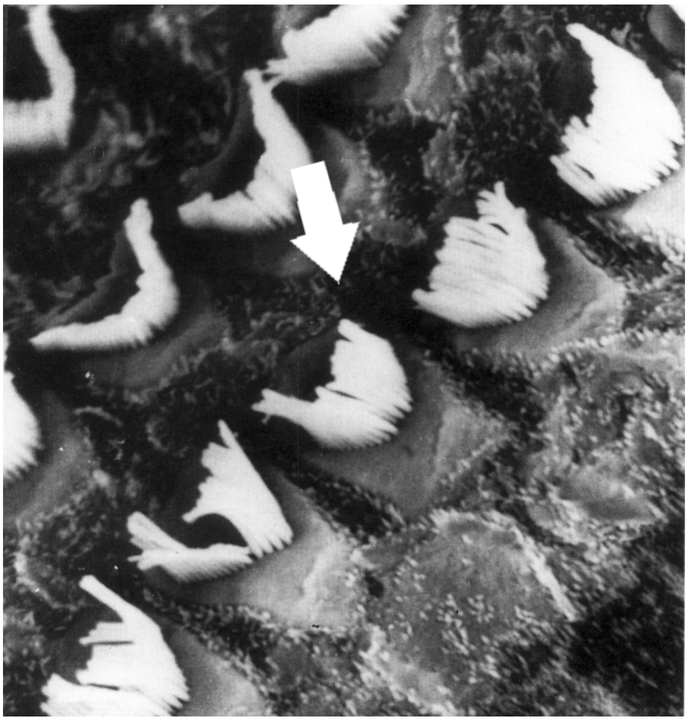

Figure 3.2(c). Changes in stereocilia, guinea pig, (X 1700) of the 110 dB group eighty days after exposure. The hearing was normal and so was the appearance of the stereocilia

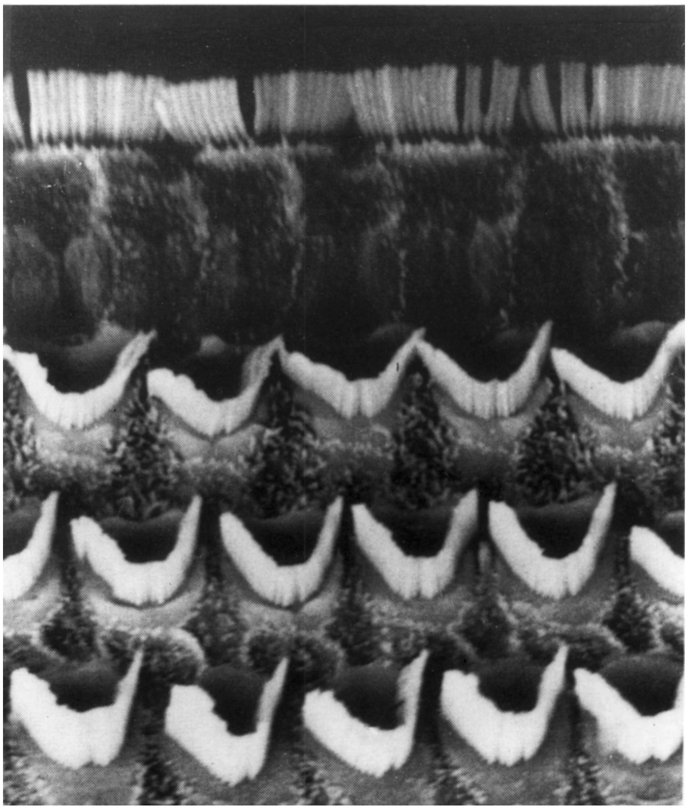

Figure 3.2(b). Changes in stereocilia, guinea pig, (X 1700) after 30 minutes exposure at 120 dB. Note complete collapse at the bases of stereocilia. The ear showed a 45 to 50 dB TTS.

Figure 3.2(d). Changes in stereocilia (X 1700) in the apical surface of the organ of Corti, guinea pig, of the 120 dB group eighty days after exposure. The surface is devoid of both stereocilia and hair cells. (from Gao et al, with permission).

3.7.1.1. Tuning curves

Each auditory nerve fibre is most responsive to a specific frequency, but as the intensity of sound increases it becomes progressively sensitive to adjacent frequencies. With OHC loss (as occurs in NIHL), the most sensitive fine tuned part of the response disappears and the nerve fibres respond at an elevated threshold to a broader band of frequencies. It is generally assumed that the sharp tuning of these curves at low intensity is due to active mechanisms in the OHCs and associated efferent nerve pathways. Their loss may be correlated with the clinical finding of poor sound discrimination, a common complaint in NIHL.

3.7.1.2. Toughening

There is some evidence that prior exposure to none damaging levels of low frequency noise protects the cochlea from damage by subsequent high intensity sound. The mechanism and importance of this phenomenon are not clear (Henderson et al, 1993; Henselman et al, 1994).

Permanent hearing loss from exposure to hazardous noise may happen quite early and an audiometric notch may be noticeable within six months or a year of starting a job in a hazardous level of sound. The international table of risk (ISO 1999E) gives these predictions. There is a great variation in the susceptibility of the ear to the effect of sound also evident in well controlled animal experiments - some people have tough ears and some have tender ears

There are military small arms instructors who over a lifetime have fired hundreds of thousands of rounds and who have little or no hearing loss at the end of it; there are recruits who after one day on the range develop a permanent notch. The international table takes this into account. It is, therefore, very difficult to state with certainty what a safe level of sound may be; a level which is safe for 85% of the population may leave 15% at risk and a level which is safe for the total population is so low that it is impractical to implement. In any event, with continuing hazardous sound exposure, the hearing continues to worsen although the greatest loss occurs in the first ten years and thereafter the rate slows.

How to determine susceptibility to noise exposure before the event is elusive. Attempts to correlate TTS after one day's exposure to long term loss have repeatedly failed. TTS at the end of a work shift does mark the upper bound of the PTS produced by the same sound exposure after ten years. However the PTS may be much less. A promising (and fashionable) test is based on changes in oto-acoustic emissions; some investigators have suggested that there is a reduction in these emissions before a change is evident in the pure tone threshold, giving an early warning of incipient damage.

3.7.2. Asymmetric Hearing Loss

Usually if both ears are exposed to the same level of sound, the hearing loss is symmetrical. The left ear may be a little worse because, in general terms, the hearing in the left ear of males is slightly worse than the right by about 4 dB at 4 kHz (Pirila et al, 1991). However, causes for greater asymmetry should be sought. These may be industrial and non-industrial.

Not all industrial noise exposure is equal in both ears. Usually sound level measurements in industry are made at the work site, they are not taken at the worker's head.

There are many processes where the sound is more intense at one side of the head than the other and indeed the head may produce a sound shadow. A classic example is rifle firing where the left ear which is nearest the muzzle in a right-handed person, is exposed to more sound than the right ear, which is protected by the head shadow and the result is a notched hearing loss in the left ear. Use of hard rock drills in mining produces a similar affect and so may the use of heavy electric drills into concrete where there can be up to 8 dB difference in the sound pressure level between the ears which may translate into different hearing losses of the two ears. This is also a common finding in agricultural workers, particularly tractor drivers (especially if there is no cab), who sit with their head turned watching what they are pulling with the leading ear exposed to the exhaust at the front of the equipment. Much further study is required of the noise exposure at the ear as opposed to sound pressure levels at the work site.

3.7.3. Social Noise Exposure

Social noise exposure is also a significant source of acoustic trauma, both from recreational pursuits (Clark, 1991) and from the noise enveloping the cities of the developing world. There are good studies of city sound levels in Asian cities showing sound levels sustained at hazardous levels for many hours of the day(e.g., Bosan, 1995; Chakrabarty, 1997). Exposure to city sound levels may interact with industrial noise exposure and it may be difficult to decide how much of a hearing loss is due to workplace hazards and how much due to recreational or environmental sounds. The factors which are important vary by community. Further discussion is beyond the scope of this chapter.

3.7.4. Progression of Hearing Loss

It has already been mentioned that with prolonged exposure to the same noise, hearing loss continues to worsen. The international standard, ISO 1999, allows one to predict how much hearing loss may be expected for a given noise exposure for varying periods of time. For a given hazardous sound level, the maximal effect is in the first few years, although there is a slow, continuing progression of hearing loss thereafter as long as the noise exposure continues. However, at the same time, all people are subject to the hearing loss of ageing, known as presbyacusis, in which there is a gradual loss of hearing in later years caused in part by hair cell degeneration. Individual variation is great: some people maintain good hearing into old age, others do not (Corso, 1980; Macrea, 1991; Robinson, 1991; Rosenhall, 1990). Tables exist to predict the amount and range of presbyacusis, and they are also incorporated into the noise standard, ISO1999.

The interaction between noise exposure and presbyacusis as causes of hearing loss are important and complex. Are the two additive, or is an ageing ear more or less susceptible to the affects of hazardous noise? It seems that in the earlier years they are additive, but thereafter as the exposure continues and the subject ages, the hearing loss is less than would be expected by simply adding the predicted loss from noise in dB to that predicted from ageing in dB. Many formulae have been devised to attempt to separate the affects of noise from ageing (Dobie, 1992; Robinson, 1987, Bies and Hansen, 1990).

The question is often asked whether hearing loss from noise continues after removal from the noise source. It is overwhelmingly accepted, although not universally, that this does not occur and that any worsening that happens in the months and years after quitting working in a noisy place is due to other causes, almost always presbyacusis.

3.7.5. Trauma

The inner ear can be damaged by direct head injury or by blasts such as explosions, or pressure changes.

3.7.5.1. Head injuries

Head injuries, even those that do not produce unconsciousness, can produce disruption of the cochlea with a sensory-neural hearing loss. This is not necessarily notched as with noise but may be flat. More severe head injury can produce a fracture of the temporal bone leading to disruption of the middle ear, as well as well as to trauma to or a fracture through the cochlea itself, and thus a conductive loss as well as a sensory neural loss; the latter destroying the hearing totally.

3.7.5.2. Explosions

Blast injuries, i.e. ones where the sound levels exceed those normally found in industry, can produce physical disruption to the cochlea. Any sound loud enough to produce more than a 40 dB temporary threshold shift is likely to produce permanent trauma to the cochlea. The cochlea, like all other tissue in the body, responds to trauma with an inflammatory reaction and cells may be repaired, in which case some recovery of hearing takes place or the cells may be so badly damaged that they degenerate and are absorbed, producing hearing loss. In general terms, if the trauma is loud enough to snap the cilia, the cells will not recover (see above). This type of damage occurs with blasting accidents in mining, gas explosions and in the military (Borchgrevink, 1991; Cudennec et al., 1986; Phillips & Zajtchuk, 1989; Roberto et al., 1989).

3.7.5.3. Baro-trauma

Extreme pressure changes can cause temporary and permanent damage to the ear. The changes associated with flying are the best known, such as pain on ascent and particularly on descent, caused by inadequate function of the Eustachian tube, the small passage which connects the middle ear to the nose. Most readers will be familiar with a stuffy sensation in the ears when riding a high speed elevator in a tall building. Similar problems occur with industrial elevators in mines, where workers may descend several hundreds of metres at high speed to reach the active mining site. Ear pressure equalization problems are a common complaint amongst workers in the deeper gold and nickel mines.

The greatest hazard to the ear related to pressure comes from working in higher than normal atmospheric pressure such as in some tunnelling operations and in diving. When a person is exposed to higher than normal pressures the blood gasses equilibrate with the surrounding gas and greater amounts are absorbed into the body. If the ambient pressure suddenly returns to normal, the gas dissolved in the body tissues comes out of solution, and particularly nitrogen, forms bubbles in body tissues. These are painful and may produce damage by preventing oxygen reaching the tissues. The condition is known as “The Bends” and can affect the ear, producing permanent damage to the cochlea, and with it, varying degrees of hearing loss (Al-Masri et al, 1993; Molvaer et al, 1990; Talmi et al, 1991).

It is also suggested that exposure to high noise levels while exposed to high pressure may be more hazardous to the hearing than the same noise at ambient pressure.

3.7.6. Complex Interactions

It is becoming clear that noise is not the only industrial hazard to hearing; exposure to certain chemicals such as toluene and trichlorethylene can produce hearing loss (Boettcher et al, 1992; Franks et al, 1996); as can interaction with certain medicines (Aran et al, 1992). More important, the interaction between noise and the chemicals may produce more hearing loss than expected; i.e., they act synergistically (Johnson et al, 1995; Morata et al, 1995). The same is true of those subject to vibration induced white hand, as may occur in the forestry industry; they develop more hearing loss from the same exposure than fellow workers whose hands do not turn white (Iki 1996).

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INTERNATIONAL STANDARD

Title of the following standard related to or referred to in this chapter one will find together with information on availability in chapter 12:

ISO 1999

FURTHER READING

Axelsson, A., Borchgrevink, H., Hamernik, R.P., Hellstrom, P.A., Henderson, D. and Salvi, R.J. (1996): *Scientific Basis of Noise-Induced Hearing Loss*. New York, Thieme.

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4

EXPOSURE CRITERIA, OCCUPATIONAL EXPOSURE LEVELS

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4.1. GENERAL CONSIDERATIONS

Airborne sound can be described as propagating fluctuations in atmospheric pressure capable of causing the sensation of hearing. In occupational health, the term "noise" is used to denote both unwanted sound and wanted sound as they can both damage hearing. Noise-induced hearing loss has been recognized and reported for several hundred years. However, prior to about 1950, reliable dose-effect data were not available. Before World War II, due to lack of uniformity in instrumentation and related units and scales, studies from various parts of the world often yielded significantly different results.

Present day American, European, and International standards (ANSI S3.6-1989, ANSI S1.4-1983, ANSI S1.25-1991 and IEC 60804-1985) relating to the instrumentation and methodology of both noise and hearing acuity measurements are now in reasonable accord. Recently, this accord resulted in an International Standard, ISO 1999-1990. This standard, although generally well accepted internationally, is not universally accepted (Bies & Hansen 1990, Bies 1990, Clark and Popeika 1989, Kraak et al. 1977 and Kraak 1981). It has been available for more than 12 years for review. It is the standard that is the basis of the occupational noise exposure limits, the time-intensity trading relation, and the method for combining continuous noise with impulse noise.

The exposure criteria for the following sections 4.2 and 4.3 are an adaptation of the background documentation supporting the American Conference of Governmental Industrial Hygienists (ACGIH) Occupational Exposure Levels (OEL). However, the same criteria can also be used to support different OEL.

4.2. CRITERIA FOR CONTINUOUS AND INTERMITTENT NOISE

4.2.1. Introduction

The statement in the occupational exposure limit that the proposed OEL (85 dB(A)) will protect the median of the population against a noise-induced permanent threshold shift (NIPTS) after 40 years of occupational exposure exceeding 2 dB for the average of 0.5, 1, 2, and 3 kHz comes from ISO-1999-1990. Specifically, Table 4.1 provides median NIPTS values for a 40-year exposure to 85 dB(A). These values are 0, 0,2, and 5 dB for the audiometric frequencies of 0.5, 1, 2, and 3 kHz, respectively. Table 4.2 provides the same data for a 40-year exposure to 90 dB(A). These values are 0, 0, 6, and 12 dB for 0.5, 1, 2, and 3 kHz, respectively. The average value for the audiometric frequencies of 0.5, 1, 2, and 3 kHz is 4.5 dB. The corresponding average value for a 40-year daily exposure of 95 dB(A) is more than 10 dB.

Table 4.1: NIPTS values (dB) for a 40 year exposure to 85 dB(A).

Frequency, Hz	Exposure Time, Yr								
	10			20			40		
	Fractiles								
	0.9	0.5	0.1	0.9	0.5	0.1	0.9	0.5	0.1
500~~0~~	0	0	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0	0	0
2000	0	1	1	1	1	2	1	2	2
3000	2	3	5	3	4	6	3	5	7
4000	3	5	7	4	6	8	5	7	9
6000	1	3	4	2	3	5	2	4	6

Table 4.2. NIPTS values (dB) for a 40 year exposure to 90 dB(A).

Frequency, Hz	Exposure Time, Yr								
	10			20			40		
	Fractiles								
	0.9	0.5	0.1	0.9	0.5	0.1	0.9	0.5	0.1
500~~0~~	0	0	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0	0	0
2000	0	2	6	2	4	8	4	6	1
3000	4	8	13	7	10	16	9	12	1
4000	7	11	15	9	13	18	11	15	2
6000	3	7	12	4	8	14	6	10	1

The ISO 1999-1990 standard provides a complete description of NIPTS for various exposure levels and exposure times. From these tables, it can be seen that there is clearly no fully obvious level at which to set the OEL. The 85 dB(A) limit for 8 hours is recommended by the ACGIH and has found acceptance in most countries. Because some countries still use 90 dB(A) or both for different steps of action and indeed the early OEL was at 90 dB(A), a short review of the ACGIH recommending an A-weighted 8-hour equivalent level of 85 dB(A) is in order.

4.2.2. Octave Band vs. A-Weighting

Before 1950, overall sound pressure levels, in decibels, were used to define the noise aspect of damage-risk criteria (Olishijski and Hartford 1975). Following recognition that the overall intensity of a noise by itself was not sufficient to describe the potential for damage, and that the frequency characteristic must also be considered, criteria incorporating spectral levels, usually octave-band levels, were developed.

Since 1954 different national and internationl committees discussed this issue.

In 1961, the ISO/TC 43 discussed a series of noise rating curves and proposed that the noise rating curve, NR-85, be used as the limit for habitual workday exposure to broadband noise.

An octave-band analysis is a relatively lengthy procedure requiring expensive instrumentation. There was some concern that the layman had difficulty in interpreting the results. Recognizing the desirability of a single reading and the fact that most industrial data on NIPTS were available for single-weighted noise levels, the Intersociety Committee, in 1967, proposed the use of A-weighted sound levels in the development of criteria (Ad Hoc Intersociety Guidelines 1967). The A-weighted characteristic of a sound level meter is designed to approximate the frequency selective response of the human ear at low sound pressure levels. In one report, Botsford demonstrated that A-weighted levels are as reliable as octave-band levels in the prediction of effects on hearing in 80% of the occupational noises considered and slightly more conservative (more protective) in 16% of the cases (Botsford 1967). Passchier-Vermeer (1968) and Cohen et al. (1972) similarly demonstrated that A-weighted levels provide a reasonable estimate of the hazard to hearing in most industrial environments. The abbreviation dB(A) is used to denote decibels A-weighted and can be described as a unit of measurement of sound level corrected to the A-weighted scale as defined in IEC 60651. Today, A-weighted sound levels are in general use in hearing damage risk criteria.

4.2.3. 85 dB(A) vs. 90 dB(A)

Permanent noise-induced hearing loss is related to the sound pressure level and frequency distribution of the noise, the time pattern and duration of exposure, and individual susceptibility. The ability to hear and understand everyday speech under normal conditions is regarded as the most important function of the hearing mechanism. Thus, most present-day studies focus on the resultant or predicted hearing loss in the speech frequency range.

The zero settings on the audiometer are based on response levels derived from the testing of large groups of young people. There is general agreement that progression in hearing loss at frequencies of 500, 1000, 2000, and 3000 Hz eventually will result in impaired hearing, i.e., inability to hear and understand speech..

Among several other studies a study by Burns and Robinson (1978) included such factors as the use of A-weighted decibels (dB(A)), (which was supported), variability in audiometric measurement, relationship of temporary threshold shift to permanent loss, and use of the equal-energy approach. The results from the study are discussed in the 1972 NIOSH criteria document and summarised in the following paragraph.

The NIOSH, in 1972, published “Criteria for a Recommended Standard–Occupational Exposure to Noise” (National Institute of Occupational Safety and Health 1972). Audiometric and noise exposure data were obtained from 792 noise-exposed workers from various industries and 380 non-noise exposed workers from the same industries. An analysis of the data indicated approximately 19% risk of impairment (HLI[O.5,1,2] >25 dB(A)) for workers exposed for more than 30 years to 85 dB(A). The NIOSH document contained a comprehensive review of published data from other studies.

In 1974, the U.S. Environmental Protection Agency (EPA 1974) published the "levels" document. In this document, an 8-hour level of 75 dB(A) was established as the level that would protect "public health and welfare with an adequate margin of safety." Much of this result was based on the work of Johnson (1973). He combined the works of Passchier-Vermeer (1968), Baughn (1973), and Burns and Robinson (1978). These were the same data available to the TLV Committee. A major difference, however, was the use of 4000 Hz as the most sensitive indicator of hearing loss. Johnson (1973) observed that the difference between protecting 4000 Hz and the average of 0.5, 1, and 2 kHz from the same amount of noise-induced permanent threshold shift, is that protecting 4000 Hz requires 10-15 dB(A) lower exposure levels.

In 1978, there was general agreement that the hearing level at 3000 Hz is related to the hearing and understanding of speech, particularly in the presence of noise. In 1978, in the summary of an investigation by Suter it was reported that: "Correlation tests revealed that frequency combinations that included frequencies above 2000 Hz were significantly better predictors of speech discrimination scores than the combination of 500, 1000, and 2000 Hz" (Suter 1985).

In 1979, the AAOO included 3000 Hz in their hearing impairment formula (American Academy of Ophthalmology and Otolaryngology 1970). For this reason, the TLV is based on a formula that includes 3000 Hz. Using ISO-1999, the median amount of NIPTS after 40 years of exposure to 90 dB(A) is 2 dB for the average of 500, 1000, and 2000 Hz. The same 40-year exposure at 85 dB(A) for the average of 500, 1000, 2000, and 3000 also is 2 dB. Thus, everything else being equal, inclusion of 3000 Hz will drop the 8-hour criterion level from 90 dB(A) to 85 dB(A).

4.2.4. 3 dB(A) vs. 5 dB(A)

If hearing damage is proportional to the acoustic energy received by the ear, then an exposure to a particular noise level for one hour will result in the same damage as an exposure for two hours to a noise level which is 3 dB lower than the original level. This is referred to the 3 dB(A) trading rule and is generally accepted in many parts of the world. However, 4 dB(A) and 5 dB(A) rules exist in the USA and the purpose of this section is to discuss the relative merits of the various trading rules in current use.

After experimenting with and proposing the equal energy or 3 dB(A) rule and after extensive study by the National Academy of Sciences-CHABA, the U.S. Air Force introduced the equal energy rule in its regulation on Hazardous Noise Exposure in 1956 (Eldred et al. 1955 and Air Force Medical Services 1956).

While not all researchers have supported the 3 dB(A) rule, (Bies & Hansen 1990, Bies 1990, Clark and Popeika 1989, Kraak et al. 1977 and Kraak 1981). an overwhelming general consensus favoured its use at a special meeting of the TLV Committee at Aberdeen, MD, in 1992 (Sliney

1993).

There was also a special meeting in 1982 at Southampton, England. Many leading investigators of noise-induced hearing loss reviewed the available literature with respect to the use of equal energy (von Gierke et al. 1981). The group endorsed the use of equal energy as the most practical and reasonable method of measuring both intermittent and impact/impulse noise between 80 dB(A) and 140 dB(A). This meeting produced the international consensus that is the basis of ISO-R-1999.

Suter (1992) also concluded that the 3 dB(A) exchange rate was the method most firmly supported by the scientific evidence now available. Some key arguments summarized were:

“1. TTS2 (TTS measured 2 minutes after exposure) is not a consistent measure of the effects of a single day's exposure to noise, and the NIPTS after many years may be quite different from the TTS2 produced at the end of an 8-hour day. Research has failed to show a significant correlation between TTS and PTS, and the relationships between TTS, PTS, and cochlear damage are equally unpredictable.
2. Data from animal experiments support the use of the 3 dB(A) exchange rate for single exposures of various levels within an 8-hour day. But there is increasing evidence that intermittentcy can be beneficial, especially in the laboratory. However, these benefits are likely to be smaller or even nonexistent in the industrial environment where sound levels during intermittent periods are considerably higher and where interruptions are not evenly spaced.
3. Data from a number of field studies correspond well to the equal-energy rule.
4. CHABA's assumption of the equal temporary effect theory is also questionable in that some of the CHABA-permitted intermittent exposures can produce delayed recovery patterns even though the magnitude of the TTS was within "acceptable" limits, and chronic, incomplete recovery will hasten the advent PTS. The CHABA criteria also assume regularly spaced noise bursts, interspersed with periods that are sufficiently quiet to permit the necessary amount of recovery from TTS. Both of these assumptions fail to characterize noise exposures in the manufacturing industries, although they may have some validity for outdoor occupations, such as forestry and mining."

In addition to Suter's (1992) conclusions, there are several other reasons to change to the equal energy rule. These reasons should benefit industry as well as increase assessment accuracy. One of the foremost reasons is the elimination of the all-or-nothing limit of 115 dB(A). A short burst of noise, such as an aircraft flyover or a siren, might exceed this limit. Yet, a burst of broadband noise as long as 10 msec at 130 dB has been shown to cause almost no TTS (Kryter et al. 1965, Schori 1976, Johnson and Schori 1977). On the other hand, research has shown that broadband noise of 115 dB for 15 minutes is likely to cause excessive TTS (Schori 1976). Use of equal energy eliminates this arbitrary 115 dB limit.

Second, use of equal energy better predicts the hazard of noise for exposure durations greater than 8 hours. For an 8-hour criterion level of 85 dB(A), the 5 dB(A) rule would dictate a 16-hour exposure at 80 dB(A) and a 24-hour exposure at 77 dB(A). The equal energy rule will allow 82 dB(A) for 16 hours and 80 dB(A) for 24 hours. The threshold of any TTS to broadband noise for periods as long as 24 hours has been shown to be between 78 and 80 dB(A) (Stephenson et al. 1980). On the other hand, 85 dB(A) for 8 hours will cause some TTS. It is certainly more reasonable to anchor the 24-hour point to 80 dB(A). The only time that a lower limit than 80 dB(A) would be appropriate is the very unusual circumstance when the exposure consists of a steady pure tone.

A third reason is the inclusion of 3000 Hz. What is often forgotten is that the benefit of intermittency, as shown in the CHABA WG46 curves (1956), did vary with the audiometric frequency considered. Higher audiometric frequencies required smaller trading relations than the lower audiometric frequencies to produce equal TTS. Therefore, even if the equal TTS2 model was correct, inclusion of 3000 Hz would dictate reducing the 5 dB(A) trading relation to a lower number. In some cases, this number might even be slightly lower than 3 dB(A).

In summary, the equal energy rule (3 dB(A) rule) appears to be a better predictor of noise hazard for most practical conditions and is strongly recommended by the TLV Committee.

Note: Reference is made to the following formula for determining hearing impairment. The main point at issue is the inclusion of the hearing threshold level at 3000 Hz in such a formula.

In 1970 the American Academy of Opthalmology and Otolaryngology (AOO) developed a new formula for determining hearing impairment. The formula includes the 3000 Hz frequency, and is as follows:

"1. The average of the hearing threshold levels at 500, 1000, 2000, and 3000 Hz should be calculated for each ear.
2. The percentage of impairment for each ear should be calculated by multiplying by 1.5 percent the amount by which the average hearing threshold level exceeds 25 dB(A). The impairment should be calculated up to 100 percent reached at 92 dB(A).
3. The impairment then should be calculated by multiplying the percentage of the better ear by five, adding this figure to the percentage from the poorer ear, and dividing the total by six."

4.3. CRITERIA FOR IMPULSE NOISE

The previous approach for assessing impulse/impact noise was to allow 100 impulses or impacts per day at 140 dB(A), or 1000 per day at 130 dB(A), or 10,000 per day at 120 dB(A). Impacts or impulses referred to discrete noise of short duration, less than 500 ms, where the SPL rises and decays very rapidly. One of the problems with this approach is that it is difficult, if not impossible, to properly measure impact duration. A manufactured instrument is available that can sum the number of measured impulses at each 1 dB(A) increment and divide by the number of allowable impulses. From this sum, a dose can be calculated. However, the calculation of this dose requires several assumptions that were not explicit in the previous TLV. While these assumptions could be clarified here, there exists a more accurate approach for addressing impulse/impact noise.

Besides the complexity of using the previous TLV for impulse noise, there were several fundamental problems with the old TLV limit. The first problem is that the duration of the impulse or impact was not considered. A short 1-ms pulse was considered as harmful as a long 200-ms pulse. This is not consistent with the CHABA guidelines on impulse noise (National Research Council 1968, Kryter et al. 1965) or any known research. Second, impulse or impact noise was treated separately from non-impact noise. This separate treatment is inconsistent with the research of Hamernik et al. that has shown that at exposures that cause moderate or high levels of TTS, combined impact and continuous noise can cause a synergistic effect, that is, the resultant effect is greater than just the addition of the results from the impact exposures and the results from the continuous noise exposures (Hamernik et al. 1974). Fortunately, these same researchers have shown that at exposure levels that will cause only a small amount of TTS, as much as the proposed 8-hour 85 dB(A) threshold, this synergistic effect disappears (Hamernik et al. 1980).

The proposed method of assessing impulse or impact noise resolves both these problems. By combining all sound energy between 80 dB(A) and 140 dB(A), impact/impulse noise is combined with continuous and intermittent noise. Longer impulses are considered more dangerous than short impulses. Finally, the measurement of noise becomes greatly simplified.

It should be noted that the previous TLV limit on impulse noise was already based on equal energy so the major change is the combining of all noise in one measure.

Support of this procedure comes from numerous documents and standards. The current ISO standard, ISO 1999-1990, uses this approach. The published draft standard, ANSI S3.28- 1986 also has adopted this measurement approach.

There have been several European field studies that also support the combining of impact noise with continuous noise. At the Southampton meeting on this subject (von Gierke et al. 1982), Passchier-Vermeer (1968) presented data that indicated the possibility that equal energy may slightly underestimate the combined effect, especially for 8-hour criteria levels above 90 dB(A). The majority of the researchers did not see the need for adjusting for the combined effect; however, the current ISO-1999-1990 states in note three: "The prediction method presented is based primarily on data collected with essentially broad-band steady non-tonal noise. The application of the data base to tonal or impulsive/impact noise represents the best available extrapolation. Some users may, however, want to consider tonal noise and/or impulsive/impact noise about as harmful as a steady non-tonal noise that is approximately 5 dB(A) higher in level."

Because the TLV is an 8-hour criterion level of 85 dB(A), such a correction was not used nor is such a correction recommended.

The selection of 140 dB(A) for unprotected ears remains a reasonable level. This level was reviewed by the working group that prepared ANSI S3-28. After this review, the working group recommended the continuation of this limit. The key research on which that limit was based was that of Ward (1961) and of Price (1981). A recent CHABA report (1992) also suggested this level as the break point above which the CHABA criteria of 1969 should be used.

The use of a C-weighted peak resolves a long standing problem with measurement of the peak. The term "unweighted peak" is undefined. Without specifying the low end cutoff frequency of the measurement devices, measurements with different devices could vary greatly. For example, an innocuous car door slam might cause a unweighted peak greater than 140 dB on some instruments but not on others. Use of C-weighting defines the frequency response of the instrument and eliminates very low frequency impulses and sounds. The C-weighting discounts such sounds. Thus, the harmless effect from a low-frequency impulse that comes from closing a car door or other such innocuous very low-frequency impulses can be more properly assessed. Infrasound exposures (exposures below 20 Hz) will also be better assessed.

The TLV limits do not address the case in which the impulse exposure exceeds a C-weighted peak of 140 dB. It is expected that the TLV for noise for 1995 will add the recommendation that, in such cases, the military standard (MIL-STD-1474C) should be used. The MIL-STD recommends that hearing protection be worn whenever exposures exceed a peak level of 140 dB(C). In addition, guidance is provided for those situations in which double hearing protection (both muffs and plugs) should be worn. However, this military standard is too conservative and various governments are researching the actual protection that is available from hearing protective devices. In general, hearing protection protects better for impulse noise than for continuous noise. The problem is to ensure that protection is worn.

Many of these exposure conditions are summarized in the U.S. National Institute of Occupational Safety and Health (NIOSH) Noise Criteria Document (NIOSH, 1998).

4.4. EXAMPLES OF OCCUPATIONAL EXPOSURE LIMITS TO NOISE

4.4.1. Control of noise exposure in workplaces. (Policy and guidance documents of the International Labour Organization (ILO))

Convention No. 148, concerning the Protection of Workers against Occupational Hazards in the Working Environment Due to Air Pollution, Noise and Vibration, adopted by the General Conference of the International Labour Organization in 1977, provides that, as far as possible, the working environment shall be kept free from any hazard due to air pollution, noise or vibration. To this end, national laws or regulations shall prescribe that measures be taken for the prevention and control of, and protection against, occupational hazards in the working environment due to air pollution, noise and vibration. Provisions concerning the practical implementation of the measures so prescribed may be adopted through technical standards, codes of practice, and other appropriate procedures. Technical measures shall be applied to new plants or processes in design or installation, or added to existing plants or processes. Where this is not possible, supplementary organisational measures shall be taken instead.

The provisions of the Convention also specify that the national competent authority shall establish criteria for determining the hazards of exposure to air pollution, noise and vibration in the working environment and, where appropriate, shall specify exposure limits on the basis of these criteria. The criteria and exposure limits shall be established, supplemented and revised regularly in the light of current national and international knowledge and data, taking into account as far as possible any increase in occupational hazards resulting from simultaneous exposure to several harmful factors at the workplace.

Employers are responsible for compliance with the prescribed measures. Workers shall be required to comply with safety procedures. Supervision shall be ensured by inspection services. The Convention enumerates various measures for prevention, co-operation at all levels, the information of all concerned, the notification of authorities, and the supervision of the health of workers.

Neither Convention No. 148 nor the accompanying Recommendation No. 156 concerning the Protection of Workers against Occupational Hazards in the Working Environment Due to Air Pollution, Noise and Vibration, also adopted in 1977, specify exposure limits for noise at the workplace.

As of June,1997, 39 countries have ratified the Convention No. 148 of which 36 have accepted its obligation in respect of noise. The ratification of a Convention by an ILO member State involves the obligation to apply, in law and in practice, its provisions.

The Code of practice on the protection of workers against noise and vibration in the working environment was adopted by a meeting of experts in 1974 and published by the International Labour Office in 1977. Its third impression (with modifications) dates from l984. The Code provides guidance for governments, employers and workers. It sets out the principles that should be followed for the control of workplace noise and vibration (organising principles, measurement and assessment, identification of risk areas, protection equipment and reduction of exposure time, health supervision and monitoring). International standards and other international provisions existing before l984 are appended to the code. In the light of knowledge at the time of publication, a warning limit value of 85 dB(A) and a danger limit value of 90 dB(A) are recommended.

In response to technological developments, the codes of practice on the protection of workers against noise and vibrations in the working environment and on occupational exposure to airborne substances harmful to health (adopted in l980) were updated in the l996-97 biennium in the form of a single draft code covering all types of air pollutants and other ambient factors in the working environment, such as noise and vibration, temperature and humidity, illumination and radiation. The draft was submitted to a tripartite meeting of experts for final revision and approval in 1999 and is expected to be published in the 2000-01 biennium . It will provide guidance on the implementation of the ILO Convention, 1977 (No. 148) and the ILO Recommendation, 1977 (No. 156), both cited above.

4.4.2. Occupational Exposure Levels reported and recommended by I-INCE

In 1997 the final report on “Technical Assessment of Upper Limits on Noise in the Workplace“ had been approved and published by the International Institute of Noise Control Engineering (I-INCE). It comprises the results of a Working Party started in 1992 to “review current knowledge and practice“ in this field. The executive summary says:“The setting of specific limits on exposure to noise is a political decision, with results that vary between jurisdiction depending on economic and sociological factors. It is however also important that regulations be harmonized internationally. The report therefore makes specific recommendations...“ Its elements are shown in the following :

1. Limit of 85 dB(A) for 8 hour workshift for jurisdiction desirable as soon as possible.
2. Maximum sound pressure level as limit of 140 dB for C-weighted peak..
3. Exchange rate of 3 dB per doubling or halving of exposure time.
4. Efforts to reduce levels to the lowest economically and technologically reasonable values.
5. In the design stage consideration to sound and vibration isolation between noisier and quieter areas, significant amount of acoustical absorption in rooms occupied by people.
6. Purchase specifications for machinery should contain clauses specifying the maximum emission values.
7. A long-term noise control program at each workplace where daily exposure exceeds 85 dB(A).
8. Use of personal hearing protection should be encouraged when engineering noise control measures are insufficient to reduce daily exposure to 85 dB(A), should be mandatory when exposure level is over 90 dB(A).
9. Employers should conduct audiometric testing of workers exposed to more than 85 dB(A) at least every three years, test results should be preserved in the employee‘s file.

The I-INCE report includes also a table of examples of the legislation in various countries, see table 4.3.

Table 4.3 Some features of legislation in various countries (I-INCE, 1997)

Country (Jurisdiction)	8-hour average A-weighted sound pressure level (dB)	Exchange rate (dB)	8h-average A-wtd limit for engineering or administrative controls (dB)	8h-average A-wtd limit for monitor-ing hearing (dB)	Upper limit for peak sound pressure level (dB)
Argentina	90	3			110 A Slow
Australia (varies by state)	85	3	85	85	140 unwgted peak
Austria (a),(c)	85		90		
Brazil	85	5	90, no exposure > 115 if no protec-tion, no time limit	85	130 unwgted peak or 115 A Slow
Canada (Federal) (ON, PQ, NB) (Alta, NS, NF) (BC)	87 90 85 90	3 5 5 3	87 90 85 90	84 85 (b)	140 C peak
Chile	85	5			140 unwgted peak or 115 A Slow
China	70-90	3			115 A slow
Finland (c)	85	3	90		
France (c)	85	3	90	85	135 C peak
Germany (c),(d)	85	3	90	85	140 C peak
Hungary	85	3	90		140 C peak or 125 A Slow
India	90				140 A peak
Israel	85	5			140 C peak or 115 A Slow
Italy (c)	85	3	90	85	140 C peak
Japan	90		85 hearing protection mandatory at 90	85	
Netherlands (c)	85	3	90	80	140 C peak
New Zealand	85	3	85	85	140 unwgted peak
Norway	85	3		80	110 A slow
Poland	85	3			135 C peak or 115 A Slow
Spain (c)	85	3	90	80	140 C peak

Sweden (c)	85	3	90	80	140 C peak or 115 A Fast
Switzerland	85 or 87	3	85	85	140 C peak or 125 ASEL
United Kingdom	85	3	90	85	140 C peak
USA (e) USA (Army and Air Force)	90 (TWA) 85	5 3	90	85 85	140 C peak or 115 A Slow 140 C peak
Uruguay	90	3			110 A Slow
This Report recommends	85 for 8-hour normalized exposure level limit	3	85. See also text under recommen-dend engineering controls	on hiring, and at intervals thereafter, see text under audiometric programs	140 C peak

See the notes to the table

* Information for Austria, Japan, Poland, and Switzerland was provided directly by these Member Societies of I-INCE. For other countries not represented by Member Societies participating in the Working Party the information is taken with permission from Ref. 15

(a) Austria also proposes 85 dB (AU-weighted according to IEC 1012) as a limit for high frequency noise, and a separate limit for low frequency noise varying inversely as the logarithm of frequency.

(b) A more complex situation is simplified to fit this tabulation.

(c) All countries of the European Union require the declaration of emission sound power levels of machinery, the use of the quietest machinery where reasonably possible, and reduced reflection of noise in the building, regardless of sound pressure or exposure levels. In column 4, the limit for other engineering or administrative controls is 90 dB or 140 dB C-weighted peak. In column 6, the upper limit for sound pressure level is 140dB C-weighted peak (or lower) or 130 dB A-weighted impulse.

(d) The rating level consists of time-average, A-weighted sound pressure level plus adjustments for tonal character and impulsiveness.

(e) TWA is Time Weighted Average. The regulations in the USA are unusally complicated. Only A-weighted sound pressure levels of 80 dB or greater are included in the computation of TWA to determine whether or not audiometric testing and noise exposure monitoring are required. A-weighted sound pressure levels less than 90 dB are not included in the computation of TWA when determining the need for engineering controls.

4.4.3. Occupational Exposure Levels recommended by NIOSH

In 1972, NIOSH published Criteria for a Recommended Standard: Occupational Exposure to Noise, which provided the basis for a recommended standard to reduce the risk of developing permanent hearing loss as a result of occupational noise exposure (NIOSH 1972).

The NIOSH document contained a comprehensive review of published data from other studies. The NIOSH percent risk values for long-term exposures to various noise levels were compared with those derived from three other studies:

1) the Intersociety Study, (Ad hoc Intersociety Guidelines 1967).
2) the earlier ISO Standard 1999-1990 and
3) the Burns and Robinson Study (1978).

NIOSH has now evaluated the latest scientific information and is revising some of its previous recommendations (NIOSH 1998),as it is summarized in the foreword of the new document.

The NIOSH recommended exposure limit (REL) of 85 dBA for occupational noise exposure was reevaluated using contemporary risk assessment techniques andincorporating the 4000-Hz audiometric frequency in the definition of hearing impairment. The new risk assessment reaffirms support for the 85-dBA REL. The excess risk of developing occupational noise-induced hearing loss (NIHL) for a 40-year lifetime exposure at the 85 dBA REL is 8%, which is considerably lower than the 25% excess risk at the 90 dBA permissible exposure limit currently enforced by the Occupational Safety and Health Administration (OSHA) and the
Mine Safety and Health Administration (MSHA).

NIOSH previously recommended an exchange rate of 5dB for the calculation of time-weighted average exposures to noise, but it is now recommending a 3-dBexchange rate, which is more firmly supported by scientific evidence. The 5-dB exchange rate is still used by OSHA and MSHA, but the 3-dB exchange rate has been increasingly supported by national and international consensus.

NIOSH recommends an improved criterion for significant threshold shift, which is an increase of 15 dB in hearing threshold at 500, 1000, 2000, 3000,4000, or 6000 Hz that is repeated for the same ear and frequency in back-to-back audiometric tests. The new criterion has the advantages of a high identification rate and a low false-positive rate. In comparison, the criterion recommended in the 1972 criteria document has a high false-positive rate, and the OSHA criterion, called the Standard Threshold Shift, has a relatively low identification rate.

Differing from the 1972 criteria document, NIOSH no longer recommends age correction on individual audiograms. This practice is not scientifically valid, and would delay inter-vention to prevent further hearing losses in those workers whose hearing threshold levels have increased due to occupational noise exposure. OSHA currently allows age correction only as an option.

The Noise Reduction Rating (NRR) is a single-number, laboratory-derived rating required by the Environmental Protection Agency to be shown on the label of each hearing protector sold in the U.S. In calculating the noise exposure to the wearer of a hearing protector at work, OSHA has implemented the practice of derating the NRR by one-half for all types of hearing protectors. In 1972, NIOSH recommended the use of the full NRR value, but now it recommends derating the NRR by 25%, 50% and 70% for earmuffs, formable earplugs and all other earplugs, respectively. This variable derating scheme, as opposed to OSHA's straight derating scheme, takes into consideration the performances of different types of hearing protectors.

This document also provides recommendations for the management of hearing loss prevention programs for workers whose noise exposures equal or exceed 85 dBA . The recommendations include programme evaluation, which was not articulated in the 1972 criteria document and is not included in the OSHA and MSHA standards.

Adherence to the revised recommended standard will minimize the risk of developing occupational NIHL.

4.4.4. Occupational Exposure Levels in the European Union

The European Union has already established a common policy aimed at controlling the risks due to the exposure of workers to noise and harmonising the relevant legal requirements existing at national level. Its principal instrument is the Council Directive 86/188/EEC on the protection of workers from the risks related to exposure to noise at work (Official Journal No L 137 / 24 - 5 - 1986 p.28).

Council Directives are legal instruments binding on the Member States as to the result to be achieved, but leave to the national authorities the choice of forms and methods. They are decided on by the Council of Ministers following a proposal made by the Economic and Social Committee. During this procedure extensive consultation of workers and employers organisations take place. Council Directives concerning safety and health at work set out minimum requirements and Member States have power to introduce more stringent measures of protection.

The EU health and safety legislation concerning noise addressed the risk of hearing impairment caused by occupational noise, because there was sufficient scientific documentation of the exposure - effect relationship. As regards the non - auditory effects of noise (which range from physiological disorders to interference with the proper execution of tasks requiring attention and concentration) scientific knowledge was not sufficiently advanced to justify a quantitative limitation of exposure. In this context decisions were taken on some fundamental issues:

1. The mandatory values will apply only to the noise reaching the ear, so if noise emission cannot be prevented or reduced at source, other measures should be taken to regulate noise energy emission; furthermore the situation in the member States did not make it possible to fix a noise - exposure value below which there is no longer any risk to workers hearing.
2. If a worker is exposed to noise bursts, the peak sound pressure must be limited and the acoustic energy must be included in the allowable daily exposure; in order that this requirement is fulfilled, an instrument capable of measuring directly the maximum (peak) value of the unweighted instantaneous sound pressure is needed (an instrument having an onset time constant not exceeding 100µs is suitable for industrial situations). See Section 4.3 for more detailed guidance and a discussion on the unsuitability of “unweighted” measurements.
3. A 3 dB rate was chosen as the most appropriate rule for managing intensity and exposure duration, because it is consistent with international standardisation and is simple to use in industrial situations, when a given level of workers’ protection has to be guaranteed.

For the purposes of the Directive on “noise”, the following terms have the meaning hereby assigned to them:

1. Daily personal noise exposure of a worker $L_{EP,d}$

The daily personal noise exposure of a worker is expressed in dB(A) using the formula:

$$L_{EP,d} = L_{Aeq,T} + 10\log_{10}\frac{T}{T_0}$$

where:

$$L_{Aeq,T} = 10\log_{10}\left\{\frac{1}{T}\int_0^T\left[\frac{p_A(t)}{p_0}\right]^2 \mathrm{d}t\right\}$$

T = daily duration of a worker's exposure to noise (hours),
T_0 = 8 hours
p_0 = 20 µPa,
p_A = A-weighted instantaneous sound pressure in pascals to which is exposed, in air at atmosphere pressure, a person who might or might not move from one place to another while at work; it is determined from measurements made at the position occupied by the person's ears during work, preferably in the person's absence, using a technique which minimises the effect on the sound field.

If the microphone has to be located very close to the person's body, appropriate adjustments should be made to determine an equivalent undisturbed field pressure. The daily personal noise exposure does not take account of the effect of any personal ear protector used.

(The term "*Daily personal noise exposure of a worker $L_{EP,d}$* " is the same as the term " *noise exposure level normalised to a normal 8hr working day, $L_{EX,8h}$* ", adopted later on by the ISO 1999 standard and used in Chapter 7 - ed).

2. Weekly average of the daily values $L_{EP,w}$

The weekly average of the daily values is found using the following formula:

$$L_{EP,w} = 10\log_{10}\left\{\frac{1}{5}\sum_{k=1}^{m} 10^{0.1(L_{EP,d})_k}\right\}$$

where $(L_{EP,d})_k$ are the values of $L_{EP,d}$ for each of the m working days in the week being considered. *(The term $L_{EP,w}$ is the same as the quantity $L_{EX,w}$ used in Chapter 7 - ed)*

The Directive specifies the employers obligations in reducing the risks arising from exposure to occupational noise to the lowest level reasonably practicable, taking account of technical progress and the availability of measures to control the noise, in particular at source. In this context different values are used, which trigger the specific actions. These values are:

1. 200 Pa as peak (140 dB in relation to 20 µPa). If the maximum value of the 'A' - weighted sound pressure level, measured with a sound - level meter using the time characteristic I (according to IEC 60651) does not exceed 130 dB(AI), the maximum value of the

unweighted instantaneous sound pressure can be assumed not to exceed 200 uPa)
2. 85 $L_{EP,d}$,
3. 90 $L_{EP,d}$.

When the daily personal noise exposure of a worker is likely to exceed 85 dB(A) or the maximum value of the unweighted instantaneous sound pressure is likely to be greater than 200Pa, workers and / or their representatives must be informed and trained on the potential risks to their hearing, the specific locations of the risk, the preventative measures taken, the wearing of personal protective equipment's and the role of hearing checks, the results of noise assessments and measurements as well as their significance, - personal ear protectors must be made available to workers.

When the daily personal noise exposure of a worker is likely to exceed 85 dB(A), workers shall be able to have hearing examinations in order to diagnose any hearing impairment by noise.

When the daily personal noise exposure of a worker is likely to exceed 85 dB (A) or the maximum value of the unweighted instantaneous sound pressure is likely to be greater than 200Pa, the areas in question must be appropriately signed, be delimited and access to them must be restricted. The employer has to identify the reasons for the excess levels, to draw up and implement a programme of measures of technical nature (engineering control) with a view to reducing the noise exposure as far as reasonably practicable. Personal ear protectors must be worn, which have to be adapted to the individual worker and to his / her working condition, taking account of his / her safety and health.

Finally, *whenever work equipment, intended for use at work, emits a noise that is likely to cause*, for a worker who uses it properly for a conventional eight-hour period, a daily personal noise exposure greater than 85 dB(A) or the maximum value of an unweighted instantaneous sound pressure is equal to or greater than 200Pa, the employer must be informed of that risk in order to take necessary measures to meet his / her obligations.

4.4.4.1. Checking workers hearing under the EU directive on noise

Council Directive 86/188/EEC has particular provisions concerning the hearing check of workers as part of an overall preventative policy aiming at reducing the risks to hearing.

The purpose of the check is the early diagnosis of any hearing impairment by noise, so that further deterioration can be prevented by various means.

There is a specific Annex with instructions for checking workers' hearing, which includes an audiometric test which should comply with the specifications of standard ISO 6189, but also covers the frequency of 8000 Hz; the ambient sound level must be sufficiently low to enable a hearing threshold level equal to 0 dB in relation to ISO 389 to be measured.

4.4.5. ACGIH Occupational Exposure Limits to Noise

The American Conference of Government Industrial Hygienists (ACGIH) has recommended threshold limit values (TLV) for occupational noise. The Occupational Exposure Limits (OEL) presented herein are an adaptation of the ACGIH's TLV limits. It should be noted that membership on the committee includes members from both Europe and Asia.

4.4.5.1. Foreword

The OEL's refer to sound pressure levels and exposure durations that represent conditions under which it is believed that nearly all workers may be repeatedly exposed without adverse effect on their ability to hear and understand normal speech. Prior to 1979, the medical profession had defined hearing impairment as an average hearing threshold level in excess of 25 dB(A) (ISO-7029-DIS) at 500, 1000, and 2000 Hz. The limits that are given here have been established to prevent a hearing loss at 3000 and 4000 Hz. The values should be used as guidelines in the control of noise exposure and, due to individual susceptibility, should not be regarded as fine lines between safe and dangerous levels. The proposed limits should protect the median of the population against a noise-induced hearing loss exceeding 2 dB(A) after 40 years of occupational exposure for the average of 0.5, 1, 2, and 3Hz.

It should be recognized that the application of the OEL for noise will not protect all workers from the adverse effects of noise exposure. A hearing conservation program with all of its elements including audiometric testing is necessary when workers are exposed to noise at or above the OEL.

4.4.5.2. Continuous or Intermittent Noise

The sound pressure level should be determined by a sound level meter, integrating sound level meter or dosimeter conforming, as a minimum, to the requirements of the IEC 60804.-1985. The measurement device should be set to use the A-weighted network. The duration of exposure should not exceed that shown in Table 4.4.

These values apply to total duration of exposure per working day regardless of whether this is one continuous exposure or a number of short-term exposures.

When the daily noise exposure is composed of two or more periods of noise exposure of different levels, their combined effect should be considered rather than the individual effect of each. If the sum of the following fractions:

$$\frac{C_1}{T_1} + \frac{C_2}{T_2} + \ldots\ldots\ldots\ldots \frac{C_n}{T_n}$$

exceeds unity, then the combined exposure should be considered to exceed the TLV. C_i indicates the total duration of exposure at a specific noise level and T_i indicates the total duration of exposure permitted at that level. All on-the-job noise exposures of 80 dB(A) or greater should be used in the above calculations. With sound level meters, this formula should be used for sounds with steady levels of at least 3 seconds. For sounds in which this condition is not met, a dosimeter or an integrating sound level meter must be used. The limit is exceeded when the dose is more than 100% as indicated on a dosimeter set with a 3 dB(A) exchange rate and a criterion level of 85 dB(A).

The OEL is exceeded on an integrating sound level meter when the average sound level exceeds the values given in Table 4.4.

Table 4.4 Allowable exposure durations[A] (per IEC 60804).

Duration per Day	Sound Level, dB(A)[B]
Hours	
24	80
16	82
8	85
4	88
2	91
1	94
Minutes	
30	97
15	100
7.50*	103
3.75*	106
1.88*	109
0.94*	112
Seconds*	
28.12	115
14.06	118
7.03	121
3.52	124
1.76	127
0.88	130
0.44	133
0.22	136
0.11	139

A No exposure to continuous, intermittent, or impact noise in excess of a peak C-weighted level of 140 dB.

B Sound levels in decibels are measured on a sound level meter, conforming as a minimum to the requirements of the American National Standard Specification for Sound Level Meters, S1.4 (1983) Type S2A, and set to use the A-weighted network with a slow meter response.

* Limited by the noise source, not by administrative control. It is also recommended that a dosimeter or integrated sound level meter be used for sounds above 120 dB.

Editors' note **:** *Although formally correct the table looks as a 24 h exposure with 80 db(A) is permitted but the presumptions of the OEL should be observed, see section 4.5.*

4.4.5.3. Impulsive or Impact Noise

By using the instrumentation specified by the IEC 60804-1985, impulse or impact noise is automatically included in the noise measurement. The only requirement is a measurement range between 80 and 140 dB(A) and the pulse range response as defined in IEC 60804-1985 must be at least 63 dB. The frequency response must be equivalent to or better than a type 2 instrument. No exposures of an unprotected ear in excess of a C-weighted peak sound pressure level of 140 dB should be permitted. If instrumentation is not available to measure a C-weighted peak, an unweighted peak measurement below 140 dB may be used to imply that the C-weighted peak is below 140 dB.

Note: For impulses above a C-weighted peak of 140 dB, adequate hearing protection should be worn. The military of some governments have standards that provide guidance for those situations in which single protection (plugs or muffs) or double protection (both muffs and plugs) should be worn (e.g., U. S. Army's MIL-STD-1474C).

4.5. OTHER CRITERIA

The exposure criteria discussed above are based on a statistical average of population with normal health and should not be used to predict the generation of hearing loss of an individual person. In so far the exposure criteria constitute a minimum standard for prevention and conservation. Therefore one should have in mind that not only individuals but also groups of them with properties differing from average may follow more stringent criteria, e.g. young persons, pregnant women (e.g.ACGIH 1999a) ,or handicapped individuals especially with hearing disabilities. Another issue is the combined exposure, e.g. noise-vibration, noise-solvents or noise-metal dust, which is discussed in chapters 3 and 8 and in Carter and Job (1998), ACGIH (1999a) .

It should be considered also that these exposure criteria are based on the presumption of an 16 hour hearing recovery time under a noise level of less than 75 dB(A).Therefore in spaces for workers to relax or sleep and which are related to workplaces as on ships or on drilling platforms the background noise level should be below 70 dB(A) or below, see e.g. ACGIH (1999b).

Another issue is the effect of noise containing sound of frequencies outside the usual auditory capabilities from 20 Hz up till 20 kHz, i.e. infrasound beneath 20 Hz and ultrasound above 20 kHz with its extraaural effects and also effects on hearing in case of higher levels.

Noise of high levels can affect the general safety of workers when the recognition of danger signals is disturbed or destroyed.

Noise of every kind and also low level noise can disturb or damage badly the speech intelligibility which might be an important prerequisite for communication in dangerous situations.

Noise of levels beneath 80 dB(A) can be such an annoyance that the efficiency to achieve a certain goal or quality in the progress of work is diminishing.

4.5.1. Exposure to infrasound and ultrasound

Before the nineties it was said infrasound exposures are rare and, even if they could occur, are not likely to be dangerous, at levels found in industry directly, to a person's hearing or health (von

Gierke and Parker 1976, Johnson 1975, 1982). Complaints of persons working with ultrasound equipment were more frequent, but very often it shows that the reason for complaining was audible sound generated as subharmonics of the original sound source which caused e.g. workpieces to vibrate. So one started to ask if the frequency range of audible sound was real or only the result of inappropiate technical means to shape audiometric tests for frequencies called infra- and ultrasound. It seems now that there is a hearing threshold level outside both ends of the range 20 Hz to 20 kHz investigated by Ising (1980) and Herbertz (1984). Unfortunately the existence of these thresholds is not sufficient to define OELs, because in practice one cannot suppress either the extraaural effects of infrasound to cause body vibrations or the general impact of ultrasound on the complete hearing organ which generates a vague sensation. But the dicussion of the last years resulted in some standards to define boundaries between the different kinds of sound as ISO 7196 or IEC 1012 for measurement purposes, and in some recommendations containing OELs for ultrasound, e.g. IRPA (1984)**,** ACGIH (1999a) . Internationally agreed recommendations on infrasound are missing. There is the tendency to use the hearing thresholds in frequency bands as limits for the exposure in this frequency region considering aural as well as extraaural effects (Moeller 1985,Vercammen 1989, ACGIH 1999a).

4.5.2. Recognition of danger signals

If there is the risk of an unpredictable event like fire or the outflow of dangerous materials in a working area one of necessary precautions will be the installation of devices generating an appropiate auditory danger signal. Naturally this installation needs a check of recognition at the most critical working positions taking into account the worst case of ambient noise and the use of hearing protectors and personal electroacoustical systems. Because of certain properties of the hearing it is required to determine the ambient noise, the insertion loss of protectors and headsets and the danger signal itself in octave band levels. Then the standards ISO 7731 and 8201 give sufficient advice. The situation can also be roughly assessed with help of the A-weighted signal-to-noise ratio, that should be 10 till 15 dB at the listener‘s position according to the standards as discussed by Lazarus (1993). If octave band levels are known the signal-to-noise ratio should be more than 10 dB in more than one octave band.

4.5.3. Speech intelligibility

In many situations at normal production lines as well as on construction sites and during maintenance of large installations but even in control rooms a sufficient communication by talking or shouting is a prerequisite for safety at the workplace and good working results. It can be a more important prerequisite for difficult tasks like medical treatment. The International Standard ISO 9921 is dealing with “ergonomic assessment of speech communication“ and gives in part 1 “speech interference level and communication distances for persons with normal hearing capacity in direct communication...“ with respect to these parameters: ambient noise at the speaker‘s and the listener‘s position and the vocal effort.

There are several assumptions concerning physical and personal conditions. Most important seems to be a reverberation time less than 2 s at 500 Hz , normal hearing capacity of the persons communicating and hearing protectors worn by the speaker . ISO 9921-1 gives then first a relation between the seven steps of vocal effort from relaxed to shouting and the ambient noise level at the speaker‘s position and secondly for the same seven steps defined by the speech interference level for satisfactory speech communication the relation to the maximum distance between the speaker and listener. The communication can be assessed with the A-weighted signal-to-noise ratio at the listener‘s position also in seven steps from excellent to insuffcient. The standard says:“In order to decide what quality level of speech communication is useful for a given communication situation, the frequency, the necessity of speech communication and size of vocabulary (group of specific words, e.g. commands or warning shouts) shall be taken into consideration. For examples in homes and conference rooms, the quality “very good “ or “excellent“ should be achieved, for department stores and training workshops the quality “good“ should be adopted and for workshop the quality “satisfactory“ or at least “sufficient“ is recommended “. “Good“ refers to a signal-to-noise ratio of 6 till 12 dB and the vocal effort assumed as lower than “raised“, i.e. the average speaker‘s level in 1m distance is lower than 66 dB(A), (ISO 9921-1, Lazarus 1993).

4.5.4. Annoyance and efficiency

Whereas hearing damage is the main concern of safety regulations the other physical and psychological effects should not be neglected. There are provable psychological reactions, e.g. anger, strain or nervousness, and physical reactions, e.g. increase of blood pressure or increased excretion of magnesium, which may give rise to long-term disorders of regulation mechanisms also at A-weighted sound pressure levels below 85 dB. The efficiency can be affected too, the more likely, the more complex the task to be performed. The complexity is given by task characteristics, to be described objectively, and by the individual judgement of a person‘s ability to perform the task. So the same task can be more complex for untrained personnel. Generally a job is more complex e.g. the more information must be kept in mind, the more intellectual operations have to be performed, the higher the requirements for precise fine motor activity or the more responsible the worker is for consequences of mistakes.The more complex a task, the more sensitive a person will react to disturbances like noise, in the end with an increase of the number of mistakes and a slowdown of completion of the task , i.e. a decrease of the efficiency. ISO 11690-1 gives maximum values for the A-weighted equivalent sound pressure level for the 8 hour workshift at industrial workplaces in the range 75 to 85 dB, for routine office work in the range 45 to 55 dB and for meeting rooms or tasks involving concentration in the range 35 to 45 dB.

A further detailed description of the mechanisms that lead to a decrease of efficiency and an allocation of tasks of different complexity to proposed rating levels down to 40 dB(A) is given in the bilingual German standard VDI 2058 part 3 (1999).

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INTERNATIONAL STANDARDS

Titles of the following standards referred to in this chapter one will find together with information on availability in chapter 12:

ISO 1999, ISO 7196, ISO 7731, ISO 8201, ISO 9921-1, ISO 11690-1, IEC 60651, IEC 60804, IEC 61012.

5

NOISE SOURCES

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5.1. INTRODUCTION

Industrial machinery and processes are composed of various noise sources such as rotors, stators, gears, fans, vibrating panels, turbulent fluid flow, impact processes, electrical machines, internal combustion engines etc. The mechanisms of noise generation depend on the particularly noisy operations and equipment including crushing, riveting, blasting (quarries and mines), shake-out (foundries), punch presses, drop forges, drilling, lathes, pneumatic equipment (e.g. jack hammers, chipping hammers, etc.), tumbling barrels, plasma jets, cutting torches, sandblasting, electric furnaces, boiler making, machine tools for forming, dividing and metal cutting, such as punching, pressing and shearing, lathes, milling machines and grinders, as well as textile machines, beverage filling machines and print machines, pumps and compressors, drive units, hand-guided machines, self-propelled working machines, in-plant conveying systems and transport vehicles. On top of this there are the information technology devices which are being encountered more and more in all areas.

Noise is therefore a common occupational hazard in a large number of workplaces such as the iron and steel industry, foundries, saw mills, textile mills, airports and aircraft maintenance shops, crushing mills, among many others. In many countries, noise-induced hearing loss is one of the most prevalent occupational diseases. According to a Environmental Protection Agency (EPA)/USA report in 1981, there are more than nine million Americans exposed to a daily average occupational noise level above 85 dB(A); this number has increased to about 30 million in 1990. Most of these workers are in the production and manufacturing industries (see Table 5.1).

Studies in Germany and other industrialized countries have shown that the proportion of those exposed to daily average noise levels above 85 dB(A) can generally be taken as 12 % to 15% of all employed persons; that is 4 to 5 million persons in Germany (Pfeiffer 1992). After many years of exposure to noise, there are numerous cases of occupationally related hearing damage recognized

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Table 5.1. Workers exposed to daily L_{Aeq} exceeding 85 dB(A). (EPA, 1981)

Agriculture	323000
Mining	400000
Construction	513000
Manufacturing and Utilities	5124000
Transportation	1934000
Military	976000
Total	**9270000**

as the occupational disease "noise-related hearing impairment" according to the Occupational Diseases Ordinance. An acquired noise-related hearing impairment which leads to a reduction in earning ability of 20 % and more is compensated for in Germany in the form of a pension. Table 5.2 shows the high percentages of those with impaired hearing due to noise in relation to other selected occupational diseases.

Table 5.2. Number and percentages for some selected occupational diseases/disorders in 1998 (total in Germany, from BMA, 1999).

	cases registered for first time		cases recognized for first time without indemnity		cases registered & indemnified for first time (reduction of earning ability ≥ 20%)	
Occupational diseases/disorders	number	%	number	%	number	%
meniscus	2398	2.8	418	2.0	275	4.5
damage from vibrations	1797	2.1	234	1.1	154	2.5
impaired hearing	12400	14.5	7439	36.5	1012	16.4
silicosis	2813	3.3	2100	10.3	391	6.4
skin disorders	23349	27.3	1855	9.1	582	9.5

A cross-section analysis in Germany of working equipment and processes in operational noise areas with a hearing impairment hazard has shown that 80 % of the - several million - sound sources can be attributed to machine operations, conveying systems, control and regulation devices and turbo machines, while 20 % are accounted for by manual working and conveying operations. About three quarters of the machine operations can be attributed to machine tools (Damberg, Foss 1982). The main concern of noise control is therefore the development, production and preferred use of low-noise working equipment and processes.

The avoidance or minimization of health hazards in the working process by the appropriate design of working equipment and processes, in other words by prevention, has also been elevated to a principle on an European level. With the establishment of regulations concerning the nature of machines, devices and installations in EU Directives and more specific European standards, it can be assumed that there is a high level of safety, health and consumer protection. This noise control principle is manifested in the definition and declaration of noise characteristics for products or machines and the description of achievable values by the standards.

5.2. INDUSTRIAL NOISE SOURCES

In this section, the fundamental mechanisms of noise sources are discussed, as well as some examples of the most common machines used in the work environment. The sound pressure level generated depends on the type of the noise source, distance from the source to the receiver and the nature of the working environment. For a given machine, the sound pressure levels depend on the part of the total mechanical or electrical energy that is transformed into acoustical energy.

Sound fields in the workplace are usually complex, due to the participation of many sources: propagation through air (air-borne noise), propagation through solids (structure-borne noise), diffraction at the machinery boundaries, reflection from the floor, wall, ceiling and machinery surface, absorption on the surfaces, etc. Therefore any noise control measure should be carried out after a source ranking study, using identification and quantification techniques. The basic mechanism of noise generation can be due to mechanical noise, fluid noise and/or electromagnetic noise (Allen, 1970 and ISO/TR 11688).

The driving force for economic development is mainly the endeavour to produce consumer goods ever more cost-effectively. From the point of view of the machine manufacturer, this generally means offering products with a low space, material, energy and production time requirement (smaller, lighter, more economical and more productive). At the same time account is being taken increasingly of resource conservation and environmental friendliness, although the rise in noise levels which frequently goes along with increased output and productivity is often overlooked. Personnel are then exposed to higher noise levels than before, despite noise-reducing measures taken in the machine's design. This is because the noise emission rises non-linearly because of higher rotary and travelling speeds in machine parts.

For example, for every doubling of the rotary speed the noise emission for rotating print machines rises by about 7 dB, for warp knitting looms 12 dB, for diesel engines 9 dB, for petrol engines 15 dB and for fans is between 18 to 24 dB. For the purpose of comparison: the doubling of sound power produces an increase in emission of 3 dB only.

But even previously quiet procedures are often replaced by loud ones for reasons of cost, e.g. stress-free vibration instead of annealing for welded parts. In some cases new technologies also result in higher emissions; for example, with the use of phase-sequence-controlled electrical drives, the excitation spectrum shifts further to high frequencies, which results in a greater sound radiation from large machine surfaces. This means that some new noise problems are closely related to the use of modern technologies.

5.2.1. Mechanical Noise

A solid vibrating surface, driven or in contact with a prime mover or linkage, radiates sound power (*W* in Watts) proportional to the vibrating area S and the mean square vibrating velocity $< v^2 >$, given by;

$$W = \rho c S \langle v^2 \rangle \sigma_{rad}$$

where

ρ is the air density (kg/m^3),
c is the speed of sound (m/s) and
σ_{rad} is the radiation efficiency (see Gerges 1992).

Therefore care must be taken to reduce the vibrating area and/or reduce the vibration velocity. Reducing the vibrating area can be carried out by separating a large area into small areas, using a flexible joint. Reduction of the vibration velocity can be carried out by using damping materials at resonance frequencies and/or blocking the induced forced vibration. A reduction of the excitation forces and consequently of the vibration velocity response by a factor of two can provide a possible sound power reduction of up to 6 dB assuming that the other parameters are kept constant. Typical examples of solid vibration sources are: eccentric loaded rotating machines, panel and machine cover vibration which can radiate sound like a loudspeaker, and impact induced resonant free vibration of a surface.

5.2.2. Fluid Noise

Air turbulence and vortices generate noise, especially at high air flow velocities. Turbulence can be generated by a moving or rotating solid object, such as the blade tip of a ventilator fan, by changing high pressure discharge fluid to low (or atmospheric) pressure, such as a cleaning air jet or by introducing an obstacle into a high speed fluid flow.

The aerodynamic sound power generated by turbulent flow is proportional to the 6th to 8th power of the flow velocity ($W \sim U^{6 \text{ to } 8}$), which means that a doubling of the flow velocity (U) increases the sound power (W) by a factor of 64 to 254 or 18 to 24 dB respectively. Table 5.3 shows the effects of doubling of the typical velocity together with other primary mechanisms. Therefore care must be taken to reduce flow velocity, reduce turbulence flow by using diffusers and either remove obstacles or streamline them. The next few examples show the applications of these fundamental concepts to machinery noise reductions.

5.3. EXAMPLES OF MACHINERY NOISE SOURCES

In this section, noise sources are presented for the most common machines used in industrial installations. For each case, the mechanism of noise generation is discussed.

5.3.1. Industrial Gas Jets

Industrial jet noise probably ranks third as a major cause of hearing damage after that of impact and material handling noise. Air jets are used extensively for cleaning, for drying and ejecting parts, for power tools, for blowing off compressed air, for steam valves, pneumatic discharge vents, gas and oil burners, etc. Typical sound pressure levels at 1 m from a blow-off nozzle can reach 105 dB(A).

Table 5.3. Increase of noise given by the sound power level difference ΔL_w due to doubling of typical velocity (e.g. average flow velocity of gas jets, rotational speed of fans). [After Költzsch, 1984]

mechanism	example	Increase in sound power due to doubling typical velocity
pulsation	reciprocating compressor,	12 dB
turbulence	exhaust fan	18 dB
jet	compressed air expansion	24 dB

Reservoir compressed air pressure is usually in the range of 45 to 105 psi (300 to 700kPa). The air acceleration varies from near zero velocity in the reservoir to peak velocity at the exit of the nozzle. The flow velocity through the nozzle can become sonic, i.e. reaches the speed of sound. This results in a high generation of broad-band noise with the highest values at a frequency band between 2 to 4 kHz.

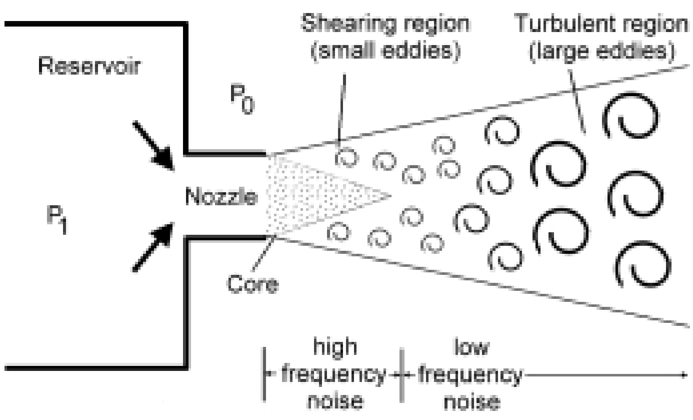

Figure 5.1. Noise sources in gas jet

The mechanisms of generation of the noise from gas jets results from the creation of fluctuating pressures due to turbulence and shearing stresses as the high velocity gas interacts with the surrounding medium (see Figure 5.1). High and low frequency bands of noise are formed, due to the complex radiation sources; high frequency noise is generated near the exit nozzle in the mixing region and the low frequency noise is generated downstream at the large scale turbulence. Therefore, the spectral character of gas-jet noise is generally broadband.

5.3.2. Ventilator and Exhaust Fans

It is rare not to find one or more ventilators or exhaust fans in each department of an industrial or manufacturing complex (see Figures 5.2 to 5.3). Fan and blower noise is the easiest and most straightforward noise problem to solve, using an absorptive type silencer.

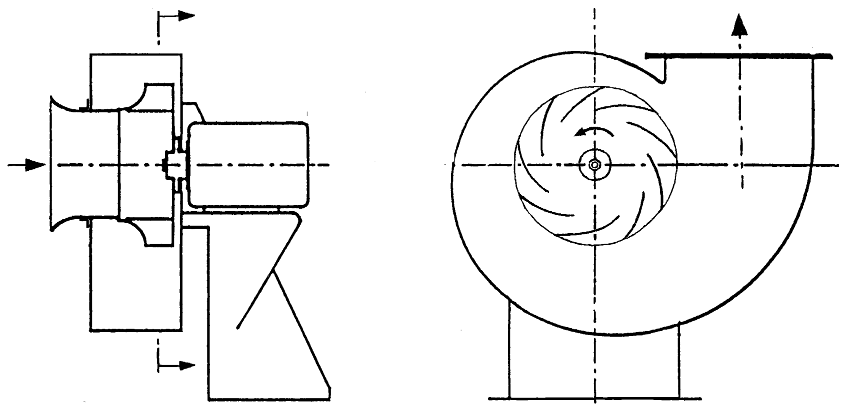

Figure 5.2 Example of a centrifugal fan, rotor with backward-curved blades

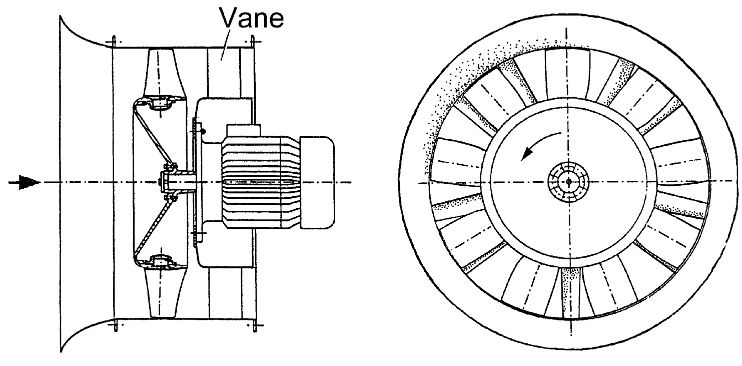

Figure 5.3. Example of a vaneaxial fan

Fans are used to move a large volume of air for ventilation, by bringing in fresh air from the outside, blowing out dust, vapour or oil mist from an industrial environment, and for a drying or cooling operation, etc. Industrial fans are usually low-speed, low-static-pressure and have a large

volume flow rate. Ideally, fans should operate at the maximum efficiency point on the pressure-flow curve characteristic. Therefore, the choice between axial or centrifugal fans is made by the manufacturer to satisfy maximum efficiency at a certain static pressure/flow rate.
Three basic noise sources are:

1. Broadband aerodynamic noise generated by the turbulent flow.
2. Discrete tones at the blade passing frequency F_p (Hz) given by:
   F_p = (Rotation in RPM x Number of blades/ 60), and the harmonics ($2F_p$, $3F_p$, etc.).
3. Mechanical noise due to mounting, bearing, balancing, etc.

The sound power level (L_w) generated by fans (without the drive motor) can be ~~easily~~ predicted in the early project stages of an industrial installation using the Graham equation [Graham, 1972] for each of the octave bands from 63 to 8000 Hz.

$$L_w = K + 10\log_{10}\bar{Q} + 20\log_{10}P_a + C \quad \text{dB}$$

Where Q is the flow rate (m^3/sec), P_a is the static pressure (kPa), K is the specific sound power level for each of the octave bands based on a volume flow rate of 1 m^3/s and a total pressure of 1 kPa and C is a constant to be added only at the octave band containing the blade passing frequency, see examples for a radial fan similar to figure 5.2 and for a vaneaxial fan similar to figure 5.3 in table 5.4.

Based on the sound power predicted by the above equation, the sound pressure levels can estimated at specified locations in certain installations. The finite element, boundary element or ray acoustics methods are available in commercial software programs for these estimates (NIT, 1995) or a simplified diffuse field model can be used for sound pressure level estimate (Bies and Hansen 1996).

Table 5.4. Specific octave band sound power levels K in dB(re 1 pW) of three types of fans with wheel size under 0.75 m based on a volume flow rate of 1m³/s and a total pressure of 1 kPa (excerpt modified from Graham's table 41.1 in Harris 1991)

Fan type	Octave band center frequency [Hz]								C
	63	125	250	500	1000	2000	4000	8000	
Radial, backward-curved (figure 5.2)	90	90	88	84	79	73	69	64	3
Radial, straight blades (no figure)	113	108	96	93	91	86	82	79	8
Vaneaxial, hub ratio 0.6-0.8 (figure 5.3)	98	97	96	96	94	92	88	85	6

NOTE: The table gives average values which widely scatter due to the properties of the complete system with ducts. The column "C" contains minimum values which even in the case of the least noisy fan with backward-curved blades may be sometimes double as high.

5.3.3. Compressors

Compressors are usually very noisy machines with high pressure. There are several types of compressor: rotary positive displacement (lobed impellers on dual shafts, as shown in Figure 5.4), gear or screw compressors (Figure 5.5), reciprocating compressors (Figure 5.6) and liquid ring compressors (Figure 5.7) are the most common.

The basic noise sources are caused by trapping a definite volume of fluid and carrying it around the case to the outlet with higher pressure. The pressure pulses from compressors are quite severe, and equivalent sound pressure levels can exceed 105dB(A). The noise generated from compressors is periodic with discrete tones and harmonics present in the noise spectrum.

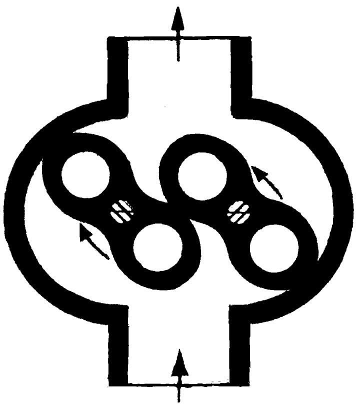

Figure 5.4. RotaryPositive Displacement Compressor

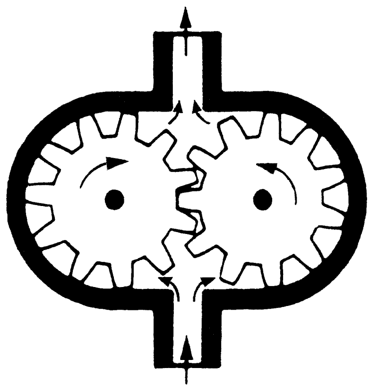

Figure 5.5. Gear Compressor.

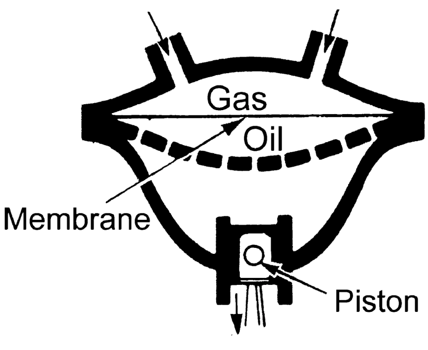

Figure 5.6. Reciprocating Compressor

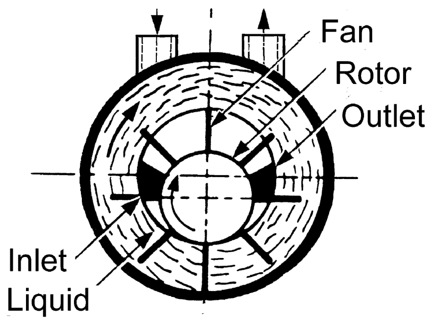

Figure 5.7. Liquid Ring Compressor

5.3.4. Electric Motors

Noise from electrical equipment such as motors and generators is generally a discrete low frequency, superimposed on a broadband cooling system noise. The electric motor converts electrical energy to magnetic and then mechanical energy with the output of a useful torque at the motor shaft. Part of the energy transformation is converted to heat, causing a rise in rotor, stator and casing temperature; therefore an electric motor must be supplied with a cooling fan system. The cooling fan can be incorporated inside as in the case of an "OPEN" motor or outside as in the case of a "Totally Enclosed Fan Cooled (TEFC)" motor. TEFC motors are more widely used, due to their robust construction which can withstand a dirty environment. OPEN motors are less used due to possible contamination by the environment. An OPEN motor is sometimes (but not always) less noisy than a TEFC motor since the noisy fans are incorporated inside.

There are three basic sources involved in the noise generated by electric motors:

1. Broad-band aerodynamic noise generated from the end flow at the inlet/outlet of the cooling fan. The cooling fan is usually the dominant noise source.

2. Discrete frequency components caused by the blade passing frequencies of the fan.

3. Mechanical noise caused by bearing, casing vibration, motor balancing shaft misalignment, and/or motor mounting. Thus careful attention should be given to the vibration isolation, mounting and maintenance.

Noise generated by the motor fan is the dominant motor noise source, especially for TEFC motors. A sharp increase in noise occurs as the shaft rotational speed increases from 1800 to 3600 RPM. For large motors in the range of 1000 kW, 3600 RPM, a sound pressure level of as high as 106 dB(A) occurs. Measurements carried out in the laboratory for a range of TEFC motors from 25 to 2500 HP, no load, with and without the straight blade motor fan, show a difference of up to 50 dB(A) in the total sound pressure level. This large distribution of the fan noise is due to the fan shape. Motor fan blades are usually straight, so that the motor cooling is independent of rotation direction. Straight blade fans are very noisy, due to the large aerodynamic turbulent sound generated. Noise reduction in electric motors can be achieved by the use of an absorptive silencer (Gerges, 1992) or by redesign of the cooling fan, e.g. with irregular spacing of straight blades as in chapter10 (see Figure 10.17.).

5.3.5. Woodworking Machines

The woodworking industry has experienced noise level increases as a result of modern, higher speed, and more compact machines. The basic noise elements in woodworking machines are cutter heads and circular saws. Equivalent sound pressure levels (L_{Aeq}) in the furniture manufacturing industry can reach 106 dB(A).

Woodworking machinery uses operations, such as cutting, milling, shaping, etc. Three basic noise sources are involved:

1. Structure vibration and noise radiation of the work piece or cutting tool (such as a circular saw blade) and machine frame, especially at the mechanical resonance frequencies.
2. Aerodynamic noise caused by turbulence, generated by tool rotation and the workplace in the air flow field.
3. Fan dust and chip removal air carrying systems.

5.3.6. Pneumatic Tools

Compressed air-powered, hand-held tools such as drills, grinders, rivetting guns, chipping hammers, impact guns, pavement breakers, etc. are widely used within a broad spectrum of different industries. There are three basic types of sources that dominate the noise generated:

1. Noise produced by contact between the machine and the working surface. The vibration transmitted from the tool tends to vibrate the working surface and work bench, generating high radiation noise, especially at mid and high frequencies.
2. Exhaust air noise caused by the turbulent flow generated as the compressed air passes the motor and by the aerodynamic noise generated in the air exhaust.
3. Sound radiation from tool vibration caused by air flow inside the tool.

The noise level of hand held tools can reach as high as 110 dB(A) at the operator's ear. Figure 5.8 shows a typical hand grinder.

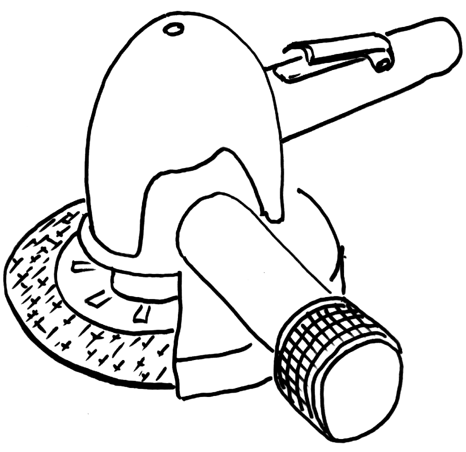

Figure 5.8. Typical Grinding Air Powered Hand Tool

5.4. TYPICAL NOISE LEVELS

As an example, data collected in Singapore in 1993 shows that only 366 factories out of 9051 factories have a hearing conservation program implemented. Table 5.5 shows a list of factories and number of workers with and without hearing conservation program implemented. Table 5.6 shows a list of 20 factories with a range of sound pressure levels and an average level for each. Data collected in Denmark on 55 pneumatic and electric hammers in different industries show an SPL of between 88 to 103 dB(A) (see Table 5.7).

Planing wood machine operators are exposed to an SPL maximum of 101 dB(A) and an SPL minimum of 96 dB(A) with an L_{Aeq} = 98 dB(A) for 8 hours, which is far above the acceptable risk values (AIHA-USA).

Data collected in a cigarette factory in Brazil show an SPL level of a compressed air cleaning process of up to 103 dB(A), with an L_{Aeq} = 92 dB(A) for 8 hours (Fredel 1990).

Economic calculations have shown that administrative and technical preventive measures are profitable. Technical progress during recent years has led to a decrease of the very high noise exposures, but not much change in moderate and low noise exposures. Measurements taken at some typical occupations show that the L_{Aeq} levels in the occupations shown by experience to have the worst noise have been 88-97 dB with highest peak levels of 101-136 dB (Table 5.8). In the referenced study, there were no findings of peak levels exceeding 140 dB (Pekkarinen, Starck, 1997). In most of the undeveloped countries, noise levels can exceed Table 5.6 values.

Table 5.5. Number of factories with Hearing Conservation Programs implemented in Singapore (Tan Kia Tang (1995)).

Singapore Standard Industry	Industry	All factories		Factories with Hearing Conservation Program(HCP)	
Code (SSIC)		Number of factories	Number of workers	Number of factories	Number of workers
38	Fabricated Metal Products	3698	219,521	199	24,093
3851	Shipbuilding and Repairing	116	21654	28	6,065
71 - 72	Transport, Storage and Supporting Services	60	4,320	10	4380
40	Electricity, Gas and Water	35	2,307	9	1,578
33	Wood and Wood Products	873	10,399	19	449
39	Other Manufacturing Industries	349	7,523	3	165
31	Food, Beverages and Tabacco	794	13,910	23	1,745
35	Chemicals and Chemical Products	903	28,439	29	2,014
34	Paper and Paper Products	927	16,839	17	1,676
32	Textile, Weaving, Apparel and Leather	867	26,635	6	380
36	Non - Metallic Products	186	4,425	4	118
37	Basic-Metal Industries	63	3,016	5	225
50	Construction	62	750	3	20
93	Social, Community, etc.	101	883	10	370
83	Engineering, Architectural Technical Services	17	246	1	24
Total		9051	339,213	366	34237

Table 5.6. Sound Pressure Levels in Manufacturing Industries in Singapore in 1993 (Tan Kia Tang (1995)).

	Industry	Number of Samples	Range L_{pA} (dB(A))	Average L_{pA} (dB(A))
1	Food manufacture	79	85-111	92
2	Manufacture of textile	28	85-108	93
3	Sawmill and other woodmills	32	85-104	93
4	Manufacture of furniture	54	85-115	93
5	Manufacture of paper and paper products	29	85-102	92
6	Printing and publishing	33	85-96	89
7	Manufacture of chemicals and chemical products	26	85-104	92
8	Manufacture of non-metal products	22	85-110	94
9	Basic metal industry	24	85-100	92
10	Manufacture of structural metal products	82	85-108	93
11	Manufacture of metal cans and containers	83	85-118	94
12	Metal forging and stamping	45	85-105	93
13	Manufacture of fabricated metal products	139	85-115	92
14	Manufacture of machinery	96	85-120	93
15	Manufacture of electrical machinery, apparatus and appliances	38	85-108	91
16	Manufacture of electronic products and components	83	85-103	90
17	Building and repairing of ships	42	85-110	95
18	Manufacture and repair of motor vehicles	24	85-105	92
19	Manufacture of aircraft	43	85-105	92
20	Other manufactures industries	33	85-105	91
	Total Average			92

Table 5.7. Noise from Pneumatic and Electric Hammers (Vedsmand, 1995)).

Product	Model/Type	Motive Power	Noise level A-weighted dB re 20µPa	Vibration Level (HA) dB re 10^{-6} m/s^2
AEG	PHM	EL/220V	101	142
Atlas Copco	TEX 11 S	Compressed air	95	142
Atlas Copco	TEX 22 S	Compressed air	100	147
Atlas Copco	TEX 23 E	Compressed air	99	136
Atlas Copco	TEX 25 E	Compressed air	97	141
Atlas Copco	TEX 32 S	Compressed air	98	150
Atlas Copco	TEX 33 E	Compressed air	94	140
Atlas Copco	TEX 42 S	Compressed air	94	146
Atlas Copco	TEX 43 E	Compressed air	96	142
Berema	REBEL 20	Electricity	92	140
Bosch	UHS 10	Electricity	88	142
Bosch	UHS 27	-	95	138
Bosch	UHS 12/50	-	88	146
Compair Holman	Zitec 9	Compressed air	98	148
Compair Holman	Zitec 12	Compressed air	97	148
Compair Holman	Zitec 14	Compressed air	97	146
Compair Holman	Zitec 20	Compressed air	98	148
Compair Holman	Zitec 27	Compressed air	95	149

The Canadian Center for Occupational Health and Safety (CCOHS) has developed a Noise Levels data base to bring together noise exposure data on a wide range of workplaces, operations, machinery and occupations. The contents of the data base have been compiled from data reported in journals, health and safety reports, and surveys by various industries and agencies.

Table 5.8. Average L_{Aeq} values and L_{Cpeak} values at different industrial workplaces (*n* = number of measurements) (Pekkarinen, Starck 1987).

Industrial Branch	n	L_{Aeq} dB(A)	L_{Cpeak} dB(*C*)
Foundry	24	93	127
Plastic packing	12	83	112
Metal packing	22	92	119
Printing press	24	93	119
Shipyard	28	92	134
Brewery	36	96	117
Porcelain fabric	9	88	128
Glass factory	7	95	113
Glass fibers factory	3	97	101
Confectionery factory	11	86	106
Weaving factory	13	95	119
Stretch factory	7	88	114
Paper mill	21	92	130
Saw mill	14	94	123
Copper tube factory	5	96	136

5.5. ROLE OF STANDARDS AND DATA BASES

5.5.1. Introduction

As illustrated in Figure 5.9, regulations and standards have an important influence on both the design of quiet equipment as well as the design of a quiet work place.
In the domain of machine safety, the Directive 89/392 (Annex I, section 1.5.8) of the European Union requires that machines are designed and constructed in such a way that hazards from noise emissions are reduced to the lowest level achievable with due regard to technical progress and technology available, primarily at the source.

In order to evaluate the noise emitted by machines, declarations of the noise emission based on the European Directives 86/188 (Art. 8, Par. 1b) and 89/392 (Annex I, Section 1.7.4f) are demanded. This enables potential buyers to select from comparable makers of machine, that machine with the highest noise-related quality (stimulation for manufacturers via the market). At the same time it enables the buyers to meet their statutory obligation for machine operators to use the least hazardous equipment possible (see EC Directive 86/188, § 5 (1)). Although there are no other statutory regulations, the international standards have a similar role to foster these intentions as shown in the structure of noise reduction of ISO 11690-1, see Figure 5.9.

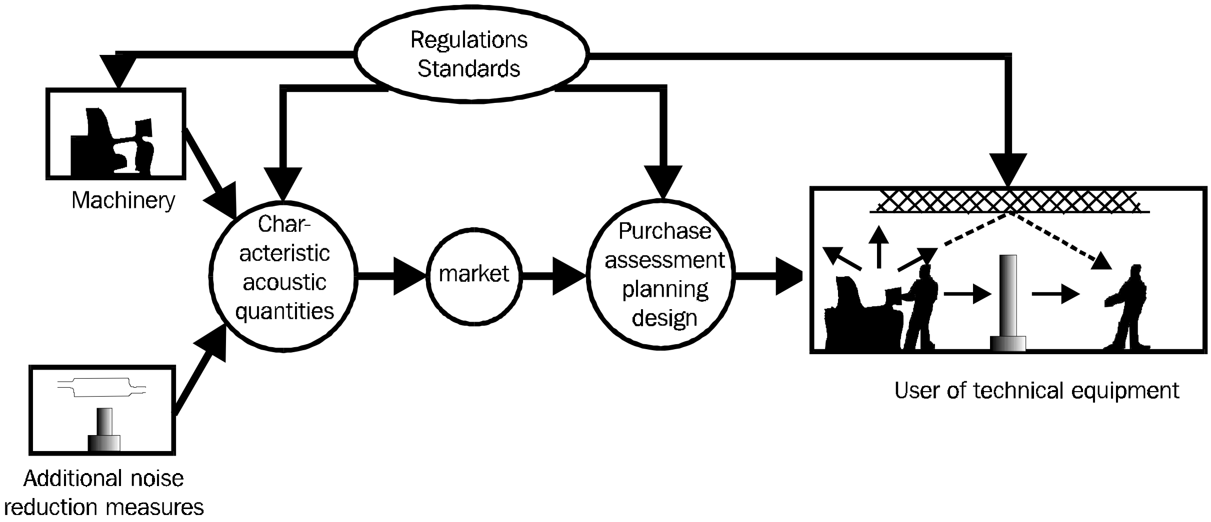

Figure 5.9. Role of regulations and standards

5.5.2. Framework Standards for Noise Measurement at Machines

The determination of the sound power is conducted internationally according to the ISO 3740 series, especially ISO 3744 and ISO 3746; the ISO standards have been revised since 1989. In these standards the enveloping measurement surface procedure is used to determine the sound power level. The subjects of the standards are in particular the selection of the measurement surface, the arrangement of measuring points, the determination of the environmental and background noise correction, the principles for the selection of the mounting and operating conditions and for determining measurement uncertainties.

The emission sound pressure level is determined internationally according to ISO 11201, ISO 11202, ISO 11203, ISO 11204. These standards address , as a complement to ISO 3744, selection of the measuring point or points for the workplace or workplace area and the environmental correction for one or more measuring points. Since the emission sound pressure level is taken as a criterion for the type and scope of the noise declaration in Europe, the precise determination and reproducibility should be stressed. A method which ensures the most correct possible environmental correction for a measuring point has now been developed and it is described in ISO 11204. ISO 11203 lays down procedures for calculating the emission sound pressure level from the sound power level. This procedure could be quite effective for smaller machines for which no precise workplace has been fixed (e.g. household appliances). ISO 11201 and ISO 11202 contain simplified procedures which are only applicable to a limited extent.

The type of noise declaration and a simplified verification procedure are given in ISO 4871. The verification procedures for noise emission already exist as International Standards (ISO 7574)

Most of the framework standards for determination,, declaration and verification of the noise emission have been completed. With the noise emission declaration (see Figure 5.10) for a machine, which is in Europe mandatory for the manufacturer or importer, there is the possibility for the first time of evaluating low noise level or noise quality. This creates the conditions for achieving noise reduction at source.

Noise emission declarations are also absolutely essential for forecasts by calculation

(ISO/TR 11690-3) of the noise impact (rating level) at workplaces and in the vicinity for the noise control planning of new workshops.

Machine model number, operating conditions, and other identifying information:		
Type 990, Model 11-TC, 50 Hz, 230 V rated load.		
DECLARED DUAL-NUMBER NOISE EMISSION VALUES in accordance with ISO 4871		
	Operating mode 1	**Operating mode 2**
Measured A-weight sound power level, L_{WA} (ref 1 pW) in decibels	88	95
Uncertainty, K_{WA}, in decibels	2	2
Measured A-weighted emission sound pressure level, L_{pA} (ref 20 μPa) at the operator's position, in decibels	78	86
Uncertainty, K_{pA}, in decibels	2	2
Values determined according to noise test code given in ISO XXXX, using the basic standards ISO YYYY and ISO ZZZZ. NOTE - The sum of a measured noise emission value and its associated uncertainty represented an upper boundary of the range of values which is likely to occur in measurements.		

Figure 5.10. Example of a noise declaration.

5.5.3. Machine-Specific Safety Standards: the Section "Noise"

In addition to the machine-specific noise measurement standards, noise also has to be included in a short section of a machine-specific standard with safety requirements for machines on an European and international level. Framework standards on the safety of machines lay down principles as to how the requirements of the EC Machinery Directive can be implemented, i.e., how the hazards arising can be recognized and avoided and how the safety of machines can be increased.

Where noise hazards (see EN 414 & EN 292, part 1) caused by machines, are significant, a noise section has to be formulated in a machine-specific safety standard. A safety standard should therefore include, as a safety requirement for the machine, a "noise reduction" section with the following sub-sections:

- Measures for noise reduction at the machine (ISO/TR 11688-1),
- Noise emission values (measurement, declaration, verification),
- Verification of noise reduction with reference to the achievable noise emission values (ISO 11689).
- Because there are some examples of international standards concerning safety of machines (e.g. agricultural machinery, gears) it seems sensible to follow these principles for International and European safety standards.

5.5.4. Framework Standards for Noise Reduction at Machines

To reduce noise at machines, standards have been drawn up which deal with the planning and design of low-noise machines (ISO/TR 11688 Parts 1, 2), the collection and evaluation of emission data (ISO 11689) and noise-related requirements for noise control devices and materials (silencers, enclosures, noise absorbers, baffles).

The standard ISO/TR 11688-1 gives an overview of the principles and methods a design engineer needs to design a low-noise machine or to communicate with an acoustic professional. The following approach is specified for the design engineer:

1. Specification of the design task (standards, state of the art, requirements for noise)
2. Concept phase (principles for solving the problem, comparison and selection of concepts, machine acoustics)
3. Detail design (calculations, detail drafts)
4. Investigations on prototype (measurement, evaluation, measures, comparison with requirements)

The standard ISO/TR 11688-2 describes the principles and basics of noise control development for existing and planned machines. Noise control devices and materials are to be covered as part of the machine, if they are integrated in it, e.g. enclosures, noise absorbers, partial enclosures, near-machine baffles. The reduction in emissions is thus expressed to an equal extent in the emission values.

It was intended, for instance, to supplement ISO/TR 11688 by a collection of examples in a form which enables it to be incorporated in CAD programs or databases. The same applies for the computation methods in ISO 11689 and ISO 11690. It is absolutely necessary to adapt to the needs of computer-aided design because other requirements from the environmental domain are to be implemented in a similar fashion, e.g. recyclability of products. Longer periods must be expected when it comes to the installation of databases containing characteristic values for noise reduction materials and components. The measuring standards have to be completed first.

5.5.5. Standards for Noise Reduction Devices and Materials

Since noise control devices and materials can of course also be used subsequently and in addition, standards were drawn up separately with noise-related requirements and measuring procedures for such devices/materials: for noise control enclosures (ISO 11546, ISO 11957), for noise absorbers (ISO 11654, ISO 10534), for silencers (ISO 7235, ISO 11691, ISO 11820, ISO 14163), noise baffles (ISO 11821, ISO 10053).

5.6. ACTUAL STATE OF NOISE EMISSIONS FROM MACHINES

The collection, presentation and evaluation of noise emission data are described in ISO 11689. In order to present the current state of noise emissions, the following must be defined in particular:
- Machine group (type, arrangement area, power),
- Noise emission value (L_{WA} , L_{pA}),
- Machine-specific noise measuring standard
- Representativeness of data,
- Type of presentation.

Within the actual state of noise emissions for a machine group, the machine with the lowest emission value has a higher noise control performance than that with a higher value. To describe the noise control performance of machines, ISO 11689 proposes that the emission data of a machine group be broken down with the help of two or three defined emission values (L_1, L_2, L_3) (see Figure 5.11). Different noise control performances are then obtained according to the level of the individual emission values of the machines in one group (see Table 5.9 for examples).

In Germany the actual state of noise emissions was drawn up for a series of machine groups in VDI-ETS Guidelines, e.g. for wood-working machines (VDI 3740, Table 5.9), metal-cutting machine tools (VDI 3742), reciprocating internal combustion (RIC) engines (VDI 3753), foundry machines (VDI 3757), hand-guided tools (VDI 3761) , machines for the forming of concrete blocks (VDI 3767) etc.

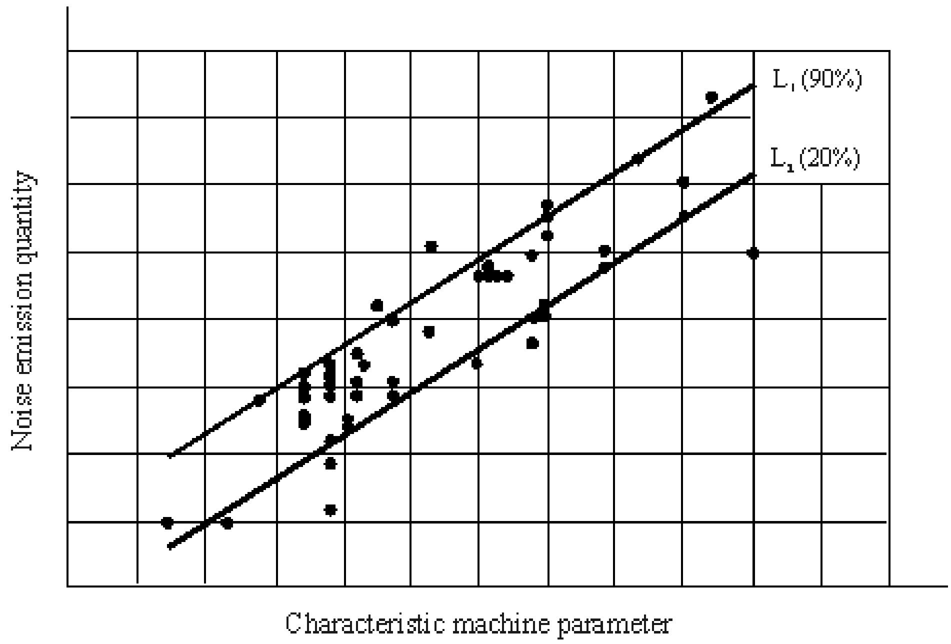

Figure 5.11. Typical noise emission as a function of machine parameter

Table 5.9. Noise emission values (sound power level L_{WA}) for surface planing machines (according to VDI 3740, Part 2).

Type of machine	Width of cutting tool in mm	Form of table lip	Operating state	Emission value (A-weighted sound power level L_{WA} in dB)					
				smallest		**medium**		**largest**	
Surface planing machine	<400	toothed	no-load	87	83	88.5	91	90	102
		untoothed		83		91.5		102	
		toothed	machining	95	94	97.0	99.0	101	105
		untoothed		94		99.0		105	
	≥400	toothed	no-load	82	82	92,0	93,5	101	102
		untoothed		90		97.0		102	
		toothed	machining	92	92	98.5	99.5	105	105
		untoothed		99		101.5		104	

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VDI 3740. Characteristic noise emission values of technical sound sources - Woodworking machines (in German)

VDI 3742. Characteristic noise emission values of technical sound sources - Cutting machine tools (in German)

VDI 3753. Characteristic noise emission values of technical sound sources - Reciprocating internal combustion (RIC) engines (bilingual German & English)

VDI 3757. Characteristic noise emission values of technical sound sources - Foundry machines (bilingual German & English)

VDI 3761. Characteristic noise emission values of technical sound sources - Electric woodworking tools (in German).

VDI 3767. Characteristic noise emission values of technical sound sources - Machines for the forming of concrete blocks (bilingual German & English)

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INTERNATIONAL STANDARDS

Titles of the following standards related to or referred to in this chapter one will find together with information on availability in chapter 12:

ISO 3740; ISO 3744; ISO 3746; ISO 4871; ISO 7235; ISO 7574; ISO 9614-1, -2; ISO 10053; ISO 10534; ISO 11201; ISO 11202; ISO 11203; ISO 11204; ISO 11546; ISO 11654; ISO/TR 11688-1, -2; ISO 11689; ISO 11690-1, -2; ISO/TR 11690 -3; ISO 11691; ISO 11820, ISO 11821; ISO 11957; ISO 14163;

FURTHER READING

Canadian Center for Occupational Health and safety (CCOHS) - *Noise Level data base*.

6

SOUND MEASURING INSTRUMENTS

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6.1. INTRODUCTION

This chapter describes the noise measuring instruments most widely used in the practice of occupational hygiene. The planning, the strategy and the practical aspects of a noise survey are discussed in Chapter 7.

Many types of measuring systems can be used for the measurement of sound depending on the purpose of the study, the characteristics of sound and the extent of information that is desired about the sound. The various elements in a measuring system are:

a. the transducer; that is, the microphone;
b. the electronic amplifier and calibrated attenuator for gain control;
c. the frequency weighting or analyzing possibilities;
d. the data storage facilities;
e. the display.

Not all elements are used in every measuring system. The microphone can, for instance, be connected to a sound level meter or directly to a magnetic tape recorder for data storage and future measurement or reference. An example of the components of the sound level meter is shown in Figure 6.1.

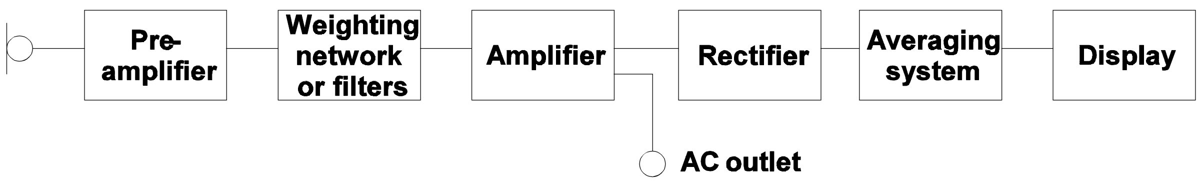

Figure 6.1. Sound level meter block diagram

The two main characteristics are:

1. The frequency response: that is, the deviation between the measured value and the true value as a function of the frequency. As the ear is capable of hearing sounds between 20 Hz and

20 kHz, the frequency response of the sound level meter should be good, with variations smaller than 1 dB, over that range.

2. The dynamic range: that is, the range in dB over which the measured value is proportional to the true value, at a given frequency (usually 1000 Hz). This range is limited at low levels by the electrical background noise of the instrument and at high levels by the signal distortion caused by overloading the microphone or amplifiers.

6.2. MICROPHONES

6.2.1. The Different Types

The microphone is the interface between the acoustic field and the measuring system. It responds to sound pressure and transforms it into an electric signal which can be interpreted by the measuring instrument (e.g. the sound level meter). The best instrument cannot give a result better than the output from the microphone. Therefore, its selection and use must be carefully carried out to avoid errors. When selecting a microphone, its characteristics must be known so that its technical performance (e.g. frequency response, dynamic range, directivity, stability), in terms of accuracy and precision, meets the requirements of the measurement in question, taking into account the expected conditions of use (e.g. ambient temperature, humidity, wind, pollution).

The microphone can be of the following types: piezoelectric, condenser, electret or dynamic. In a piezoelectric microphone, the membrane is attached to a piezoelectric crystal which generates an electric current when submitted to mechanical tension. The vibrations in the air, resulting from the sound waves, are picked up by the microphone membrane and the resulting pressure on the piezoelectric crystal transforms the vibration into an electric signal. These microphones are stable, mechanically robust and not appreciably influenced by ambient climatic conditions. They are often used in sound survey meters.

In a condenser microphone, the microphone membrane is built parallel to a fixed plate and forms with it a condenser. A potential differential is applied between the two plates using a d.c. voltage supply (the polarisation voltage). The movements, which the sound waves provoke in the membrane, give origin to variations in the electrical capacitance and therefore in a small electric current. These microphones are more accurate than the other types and are mostly used in precision sound level meters. However, they are more prone to being affected by dirt and moisture.

A variation on the condenser microphone which is currently very popular is the electret. In this case the potential difference is provided by a permanent electrostatic charge on the condenser plates and no external polarising voltage. This type of microphone is less sensitive to dirt and moisture than the condenser microphone with a polarisation voltage.

The last type is a microphone where the membrane is connected to a coil, centred in a magnetic field, and whose movements, triggered by the mechanical fluctuations of the membrane, give origin to a potential differential in the poles of the coil. The dynamic microphone is more mechanically resistant but its poor frequency response severely limits its use in the field of acoustics.

6.2.2. The Sensitivity of a Microphone

The sensitivity of a microphone is defined as the amplitude (in mV) of the output signal for an incident sound pressure of amplitude 1 Pa (94 dB) at 1000 Hz. It can also be expressed in decibels by the following expression:

$$Sensitivity = 20\log_{10}\frac{Vp_0}{V_0 p} \quad \text{dB re 1V/Pa}$$

Thus, a microphone giving an output signal *V* of 10 mV for a pressure signal *p* of 94 dB has a sensitivity of 10 mV/Pa or -40 dB. Here p_0 = 1Pa and V_0 = 1 volt.

6.2.3. Frequency Response

Good quality piezoelectric or condenser microphones have usually flat frequency response characteristics from 2 Hz to an upper limit which depends on their size. This limit is about 2 kHz for a 1" diameter microphone, 4 kHz for a 1/2" and 8 kHz for a 1/4" microphone. Below this limit, the frequency response is independent of the orientation of the microphone with respect to the noise source, and therefore the microphone can be held in any orientation. Above this limit, the frequency response will depend upon the direction of the sound wave on the microphone membrane.

Some microphones have been designed in order for the response characteristics to be flat when the sound direction of propagation is perpendicular to the membrane. These microphones are called free field microphones and should be oriented toward the most significant sound source. Figure 6.2. illustrates the frequency response characteristics of this type of microphone.

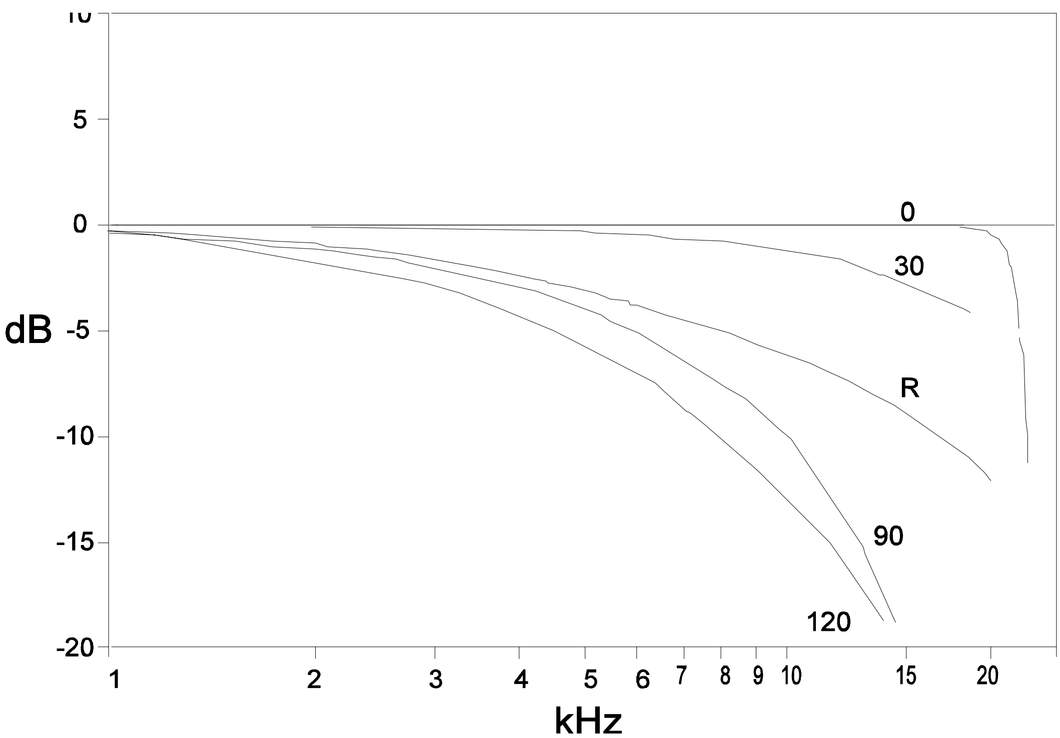

Figure 6.2. Frequency response of a free field (0°) microphone

The numbers on the curves represent the angle of incidence (in degrees) of the incoming sound wave with respect to the normal to the membrane. The quantity, “R”, represents the response to a diffuse sound field (sound incident equally from all possible directions).

Other microphones have been designed for the response characteristics to be flat when the sound comes in all directions at the same time as in a diffuse field. They are called diffuse field microphones. Their frequency response characteristic is very near the response characteristic under an incidence of 70° and these microphones should therefore be oriented at 70° toward the predominant sound source.

Figure 6.3. illustrates the frequency response characteristics of this type of microphone.

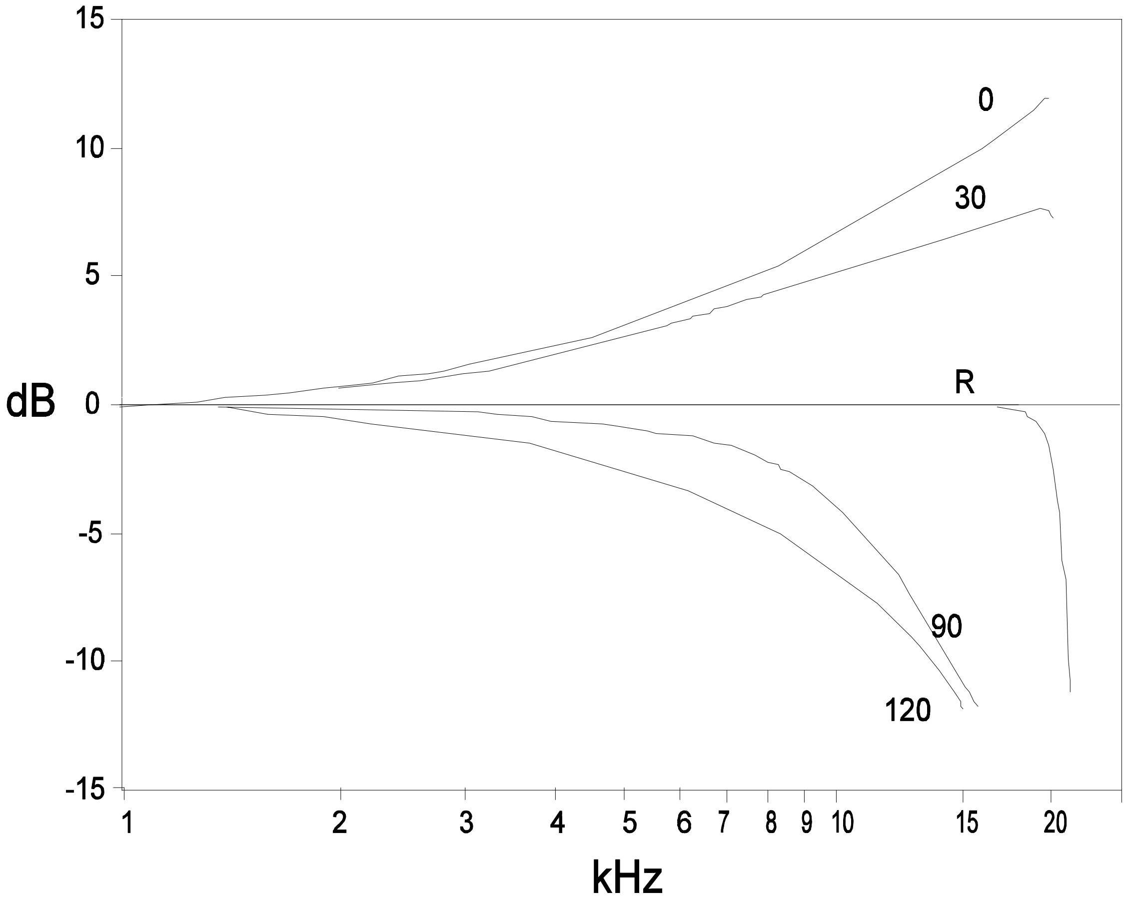

Figure 6.3. Frequency response of a diffuse field (R) microphone

6.2.4. Dynamic Range

The output of a microphone is limited on the one hand by the internal noise of the transducer and on the other hand by the distortion resulting from high noise levels. In addition, the instrument to which the output signal of the microphone is fed will saturate if the signal is too high and will also give a false result (that is, its background noise level) if the signal is too low. Therefore, high sensitivity microphones are needed to measure very low noise levels (lower than 30 dB), and low sensitivity ones have to be used for high noise levels such as for impact noise (above 130 dB). The dynamic range of typical good quality microphones is thus between 100 and 120 dB.

6.2.5. Selection and Use of a Microphone

The selection of the microphone is based on:

- the levels to be measured,
- the frequencies to be measured - low or high,
- the type of acoustic field - free or diffuse,
- the purpose and the type of measurement - overall level or frequency analysis.

As stated previously, the measurement of low noise levels requires high sensitivity microphones and for high levels, low sensitivity ones are needed. The problem arises outside the range 50 to 120 dB usually: the characteristics indicated by the manufacturer for both the microphone and the indicating instrument should be checked.

If the noise is predominantly at frequencies below 1 kHz and overall levels are to be determined, any type of microphone may be used. On the contrary, if the noise is suspected or known to include a high frequency content, or that a frequency analysis is going to be made, the frequency characteristics of the microphone must be checked. As stated earlier, the smaller the physical dimensions of the microphone, the wider the frequency range and the lesser the effects of directivity since they occur at higher frequencies. Microphones of small diameter would then be preferable. However, they are more fragile and, with the exception of certain special ones, less sensitive.

The user must then choose between free field or diffuse field microphones. When it is necessary to measure the ambient noise level at a given point regardless of the localisation of the sources or in presence of a diffuse field, a diffuse field microphone must be used: this is generally the case in occupational hygiene for the evaluation of exposure to noise.

On the contrary, for control purposes, the aim is usually to characterize the noise emitted by a particular machine. The machine should ideally be placed in a free field environment or at least in a very absorbing room and a free field microphone should be selected. If this is not possible, there exist ISO standards to assist with making the measurements “on-site” (ISO 3740, ISO11200).

Where possible, a diffuse field microphone should be directed at about 70° from the direction of the "predominant" noise source, so that the frequency responses for direct and reflected waves are the same. It should always be remembered that this concerns only high frequencies; therefore the "predominant" source is, in this regard, the one emitting the most at these frequencies, regardless of what is emitted at frequencies below 1 kHz.

Similarly, a free field 0° microphone must always be pointed toward the "predominant" source.

6.3. SOUND LEVEL METERS

6.3.1. Description

The electrical signal from the transducer is fed to the pre-amplifier of the sound level meter and, if needed, a weighted filter over a specified range of frequencies. Further amplification prepares the signal either for output to other instruments such as a tape recorder or for rectification and direct reading on the meter.

The rectifier gives the RMS value of the signal. The RMS signal is then exponentially averaged using a time constant of 0.1 s ("FAST") or 1 s ("SLOW") and the result is displayed digitally or on an analog meter.

In some cases, the sound level meter does not include a logarithmic converter. The scale on the indicating device is then exponential so that the linear signal may be read in dB. In this case, the dynamic range of the display is usually restricted to 10 to 16 dB and the precision of the reading is rather poor. In the case of intermittent noise, the user must constantly adjust the amplifier to adapt the output signal to the dynamic range of the display.

When a log converter is used, the display scale is linear in dB and its dynamic range is usually much greater. This type of display has the advantage of providing the same precision at any level and permitting a much better appreciation of the range of fluctuations of the noise to be measured. In this regard, digital displays are less useful.

The specifications of sound level meters are given in IEC 60651 for four types 0, 1, 2, 3 differing by the measurement precision. The measurement precision is reduced as the type number increases, affecting manufacturing costs significantly. The IEC 60651 standard specifies the following characteristics:

- directional characteristics
- frequency weighting characteristics
- time weighting, detector and indicator characteristics
- sensitivity to various environments.

The type 0 sound level meter is intended as a laboratory reference standard. Type 1 is intended especially for laboratory use, and for field use where the acoustical environment has to be closely specified and controlled. The type 2 sound level meter is suitable for general field applications. Type 3 is intended primarily for field noise survey applications. The frequency response for all types is defined from 10 Hz to 20000 Hz with a higher accuracy at frequencies from 100 Hz to 8000 Hz.

Type 2 and type 3 sound level meters usually include only the A-weighting network and the FAST and SLOW response. Models with AC outlets should be chosen as they make it possible to record the noise on a magnetic tape recorder for further analysis. They are usually equipped with a diffuse field piezoelectric or electret microphone.

Type 0 and 1 sound level meters are often much more versatile with the possibility of measuring vibrations or inserting octave or one third octave band filters. They usually make it possible to measure a non-weighted signal (FLAT response) as well as an A-weighted and a C-weighted signal. They come with a choice from a variety of condenser microphones of different sensitivities and characteristics.

As previously seen, the evaluation of impulses involves the determination of the peak level and the duration of the impulse. Some precision sound level meters are equipped with a circuit that makes it possible to measure the peak level: the time constant used in this case is about 50ms and a circuit is included to hold the instantaneous level. After recording the peak value, the meter must be reset in order to read another value.

Some sound level meters offer the possibility to measure the equivalent A-weighted level $L_{Aeq,T}$ according to the equal energy principle. This can be done in two ways. In the first, the integrating period is prefixed (in some cases, 60 seconds) and the instrument computes the $L_{Aeq,T}$ level progressively: intermediary readings are then irrelevant and the user may only record the final value. In the second type, the integrating period is not fixed and the instrument actually gives the $L_{Aeq,T}$ level computed during the time elapsed since it was started. This type is of more

use than the first one as the user does not have to define before hand the integrating time to be used. A different type of integrating sound level meter will be more thoroughly discussed in section 6.5.
(Editors' note: The International Standards IEC 60651 and 60804 define classes of instruments instead of types. The ongoing revision of these standards will result in one single standard which will define only classes 1 and 2 for normal and integrating sound level meters as well.)

6.3.2. Use of Sound Level Meters

This section describes how to use physically the instrument in order to correctly measure the noise level existing at the point where the microphone is placed. The following steps must be taken successively:

1. Batteries must be checked before use (see Section 6.9) and during long measuring sessions.
2. A wind shield must be used if the air velocity is noticeable. It should anyway be used all the time as a dust shield (see Section 6.9).
3. The microphone should be oriented as described previously.
4. All intruding objects such as the body of the sound level meter (SLM) or the operator itself will degrade the frequency response of the microphone at high frequencies and directivity effects will appear at much smaller frequencies. Therefore, the SLM should be, whenever possible, installed on a stable and sturdy tripod equipped with resilient blocks to isolate the sound level meter from vibration and consequent spurious readings. The operator should be at a reasonable distance (2-3 m) behind the sound level metert. Extension cables should be used if possible when measurements are to be made in a restricted area (see section 6.9). When the instrument makes it possible, an extension rod should be used for the microphone. For walk-through surveys, the SLM should be held well away from the body.
5. The SLM must be calibrated before any measuring session using a calibrator described in Section 6.8. If the temperature of the instrument is significantly different from the ambient temperature where it will be used, it should be first warmed up (see Section 6.9) before calibration and use. The calibration must be checked at the end of the session. If the instrument is not calibrated anymore, the data might have to be discarded and the reasons for this calibration change should be investigated as this might indicate an important malfunctioning of the instrument.
6. Nowadays, it is much more advantageous to use an integrating sound level meter to determine the $L_{Aeq,T}$ over a representative period of time T than to use a simple SLM on fast or slow giving an instantaneous value.

6.4. FREQUENCY ANALYZERS

6.4.1. Description

The objective of frequency analysis is to determine how the overall level is distributed over a range of frequencies. The most usual analysis for occupational hygiene noise studies is octave band analysis. For more detailed information, narrower bands can be used such as one-third octave analysis or constant bandwidth analysis.

A number of analyzers are available for use with the sound level meter. The simplest models are sets of passive filters (octave or one third octave) that can be inserted between the two amplifiers of the SLM. Other analyzers are specific instruments making it possible to automatically scan the whole range of frequency bands. These are sequential instruments making measurements in one band at a time. This strongly restricts their use as the noise must be constant both in amplitude and in frequency during the 5 to 10 minutes of the analysis.

More sophisticated analyzers have the possibility to make the frequency analysis in all desired bands at the same time. These are analyzers using a set of parallel filters or using the fast fourier transform of the input signal before recombining the data into the desired bands.

One important aspect to be considered about the filters is their frequency characteristics. Ideally, the filter should provide an attenuation of infinity outside the band. In practice, this is never the case. For most common filters, the attenuation at the cut off frequencies is usually around 3 dB and is some 24 dB per doubling of frequency outside that range. Figure 6.4. gives the typical frequency characteristic of an octave band filter. The practical implication of this is that a signal of 100 dB at 1000 Hz for instance will give a reading of 76 dB in the octave bands centred at 500 Hz and 2000 Hz, although no energy is present at frequencies covered by these two octave bands.

The user must then be very careful when interpreting the results of the frequency analysis of a noise that includes a strong pure tone.

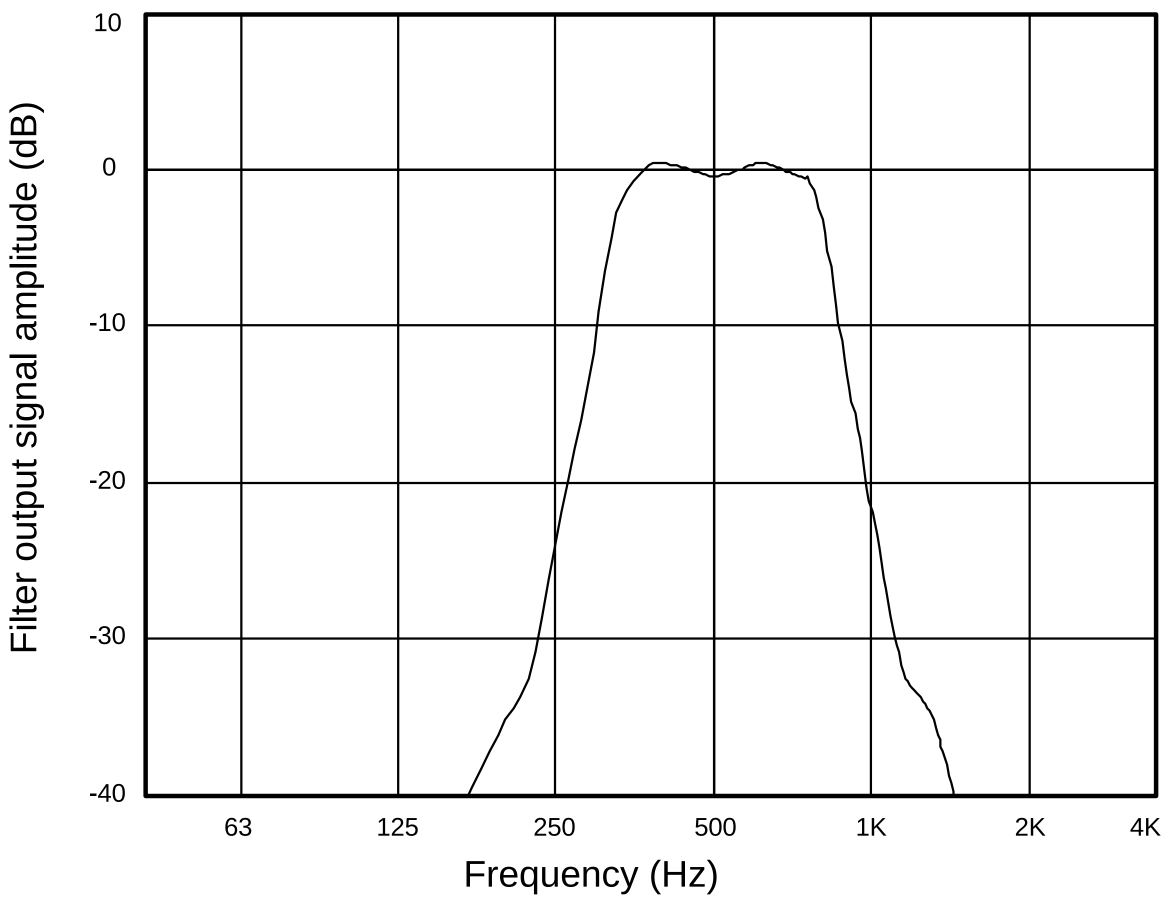

Figure 6.4. Typical 500Hz octave band filter characteristic

As an example, consider the octave band spectrum of figure 6.5, presenting a predominant value for the 1000 Hz octave band (106 dB). A pure tone of 106 dB at 1000 Hz would give a reading of 106 - 24 = 82 dB both for the 500 Hz and the 2000 Hz octave bands. The levels of 90 and 91 dB respectively would not be very much influenced by this and therefore would reflect the total intensity at frequencies inside these bands.

However the frequency of the pure tone might be 1175 Hz: the attenuation provided by the 2000 Hz octave band filter would then be 15 dB and the level in this band 91 dB. Similarly for a 860 Hz tone, the attenuation for the 500 Hz octave band would be 16 dB and the level wrongly estimated at 90 dB.

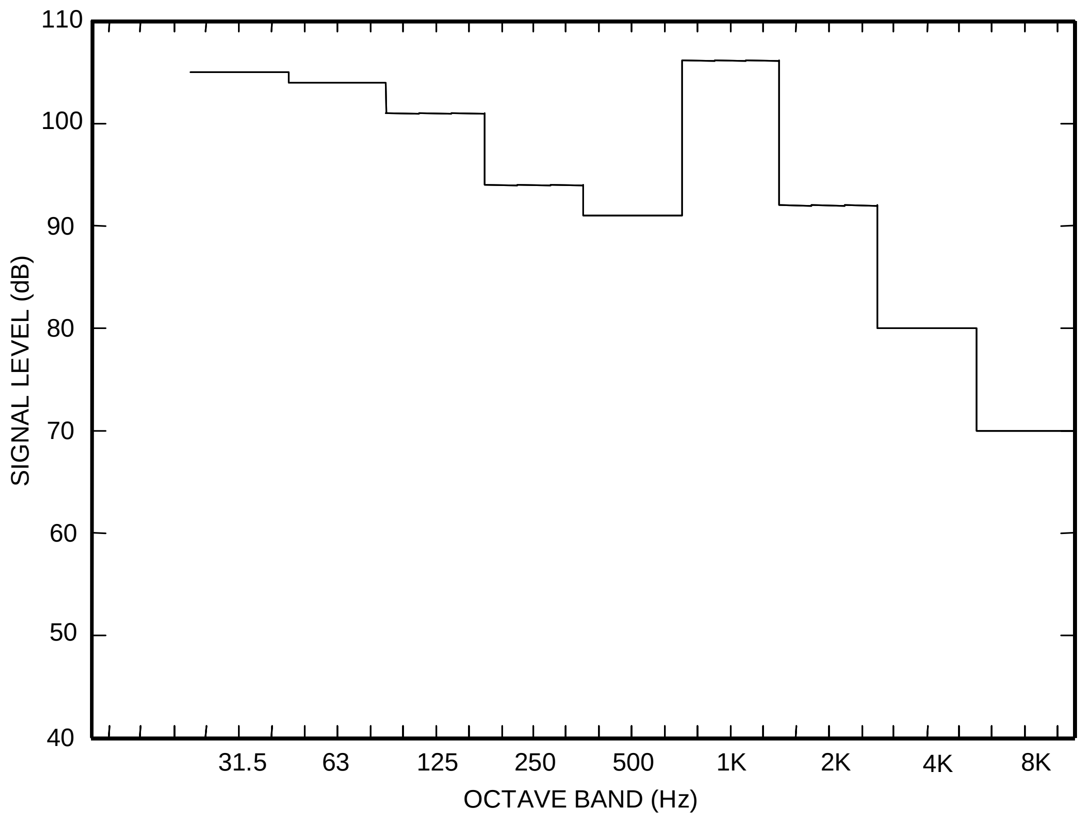

Figure 6.5. Example of the octave spectrum of a noise including a pure tone in the octave centred at 1000 Hz

It is clear that, unless more sophisticated frequency analyses are performed, it is impossible to know precisely the frequency of the tone and therefore to determine whether the levels in the side bands are correct or not. Faced with cases like this, the user must proceed with more sophisticated analyses.

For more sophisticated instruments and especially for digital equipment, the problem is of a lesser importance as the filter attenuation with frequency is usually much higher (typically over 90 dB per octave).

6.4.2. Use of Frequency Analyzers

The procedure described here for carrying out a frequency analysis will only be concerned with the use of sequential octave or one-third octave filters, as with more sophisticated parallel filter equipment, the procedure might be very instrument specific. Again, only technical aspects will be presented here: the problem of deciding what type of analysis needs to be done, when and for what purpose being discussed elsewhere. Basic elements are:

1. Usually frequency analyses are performed on unweighed signals. If it is not the case, the weighting used must be clearly indicated (e.g. "A-weighted").
2. It is obvious that the noise must be fairly steady both in frequency and in amplitude during the time of the sequential analysis. If it is not steady, the noise must be recorded on a magnetic tape and the sample must be successively analyzed with each filter. Clearly this problem would not exist in equipment with parallel or FFT filters.
3. As the width of octave or one-third octave bands is smaller for low bands (31.5 and 63 Hz) than for higher ones, the fluctuations of the noise are usually much greater. Therefore the sampling time in order to get a reliable evaluation of the band level must be higher: actually, the sampling time must be inversely proportional to the width of the band (in Hz).
4. The frequency analysis should be carried on only for those bands for which the frequency characteristic of the microphone and the input amplifier is flat. Corrections may not simply be added to measured levels.
5. As shown in figure 6.1, the filters are inserted between the input amplifier which receives the total signal and the output amplifier which must prepare the filtered signal for detection and display. For a noise such as the one represented in Figure 6.5, the overall level was 113 dB, while the 8 kHz octave band level was 70 dB. The difference in this case is 43 dB which means that the output signal of the filter was 140 times (10 to the power 2.15) lower than the input signal. In such a case, care must be taken for the input signal not to saturate the input amplifier and/or the output signal not to be covered by the internal electronic noise of the output amplifier. The instruction manual of the measuring instrument should be consulted about the procedure to prevent this. Some sound level meters are provided with overload indicators for each amplifier to check that this is not the case.
6. Data for octave and one third octave analyses must be reported in a bar graph format instead of by simply joining the different points plotted at centre frequencies (see Figure 6.5).

6.5. NOISE DOSIMETERS

6.5.1. Principles

The need to ascertain the noise exposure of workers during their normal working day, has led to the development of the noise dosimeter. This is a small, light and compact instrument to be worn by the worker. It measures the total A-weighted sound energy received and expresses it as a proportion of the maximum A-weighted energy that can be received per day. This instrument is particularly useful whenever the exposure varies appreciably during the working day.

The maximum A-weighted energy that is permitted to be received per day is defined in standards or regulations: it is absolutely necessary that the dosimeter be calibrated on the basis of the adopted standard (e.g. 85 dB(A) or 90 dB(A) for an 8-hour exposure), including the accepted trading rule, which is 3 dB(A) in accordance with the ISO 1999 - 1990 standard (and for most European countries) and 5 dB(A) for the OSHA Standard (USA). The 3 dB(A) trading rule is consistent with the equal energy principle: 96 dB(A) during 2 hr providing the same energy as 93 dB(A) during 4 hours or 90 dB(A) during 8 hours. The 5 dB halving rate assumes that 90 dB(A) during 8 hours is equivalent to 95 dB(A) for 4 hours or 100 dB(A) for 2 hours.

(Editors' note: NIOSH recommended in 1998 a 3-dB exchange rate, see Chapter 4)

Dosimeters are actually sound level meters having a DC output signal converted into a series of impulses which are counted to provide the dose. The technical characteristics of dosimeters must then be the same as for type II sound level meters.

6.5.2. Use

The noise dosimeter is clipped to the workers' clothes with the microphone close to the ear, and can be worn without hampering work. The dose provided by the instrument is of course dependent on the duration during which the instrument is used. Therefore, it should first be corrected for an 8 hour period and then converted to the daily noise exposure ($L_{EX,8}$) level according to the relevant formula (ISO or OSHA).

It is important to know that some old dosimeters do not take into account levels below 89 dB(A) or 80 dB(A), as they assume that lower levels do not lead to hearing impairment. The $L_{EX,8}$ is then physically not correct. These dosimeters are obsolete and should be discarded. On certain instruments, a warning marker is activated if the peak level ever exceeds 140 dB.

It is worth noting that the characteristics of the dosimeters have never been standardized. Furthermore, they are extremely limited as they provide one single value at the end. It is strongly recommended to abandon this type of instrument and use the personal sound level meters described in the next section.

6.6. PERSONAL SOUND LEVEL METERS

6.6.1. Principles

Personal sound level meters are in fact integrating sound level meters designed as dosimeters in order to be worn by the worker during his regular work. These instruments make it possible to record on almost any increment of time the equivalent level, the peak level or any statistical parameter. Typically it will record the $L_{Aeq,T}$ (in dB(A)) and L_{peak} (in dB) every second. This is extremely interesting as it makes it possible to analyse the evolution of the noise exposure during the day and to correlate it to the type of work or the location of the worker.

This type of instrument makes use of the equal energy principle and offers generally a much broader dynamic range than dosimeters discussed in section 6.5. They are definitely expected to replace dosimeters in the near future and in fact are already referred to as dosimeters by some manufacturers and users. Personal sound level meters or personal sound exposure meters conform to the IEC 61252 standard.

6.6.2. Use

Their use is identical to the one of dosimeters with the microphone located closer to the ear of the worker.

6.7. RECORDERS

6.7.1. Graphic Level Recorder

If the sound level meter has a logarithmic DC output facility, common graphic recorders can be used to obtain a permanent record of the evolution of the sound level, providing that their writing speed is compatible with the SLOW or FAST characteristics of the SLM.

If there is no DC output or if this output is not proportional to the dB level but only to the RMS pressure, then a special recorder must be used. Many different types are available and it is not intended to review them. The essential characteristics for this type of equipment are:

- the RMS detection capabilities;
- the frequency response;
- the writing speeds, that should at least correspond to the slow and fast characteristics of the sound level meter. For reverberation time measurements, however, much faster writing speeds are needed;
- the dynamic range of the graph (often 25 or 50 dB) and of the instrument.

  It is usually not practical to record graphically the instantaneous noise level at a workplace for extended periods of time: the graph allows only the determination of maximum and minimum levels and cannot be used to define any average level. The use of this technique should be restricted to special cases such as:

- the characterisation of short events of noise;
- the determination of the intermittency of a noise;
- the study of the reverberation time;
- the recording of frequency analysis.

A graphical record of the history of the L_{Aeq} noise level is usually possible with the exposure meters described in Section 6.6.

6.7.2. Magnetic Tape Recorders

Magnetic tape recorders are used to make a permanent recording of the noise for future analysis or reference. Some HIFI audio recorders can be used, providing their frequency response and dynamic range are suitable. For general surveys, small recorders with a frequency response of $\pm$ 3 dB in the range 30 Hz to 16 kHz and a dynamic range of 40 dB may be sufficient. For precise measurements and frequency analyses, higher quality instrumentation is needed. The real objectives of the instrument have to be assessed since the relative price of these instruments may vary in the range of 1 to 20.

As the dynamic range of an analog recorder is no more than 40 to 50 dB, usually it is difficult or impossible to record impulse noise as met in industry or as used for measuring the reverberation time. Some digital recorders (referred to as DAC recorders) are now available: they have a much broader dynamic range (around 90 dB) and a good frequency response (20 - 18000 Hz).

Besides analog and digital recorders, there are also frequency modulated (FM) recorders which are of special interest for measuring vibration as their frequency range extends down to DC.

6.7.3. Use of a Tape Recorder

The criteria for the selection of a tape recorder are:

- the frequency response at the different speeds. Usually the limits are directly proportional to the speed;
- the range of speeds;
- the dynamic range;

- the cross channel attenuation;
- the presence of band pass filters enabling the elimination of low frequency noise;
- the quality of the indicating device and of the input potentiometers, preferably graduated in dB;
- the possibility of controlling the output signal;
- the protection against dust;
- the protection against vibration susceptibility which increases the internal noise level;

The procedure for making a recording is as follows:

1. Use preferably as the input signal, the AC output of a sound level meter, making it possible to control the level of this signal in steps of 10 dB. This will be assumed to be the case in the following steps.
2. In presence of the noise, adjust the SLM so that the SLM reading is between mid and full scale. Adjust the input potentiometer of the recorder (on pause) so that the signal does not saturate the amplifier of the recorder (as indicated by the V.U. meter). The meter needle should NEVER go into the red part of the scale. The input attenuation should not be too high, however, or the dynamic range of the recording will be reduced.
3. Once this is done, DO NOT modify any more the setting of the recorder. Record by voice the attenuation used on the SLM (for example 80 dB).
4. Adjust the noise calibrator (for example, 94 dB, 1000 Hz) so that the correct level is read on the SLM. Place the SLM attenuator on the corresponding attenuation (e.g. 90 dB) and record the calibration signal for 1 or 2 minutes, mentioning clearly by voice, on the tape, what will be done and what has been done. The output signal of the SLM is in this case proportional to: attenuation setting (90) + 4 (meter reading) dB. Therefore, the recorded signal will be a reference of 84 dB, if 80 is the attenuation to be used for the real recording.
5. Remove the calibrator, replace the SLM attenuator on its previous setting and after indicating orally the start of the recording and its probable duration, proceed with it. The duration of the recording is dictated by the problem to be investigated. It is well advised to make much longer recordings than at first appears needed.
6. At the end of the recording, again indicate orally the stop and give full information on what was recorded, and on any particular event that might have happened during the recording.
7. Repeat Step 4 of calibration.

If, for any reason, the settings of the recorder have been modified during the recording, the whole procedure must be repeated.

6.8. CALIBRATORS

Microphones are individually calibrated at the factory, and the calibration chart must be delivered with the instrument. In the field, calibration is performed by applying a known sound pressure level at a fixed frequency to the microphone. Calibrators are small, battery driven and operate on different principles. One operates at 250 Hz and produces a sound level of 124 dB, accurate to $\pm$ 0.2 dB. To obtain the best results, the microphone should be well sealed in the coupler opening. A change in atmospheric pressure alters the calibration level slightly, but a correction can be made using the barometer which is provided as a part of the instrument set. Another example is a pocket unit, which operates at 1000 Hz. The calibration level is 94 dB with an accuracy of $\pm$ 0.5 dB.

The use of a calibrator as defined by IEC 60942 is recommended for checking the accuracy of hand-held indicating instruments, and must be used when tape recording data, as explained previously. Accurate calibration of equipment used in the field is essential as it provides for consistency in measurements, allows accurate comparison of measurements made over long time intervals, brings to light any slight changes in the accuracy of instrumentation, and allows a re-analysis of data, if this is required at a later date. This care in the use of calibration for field measurements should be backed up by regular laboratory calibration using more accurate techniques, in order to check the frequency response as well as the amplitude response of the equipment.

6.9. STORAGE, HANDLING AND TRANSPORTATION

It is obvious that great care must be taken of the instruments. They should not be exposed to extremes of temperature or to direct sunshine. The limits that the instruments can stand are usually defined by the manufacturer. The operating range of temperature should also be specified: it is usually narrower.

- Instruments should also not be exposed to extremes of humidity, and any condensation should be carefully avoided. This means in particular that the instrument should not be taken from a cold environment (a cold car in wintertime for instance) directly to a hot and humid place. If the temperature of the instrument is lower than the dew point of this environment, condensation might occur, provoking short-circuits or general malfunctioning that might be unnoticed. The problem is of a greater importance for microphones. Condensation on the membrane might in the short term induce erroneous measurement; in the long term however, oxidation of the membrane develops and small holes might appear: in this case, the microphone must be replaced.

Before going from a cold to a hot environment, the instrument, in its tight box, should be progressively brought to a temperature near that of the new environment and certainly well above its dew point. This means also that the equipment should not be left in the cold overnight or transported in the trunk of a car.

The equipment should also be stored in a normal temperature (10 to 25°C) and dry (30 to 70% relative humidity) environment. Microphones should be taken care of by surrounding them with desiccating capsules or even storing them in a dry 20° oven when they are not in use.

Measuring instruments should not be exposed to vibration for obvious reasons. This implies that they should always be stored, handled and transported in their original box with damping materials such as plastic foam around them. This is also a further reason for not transporting them in the trunk of a car.

Measuring instruments should be protected against dust. Portable instruments such as sound level meters, and dosimeters, when not used, must be stored in their box. When used, they might be protected by either removing them from the dusty area and using extension cables, or by enveloping them in tight plastic bags. Laboratory instruments, standing on tables, should be covered with a plastic sheet when not used: such a cover is usually provided by the manufacturer. As far as the microphone is concerned, a wind shield should always be used. This shield, consisting generally of a ball of very porous plastic foam, must be cleaned carefully and regularly. The foam shield must be discarded if it shows any sign of crumbling.

Dust on the microphone membrane is however unavoidable. The user should never try to remove it either with his finger (as this will modify the position of the membrane) or by blowing air on it (as this will induce condensation). If by accident, the membrane has become very dusty, one might try to remove the larger particles carefully with a very soft paint-brush. The membrane may be cleaned with a cotton wool bud soaked in hexane.

The instruments should also be kept away from polluted areas. This is however seldom a problem if condensation is avoided. The same precautions apply here.

Batteries should be removed from the instrument when it is not used for a prolonged period of time. Non rechargeable batteries should be checked regularly and replaced as soon as they are flat, otherwise they might leak which might corrode and completely wreck the instrument. Rechargeable batteries must be kept fully charged as far as possible. The batteries of an instrument make a single set which must be charged together. Individual batteries should not be interchanged between sets and the whole set needs replacement when worn. The manufacturer should be consulted regarding how to charge the set, with what adaptor, at what rate, and how many times this can be done. For instruments powered by mains, the voltage must be kept in the range indicated by the manufacturer. A stabilized supply might be needed if the voltage fluctuates too much.

Great care must be taken of cables, connectors and switches. These are the main reasons for errors or problems. Cables should be wound very loosely when necessary. In the laboratory they should be kept straight, hung by the middle (not by a connector), loosely bent. They should be replaced as soon as the insulating plastic becomes damaged. Connectors should be checked systematically. If by accident, cables have been sharply cut or bent or exposed to high heat or any strong pull has happened on a connector, the cable must be carefully checked and ideally discarded, as short-circuits or open circuits might happen then or later, which could damage the instrument or lead to erroneous measurements. The instrument to which the cable was connected should also be checked for loose plugs, open circuiting or short-circuiting.

Switches are very delicate items, especially on recent smaller instruments. They must be operated softly and without pressure. As soon as they indicate any sign of malfunctioning, switches must be thoroughly cleaned and, if necessary, replaced. The cleaning can best be done using cotton tips soaked with alcohol or hexane. Cleaning products that might leave residue or attack the contacts (sometimes gold-plated) must be definitely rejected. Care must also be taken with microphone threads while screwing to sound level meters.

Magnetic recorders need special attention concerning the cleaning of the heads (as described above) and the choice and handling of the tapes. Tapes should be demagnetized before recording and stored away from iron or steel surfaces (and, of course, magnetic fields). They should be kept in a dry box at all times. When mounted, the recorder cover must be kept closed. Tapes should be discarded after a few uses as the magnetic noise builds up, restricting the dynamic range of recording. Heads might need special care in addition to regular cleaning: the operating manual should be consulted.

Finally, the manual of each instrument might give special instructions concerning its handling, the storage and the maintenance. Needless to say that this must not be overlooked but must be practised during the entire life of the instrument.

REFERENCES

Malchaire J. (1994).. *Programmes de conservation de l'audition* - Organisation en milieu industriel. Paris, Masson, 1994, pp. 162.

INTERNATIONAL STANDARDS

Titles of the following standards referred to in this chapter one will find together with information on availability in chapter 12:

ISO 1999, ISO 3740, ISO 11200, IEC 60651, IEC 60804, IEC 60942, IEC 61252.

FURTHER READING

Harris, C. M. (Ed.) (1991) *Handbook of acoustical measurements and noise control*. 3rd edition,New York, McGraw-Hill, Inc.

7

STRATEGIES FOR NOISE SURVEYS

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7.1. INTRODUCTION

7.1.1. Definitions

L_{inst} designates the instantaneous level indicated by a simple sound level meter set on FAST or SLOW as far as the averaging time is concerned. In recent times the L_{inst} parameter has been. replaced by the A-weighted equivalent level $L_{Aeq,T}$. This is the continuous level which, over a given period of time, T, would give the same amount of acoustical energy as the actual noise. This is the so called ISO equal energy principle. As mentioned in chapter 4, this is different from the so called OSHA principle (USA) according to which an exposure of duration ΔT at a noise level L dB(A) is equivalent to an exposure of duration $2\Delta T$ at a noise level (L-5) dB(A) (according to the ISO principle, it is equivalent to (L-3) dB(A) during $2\Delta T$).

Over a given period of time, personal dosimeters (personal sound exposure meters) offer usually the possibility of recording all or some of the following parameters:

$L_{x\%}$ the noise level (in dB(A)) exceeded during x% of the time;

L_{MAX} the highest level (in dB(A)) exceeded during that period of time (in SLOW and FAST, depending upon the setting of the instrument);

L_{peak} the highest peak level (in dB).

For hearing conservation purposes or to estimate the individual risk of hearing loss of an exposed person, it is necessary to define an average level characterising the mean exposure of the person.

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Two parameters are defined:

- the *daily noise exposure level* $L_{EX,8h}$ (= $L_{aeq,8h}$ = $L_{EP,d}$) which is the continuous level, in dB(A), which would, over a standard daily period of 8 hours, produce the same amount of acoustical energy as the actual daily exposure. This concept is used when the worker is exposed daily, for 5 days per week, to the same level.

- if this is not the case - for instance a work cycle of more than one day or less than 5 days per week - the concept of the *weekly noise exposure level,* $L_{EX,w}$ *, is* used: this is the continuous level, in dB(A), which over a standard weekly period of 40 hours, would produce the same amount of acoustical energy as the actual weekly exposure.

ISO standard 1999 introduces also the quantity, $E_{A,T}$, which is used to characterise the total noise exposure in terms of Pa^2 .h. This quantity is discussed in more detail in chapter 1. Note that many people use the units Pa^2 s $\times 10^{-3}$ (see Table 7.1)

The standard ISO/DIS 9612 (1995) indicates how to estimate the daily noise exposure level of a worker using a sample composed of n measurements having a noise level $L_{Aeq,Ti}$, carried out with a specified integration time $T_{i.}$, where the total exposure time is,

$$T = \sum_{i=1}^{n} T_i$$

$$L_{Aeq,T} = 10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} 10^{L_{Aeq,T_i}/10}\right) \tag{1}$$

$$CL = t_{n-1}\sqrt{\frac{s^2}{n} + \frac{0.026 s^4}{n-1}} \tag{2}$$

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(L_{Aeq,T_i} - L_m\right)^2} \tag{3}$$

$$LCL = L_{Aeq,T} - CL \tag{4}$$

$$UCL = L_{Aeq,T} - CL \tag{5}$$

$$L_{EX,8h} = L_{EP,d} = L_{Aeq,8h} = L_{Aeq,T} + 10\log_{10}(T / T_0) \tag{6}$$

In the equations, L_m designates the arithmetic mean of the noise levels $L_{Aeq,Ti}$, s is their standard deviation t_{n-1} the value of Student's variable for n-1 degrees of freedom at a probability threshold of **95%,** T is the total duration of the daily exposure, and T_0 is the reference duration of 1working day (i.e. 8 hours). *LCL* and *UCL* are respectively the lower and the upper confidence limit of the $L_{Aeq,T}$.

These relations apply the ISO criterion of equivalence ("Exchange Rate") between the noise level and the duration, set at +3 dB when the duration is reduced by half. American regulations from the OSHA use the 5 dB criterion. With the OSHA criterion, the daily noise exposure level is calculated by replacing the "ISO" constant equal to 10 in equation (1) with the "OSHA" constant, which is equal to 16.61.

(EDITORS' NOTE: There is a new recommendation by NIOSH(1998) concerning the exchange rate, see Chapter 4)

Equation (2) is used to estimate the confidence interval of the average value, and was proposed for the case of a normal distribution of noise levels expressed in decibels to account for the fact that the addition of decibels is a complex procedure (Bastide, 1988). If the variance of the observed distribution is relatively small, the quadratic term in equation (2) has little impact and the relation becomes a classic estimator of the confidence interval of a normal distribution. Other methods that -use additive quantities exist, including the expression of the received noise as a percentage of the permissible daily noise dose (OSHA method), and transformation of decibels into energy - expressed as $(\text{Pascal})^2$ x(seconds) (ISO 1999 method). The calculation based on the energy method has been standardised (Germany, DIN 45641 , 1990), and includes an estimate of the confidence interval of the mean sound level.

Examples

A worker is exposed during 4 hours per day, 5 days a week, to a reproducible $L_{Aeq,T}$ level of 95 dB(A). Since he/she works 5 days a week, the concept of daily noise exposure level $L_{EX,8h}$ can be used and it is equal to $95 + 10\log_{10}(4/8) = 92$ dB(A).

Another worker is exposed for 10 hours per day, 3 days per week to a reproducible $L_{Aeq,T}$ level of 95 dB(A). The concept of $L_{EX,8h}$ is this time not applicable and the $L_{EX,w}$ must be used. Being exposed during 30 hours to 95 dB(A) is equivalent to being exposed 40 hours to a noise intensity which is 30/40 or 3/4 of the intensity corresponding to 95 dB(A). Since $10 \log(3/4) = 1.3$, $L_{EX,w}$ is equal to 95-1.3 = 93.7 dB(A).

7.1.2. Objectives of the Survey

The type and the strategy of measurement will depend strongly on the objectives of the survey. Four different objectives can be pursued:

1. the determination of the *noise emission* of a given machine or ensemble of machines;
2. the identification, characterisation and *ranking of noise sources;*
3. the verification that a given worker is or is not exposed to a noise level above the legal limits *(compliance);*
4. *the prediction* of the individual *risk* of hearing loss.

These four objectives and what they imply will be discussed briefly.

7.1.2.1. Noise emission evaluation

Standards are available for the determination of the noise emission of machines in general or of specific items of equipment. Methods are described which deal with sound power, sound pressure and sound intensity. These series of International/European standards include precision, engineering and survey grade situations. These measurements are usually rather sophisticated and require great experience. They will not be described here, but are the subject of ISO standards.

7.1.2.2. Ranking of noise sources

Control of noise at the workplace does not necessarily concern the noisiest sources, but those that make the largest contribution to the total exposure; this takes into account not only the noise level but also the duration of exposure and the number of people exposed.

It is therefore important to identify each source, or at least the most significant ones, and to establish the duration of exposure and the number of workers exposed.

7.1.2.3. Compliance

To check compliance of noisy areas with regulations, it is necessary to determine the $L_{EX,8h}$ or the $L_{EX,w} = L_{EP,w}$ according to the nature of the exposure. In this approach, the conclusions are as follows according to whether or not the noise exposure level exceeds or not the occupational exposure level (OEL = 85 or 90 dB(A) usually):

$L_{EX,8h} << $ OEL: the working conditions are acceptable legally

$L_{EX,8h} >> $OEL: the conditions are unacceptable and control measures must be implemented as soon as possible

$L_{EX,8h} \approx$ OEL: additional measurements are needed to determine whether $L_{EX,8h}$ is lower or higher than the OEL.

Paradoxically, if the objective is only compliance, more measurements are made if the exposure is around the OEL than when the exposure level is below or even above the OEL.

7.1.2.4. Risk evaluation

The ISO 1999 standard describes a model for the prediction of the distribution of the hearing loss at a given frequency, in a population of a given age, after a certain number of years of exposure to a $L_{EX,8h}$ level. From this standard, Figure 7.1 was derived; it gives, as a function of $L_{EX,8h}$, the percentage of the population aged 60 years, which, after 40 years of exposure, would develop mean hearing impairments (average 500 Hz, 1 kHz, 2 kHz, 3 kHz) greater than 25 dB.

The figure shows that the risk of hearing impairment increases quadratically as a function of $L_{EX,8h}$. Therefore, if the risk is to be estimated with a given accuracy (for instance $\pm$ 2%), the accuracy required for the evaluation of $L_{EX,8h}$ increases : for instance 88 $\pm$ 2 dB(A) but 94 $\pm$ 1 dB(A).

7.1.3. Types of Noise

It is useful to have available a typology of the exposure fluctuations to simplify the description and measurement of actual noise exposure. The nature, deterministic or otherwise, of the noise level variations and the amplitude of these-variations are the two essential points that must be known to define this typology. The importance of this data is illustrated by the examples presented below.

Any modification of the production, the alternating of activities such as deliveries, the maintenance of machinery, or the momentary use of extremely noisy machinery generally lead to fluctuations in the noise exposure conditions. Such varying factors are usually not random, and can be used to divide the exposure time into different intervals that correspond to particular activities.

Occasionally, relatively *rare acoustic events* occur, and can produce noise levels significantly higher than the average for a limited time during the work-day (e.g. a few minutes at levels of at least 10 dB(A) over the average level). Such events occur, for example, when an operator uses a compressed air blower to clean a machine or clothing at the end of a shift; when an individual is obliged to intervene in close proximity to a noisy installation; when metallic pieces are being hammered, etc.

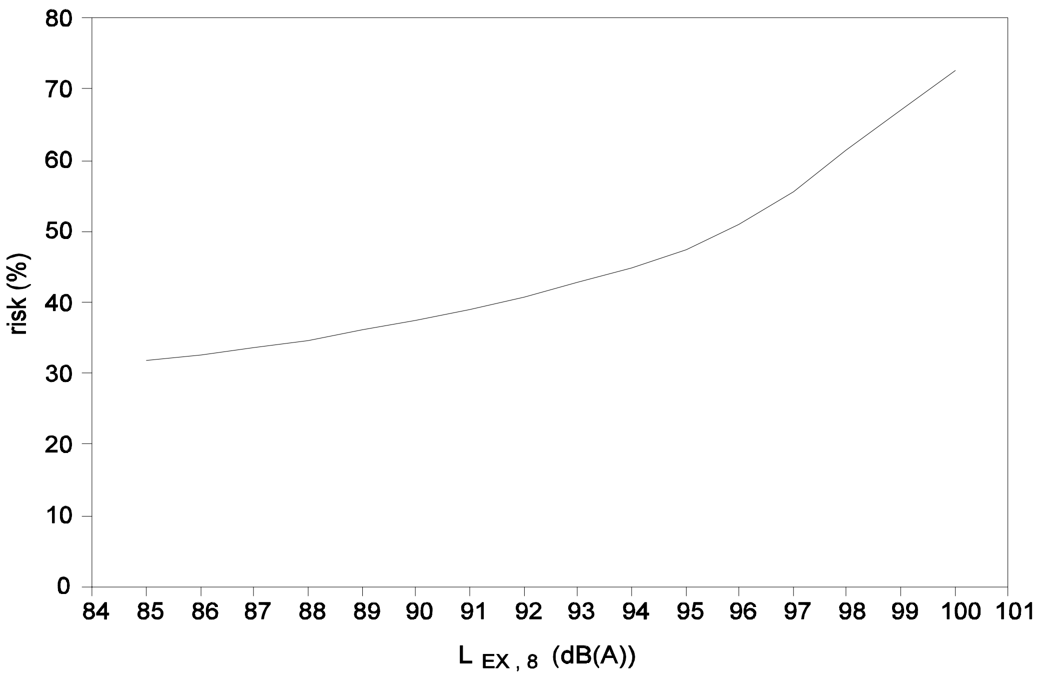

Figure 7.1. Risk of hearing impairment (mean 0.5, 1, 2, 3 kHz, deficit > 25 dB) as a function of the daily noise exposure level, $L_{EX,8h}$.

The importance of *rare acoustic events* in the measurement of noise exposure must be stressed. Even if the overall duration of such events is no longer than a few minutes, their contribution to the total daily noise exposure can be predominant. An example of this is given in Table 7.1 where a lathe operator in an engineering workshop periodically cleans the machine with a compressed air blower, thereby producing up to 105 dB(A). The average daily duration of these cleaning periods is estimated to be of the order of 5 minutes.

However, as see in the table, this type of cleaning can contribute 61% of the noise exposure, whereas the lathing, which is the principle activity of this worker, contributes only

Table 7.1. Example of a rare acoustic event: use of compressed air blower for the cleaning of a lathe.

Activity, *i*	Daily Duration	Relative Duration	Noise Level	8 hour Noise Exposure Level	Noise Exposure during Activity i	Relative Noise Exposure of Activity i
	T_i min	T_i/T_d (%)	$L_{Aeq,Ti}$ dB(A)	$E_{A,8h}$ $Pa^2.s.10^{-3}$	$E_{A,Ti}$ $Pa^2.s.10^{-3}$	(%)
1- Lathing	360	75%	84	2.89	2.17	35%
2- Cleaning with compressed air blower	5	1%	105	364	3.79	61%
3- Verifications	115	24%	80	1.15	0.28	4%
Entire day	480	100%	87.30	-	6.24	100%

The total noise exposure at this workplace is the sum of the 3 partial noise exposures. It is calculated using the quantities defined in the standard ISO 1999 (1990).

$E_{A,,8h}$: Noise exposure for an 8-hour working day, expressed in $Pa^2.s \times 10^{-3}$. The standard gives the correspondence table of this value with an equivalent noise level $L_{Aeq,8h}$ expressed in dB(A).

$E_{A,Ti}$: Noise exposure of activity *i*, calculated as $E_{A,Ti} = E_{A,8h} \times T_i/T_d$
(where T_d = 480 min or 8h)

The average noise exposure over the shift is 87.3 dB(A), which, because of the use of the compressed air cleaner, is higher than the permissible exposure level of 85 dB(A).

To make it easier to account for factors likely to create significant fluctuations in the noise levels, Thiery et al. (1994) proposed a typology of exposure situations that defines the 5 types of exposure illustrated in Figure 7.2, which include:

- exposure to a steady (or quasi-steady) noise,

- exposure to several steady noises, each having average levels separated by approximately 5 dB(A) and fixed durations,
- exposure to noise fluctuating in a repetitive cycle,
- exposure to a fluctuating noise that includes rare acoustic events that are predictable and easily identified,
- exposure to noise that fluctuates in a random, unpredictable manner.

N.B. A "steady" noise refers to a situation where, when each sample is integrated over a duration of one second (or using the "slow" setting on the sound level meter), the variations in the amplitude between samples are less than 5 dB(A).

7.1.4. The Three Steps of a Survey

As shown in Figure 7.3, the implementation of a strategy for the measurement of noise exposure that is adapted to different types of noise includes several steps. The first step consists of carrying out a preliminary study of the work place and the circumstances that govern the important variations in the level of noise exposure (Section 7.2). The second step deals with the definition of a measurement strategy and carrying out the measurements to quantify the noise exposures experienced by the workers (Section 7.3). The third step treats the interpretation of the results of the investigation (Section 7.4).

The justification for proceeding in the above manner is that it is impossible to know what exposure situations require special metrological efforts without a preliminary study. It has been shown (Damongeot, 1990) that "blind" sampling (i.e. noise measurements without any preliminary study) can lead to serious underestimation of the daily noise exposure levels (by up to 35 dB(A)) in the case of a rare acoustic event "forgotten" during the sampling). When the measurements reveal periods of over-exposure, it is necessary to not only evaluate the mean noise exposure level, but also to identify the causes of the over-exposure through a global analysis of the circumstances surrounding the real exposure.

7.2. PRELIMINARY SURVEY

As shown in Figure 7.3, related to the strategy for the evaluation of noise exposure, the preliminary survey has two particularly important objectives: to describe the circumstances surrounding the noise exposure; and to identify those factors which can cause systematic variations. A measurement strategy adapted to each exposure situation can then be developed based on this information.

The information required at this stage includes the number of exposed workers, the characteristics of their activities and the identification of any noise sources, the way in which the activities are organised and how they change as a function of time. This survey thus leads to the constitution of homogeneous exposure groups, and to the identification of characteristic time periods of the different exposure situations or stationary intervals, as proposed by Malchaire (1994).

It is also desirable to involve the workers in the preliminary survey in order to be able to take their real work situation into account, thereby rendering the study more complete and then validating the data collection scheme. Additionally, by associating the workers with the survey, they will be more aware of the risk of exposure to noise.

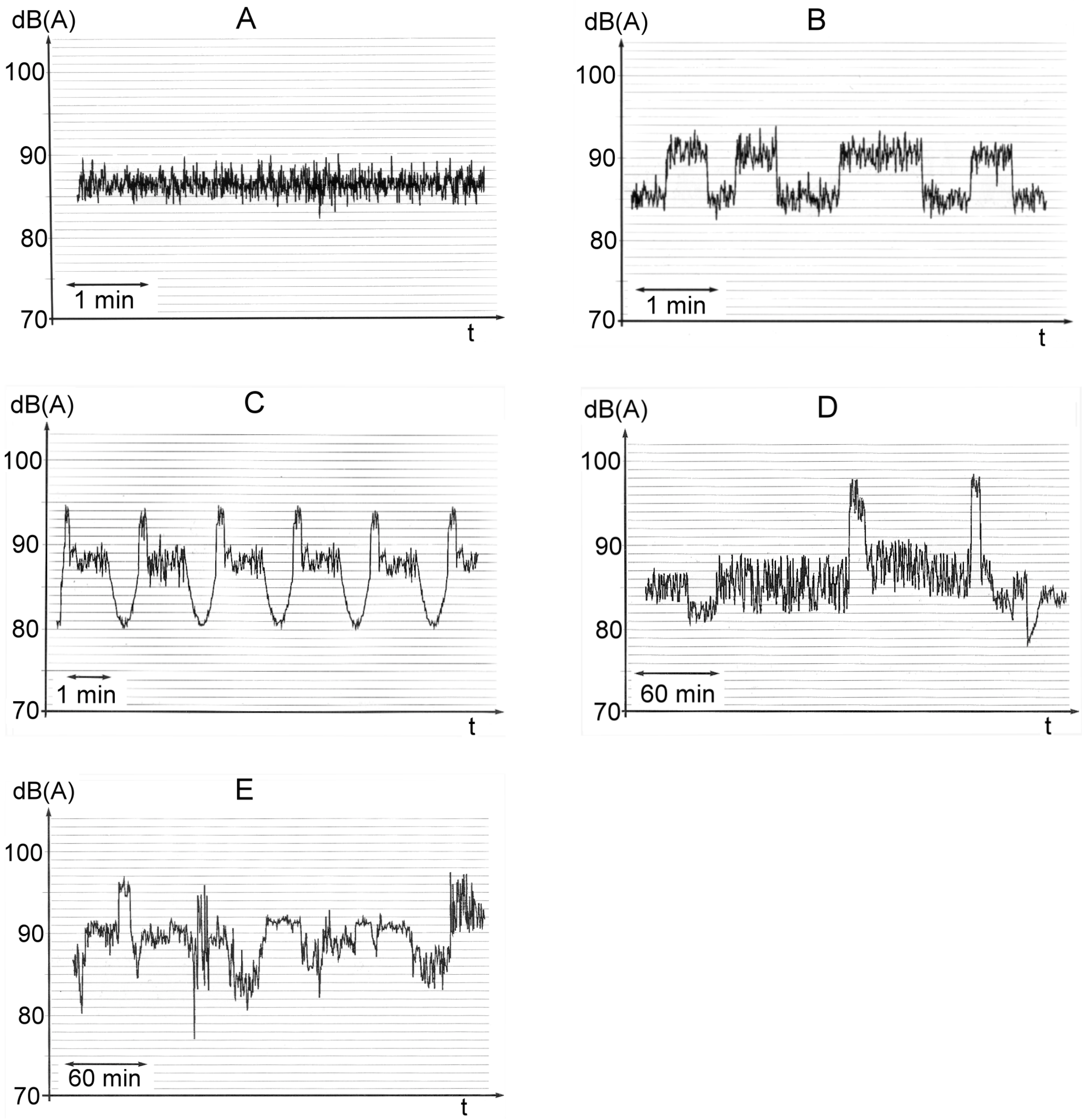

Figure 7.2. Typical noise types: (A) quasi-steady noise; (B) noise with various levels; (C) cyclic noise; (D) fluctuating noise with rare events; (E) randomly fluctuating noise.

If noise measurements made prior to the current survey are available, they can be used to specify the aspects on which the preliminary survey should focus. Otherwise, a few measurements can be made at this stage to evaluate the noise variations, or to estimate the different ambient noise levels of the different workshops. The only real objective of the measurements made at this stage is to prepare the way for the real exposure measurements that will be carried out during the second phase of the survey.

7.2.1. Location and Identification of Noise Sources in the Work Environment

In any workplace it is essential to tour the premises with the assistance of someone familiar with the premises and the working practices.

Before doing any analysis, it is useful to identify the type and position of the different sources of noise that are present in the workshop. Locating any fixed machinery likely to be noisy will be made easier through the use of the plans of the layout of the workshop. This identification will also include any mobile machinery or vehicles, manual operations that cause noise, and of course, any operations, machinery or actions likely to cause rare acoustic events.

The machinery will generally go through several different operating modes during the working day for the following reasons:

- production can change from one day to the next;
- a given fabrication process can include many steps;
- machine settings can be altered;
- there can be alternating shut-down and production phases, etc.

Noise level fluctuations can be observed during a single working day, or over the course of several days. Knowledge of the different operating cycles of machines is necessary in order to evaluate their probable impact on the noise exposure of the workers, and to define a measurement strategy that can account for such non-random variations.

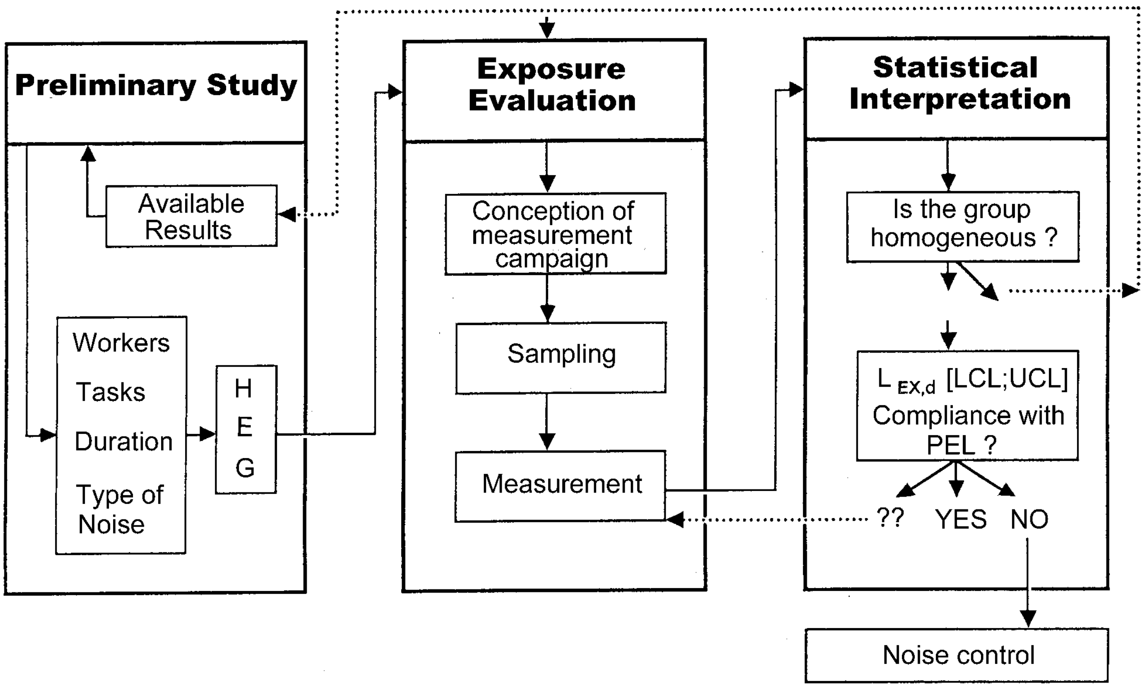

Figure 7.3. Steps in the measurement of the noise exposure of workers.

HEG:	**Homogeneous Exposure Group**
$L_{EX,d}=L_{EX,8h}$**:**	**Daily Sound Exposure Level**
PEL:	**Permissible Exposure Level**
LCL:	**Lower Confidence Limit of Daily Exposure Level**
UCL:	**Upper Confidence Limit of Daily Sound Exposure Level**

It is essential to have a workshop plan during the tour in order that information given can be transferred to the plan. The tour will also identify those areas where noise appears to be high and where noise appears to be a problem as perceived by the operators; in this instance the various operators need to be involved with the discussions. Again this information can be transferred onto the plan.

In addition, the person carrying out the survey can identify those machines he or she perceives as giving rise to high noise levels which can be identified and noted on the plan for inclusion in the noise assessment.

Following completion of the initial tour, it is advisable to obtain agreement with managers and employees that the conditions encountered are normal/average for a days activity. This should form the basis for discussion in establishing the working system seen during the tour and an analysis of the working patterns; in particular in relation to those operators who have been previously identified as being included as subjects of the measurements for the noise assessment. The information gathered can be used for a variety of purposes such as:

- establishing high noise areas;
- identifying individual noise sources and their character;
- identifying the areas/machines making contributions to the exposures of persons;
- creating a plan in order to decide what to measure and how to measure and for how long;
- deciding whether individual operators can be assessed or whether one operator can be assessed as representative of a group or whether an area can be assessed and the information applied as representative of all operators in those areas; and
- choice of the instrumentation to be used

Too much information is not a problem; any excess can be discarded at the report stage.

7.2.2. Work Analysis

The objective of the task analysis is to precisely define the characteristics of the different exposures and to identify those factors responsible for any variations in the noise exposure. Four factors are essential to this:

- the situation of the operators (fixed post, mobile post inside fixed zone, no fixed post, etc.);
- the nature of the tasks carried out by each worker (or group of workers), and the temporal breakdown of these tasks;
- the worker's environment, which also depends on the activities of neighbouring workers; and
- the type of noise exposure, including, in particular, the identification of rare acoustic events likely to cause exposure to intense noises of short duration.

Frequently, a working routine includes habitual, stable activities, as well as non-habitual activities such as *intervention* on the machines, tuning or cleaning of machinery, etc. The task analysis must then include both types of activities since the non-habitual activities often increase the noise to which an individual is exposed.

To make sure that the investigator collects all of the necessary information, several methods have been developed (e.g. Royster et al., 1986; Gamba et al., 1992; Malchaire, 1994; Thiery et al., 1994). Two notices outlining the information judged indispensable at this stage are shown in Tables 7.2 and 7.3 (from Thiery et al., 1994).

When the individual workers are carrying out clearly distinct tasks, it is necessary to make a list of these tasks and to specify the nature of each one, the average amount of time spent per day on it, and the type of noise exposure. If the duration of these tasks varies from one day to the next, an estimate of the medium-term average duration is needed.

7.2.3. Noise Characterisation

Two types of qualitative information on the noise exposure are useful to prepare the measurement strategy, and to choose a measurement method:
- the type of noise encountered
- the level of the risk involved

7.2.3.1. Type of noise

When conducting noise surveys it is important to establish the character of the noise source, which will depend on the working environment under consideration. Prior knowledge of the character of the noise being assessed is critical when selecting the most appropriate measuring instrumentation. Noise can be characterised by the following terms:

- **Steady-Continuous**; e.g. cotton/textile mill where there is little variation in perceived level.
- **Non steady-fluctuating**; e.g. woodworking mill (particle board process) where the level rises sharply when boards are being cut; concrete block machines.
- **Impulsive and impact**-drop forge, hammer mill, power press shop.
- **Broadband**-constant energy in all frequencies (e.g. bottling plant).
- **Narrow band**-energy confined to discrete frequency.
- **Tonal**-Discrete low or high frequency.
- **Sudden bursts**-High energy and short duration.
- **Infra sound**-sound at frequencies below 20 Hz.
- **Ultra sound**-sound at frequencies above 20,000 Hz.

Many work environments represent combinations of the above noise types; for example, a metal working shop would have impact noise and broadband noise. During the preliminary survey, the plan of the premises can be used to identify those areas which have different noise characteristics.

The capability of instrumentation varies enormously and it is of extreme importance to select the instrumentation capable of capturing and analysing the noise source under consideration in order that the total sound energy making up the personal exposure is measured correctly. The instrument chosen must have the appropriate response capability. Most grade 1 meters have these capabilities but it may be that the use of tape-recorders will allow measurements to be carried out for analysis later.

Table 7.2. Example of a notice summarising all of the information relative to the population of exposed workers, by type of exposure.

WORK/TASK ANALYSIS
to guide the noise exposure measurements

Notice 1: GROUPS OF EXPOSED WORKERS

This step deals with each of the workshops where noise is a problem. Its purpose is to identify groups of workers having similar activities, and those having specific activities.

In order to examine the different types of noise exposure, it is necessary to proceed step by step, taking into consideration 4 activity-related factors: the principle task, the time frame of the job, the location of the activity, and its nature.

1 - Distribution of the staff as a function of their principle activity:
Production/Handling/Maintenance/Other

2 - Distribution of the staff as a function of the working time:
Day shift/Night shift
Other specific times

3 - Location of workstation:
Fixed work places:
position on plan,
personnel concerned.
Surveillance of limited zone:
outline the limits on workshop plan,
personnel concerned.
Work places very mobile:
outline paths, zones of activity,
personnel concerned.
Located in many different sites:
List of different activities,
personnel concerned

4 - Nature of activities carried out at each work place:
Nature of the tasks really performed including the different production steps.
Personnel concerned.

Using this information:

- Regroup the workers (or work places) according to the type of exposure and define homogeneous exposure groups.
- Make a list of those workers having specific tasks.
- Verify that all exposed workers are accounted for.
- Evaluate each of them using Notice (2) based on the analysis of the circumstances of the noise exposure.

Table 7.3. Example of a notice summarising the information describing the circumstances of an exposure situation, used in preparing the measurement strategy.

WORK/TASK ANALYSIS
to guide the noise exposure measurements

Notice 2: ANALYSIS OF THE CIRCUMSTANCES OF THE NOISE EXPOSURE

For those workers having similar activities, or for those having specific activities, examine all of their task in order to identify the factors that determine the noise exposure and its variations as a function of time.

1 - Identify the nature of noisy activities

a) During normal activities:
- Use of machines, tools, vehicles...
- Noisy manual operations.
- Noise caused by activity at neighbouring work station.
- Noise caused by fixed equipment (conveyors, compressors,...).

b) During exceptional activities:
- Tasks carried out at the beginning and end of production (re-supplying, tool changes, trials, adjustments, product removal, repairs, etc).
- Cleaning.
- Repairs (Unblocking, etc).
- Periods of heavy maintenance.

c) Identification of any eventual *rare acoustic events:*
- Use of high flowrate compressed air blowers.
- Presence of compressed air vents (valve outlets, compressor purges, etc).
- Occasional metallic shocks (straightening, hammering etc).

2 - Situation of noisy activities during the work shift

a) During normal activities and exceptional tasks:
- How are the different activities spread out over the working day?
- What is their average daily duration?
- When can important changes in noise exposure occur?
- If the shop activity is cyclic, what is the average duration of a cycle?

b) If activities are not regular:
- What activities, machines or operations are supposed to be the noisiest?
- When do they occur?
- How long do they last?

c) If rare acoustic events do occur:
- When do they occur?
- How long do they last and what is the daily frequency of these events?

7.2.3.2. Level of risk

Use of a three level risk scale provides guidance for the assessment of the level of risk.

Level 1
Daily noise exposure level definitely below 85 dB(A), the limit value generally recommended in hearing protection.

Level 2
Intermediate risk, lying between Levels 1 and 3.

Level 3
Daily noise exposure level definitely over 90 dB(A), the value for which it is recommended that technical measures should be taken to reduce noise exposure.

This scale is interpreted as follows:

- For level one, exposure measurement is not needed if it is essentially certain that the limit value will not be exceeded. However, if there is a slight doubt, or if impulse noises can occur, then the situation should automatically be classified as Level 2.

- For Level 2 cases, it is likely that an over-exposure will occur. Exposure measurements are therefore necessary, and must be sufficiently precise (to within " 1 dB(A)) so that it is possible to conclude whether or not the limit exposure value has been exceeded.

- Over-exposure definitely occurs in Level 3. Exposure measurements must be carried out as in Level 2. However, in the event that the exposure exceeds the limit value by more than 5 dB(A), the precision can be relaxed a bit.

7.2.4. Homogeneous Exposure Groups

In many workshops, it is possible to split the population into Homogeneous Exposure Groups (HEG); i.e. groups of workers exposed to noise in conditions that can be considered similar. This method (Leidel et al., 1977; Hawkins et al. 1991) is typically used in industrial hygiene in order to reduce the number, and therefore the cost of exposure measurements. Different authors have proposed using this technique in the evaluation of noise exposure (e.g. Royster et al., 1986; Gamba et al., 1992; Malchaire, 1994; Thiery et al., 1994).

The definition of homogeneous exposure groups is based on the data collected during the task analysis discussed above. The objective of this stratification is to divide the workers up into the largest groups possible in such a fashion that there are no systematic exposure variations between the members of the group. This last constraint often leads to HEGs being defined for a specific task, and to the workers being classified into an HEG according to the specific exposure durations or to different stationary time intervals.

Certain workers are obviously exposed to variations in the noise level which cannot be foreseen. These could include setters, adjusters and maintenance staff etc.. These individuals cannot be put into a group with the other workers *a priori*, and individual, repeated measurements must therefore be made for them.

If the workshop consists of a variety of machines all performing different tasks then there will be a need to measure at all machines and all operators. However if there are many operators in an area and all are affected by noise from one machine or process then it may be possible select one or two operators who are representative of the group.

In situations where many operators are working in a defined area and their activities require many movements it is reasonable to establish exposures on an area basis and apply the same level of exposure to all.

Agreement needs to reached with all personnel involved, whatever strategy is adopted.

7.2.5. Definition of Measurement Times

There are two specifications concerning the measurement of the daily noise exposure level contained in the standards ISO 1999 (1990) and ISO/DIS 9612 (1995):

- use as a reference the duration of one working day, fixed by convention at 8 hours,
- choose the duration and distribution of measurement periods in order to encompass all of the important variations in the noise levels at the different work stations.

To apply these specifications, one needs to estimate the importance of any variation in the noise exposure. This is precisely the goal of the typology of noise exposure situations presented above (see Sections 7.1.3 and 7.2.3), and indicates how to account for production cycles, rare acoustic events, activity changes, etc.

When the exposure is stable from one day to the next, i.e. no variations greater than 5 dB(A), the measurements can be spread out over a single day. However, this generally is not the case, and it is thus preferable to spread the measurements out over the course of at least three working days or three stationary time intervals.

In contrast, when the preliminary survey reveals that important variations can occur from one day to the next, it is necessary to spread the measurement intervals out over as many working days as possible.

If rare acoustic events are detected during the preliminary survey, or if an excessive noise exposure situation is likely to occur during the course of non-habitual activities (e.g. adjustments, intervention in case of incident, etc.), a specific exposure measurement must include these specific exposure intervals.

The need to establish the type of noise will affect the type and complexity of instrumentation necessary for exposure assessments.

All sounds resulting from operation of the machines or process must be included in the measurement irrespective of their character, level and event time

Using the plan of the workplace (which identifies workstations and machines etc.) the positions to be used for measurements should be agreed upon. Measurements should be obtained at worker positions preferably without the worker present, but if this is not possible then at 0.10m from the ear of the worker.

There is no need to measure over the full working day but measurements must reflect the normal operating cycle of the process; i.e. all noises present during normal operation must be included in the cycle duration chosen.

The total daily exposure, i.e. $L_{Aeq,8h}$,can be assessed by obtaining a sample L_{Aeq} if the operator spends all 8 hours at the same location. If operators need to move about then measurements must be split into samples; i.e. all activities will have a sample L_{Aeq} and a time period associated with it. Under these conditions the L_{eq} value can be calculated using:

$$L_{Aeq} = 10\log_{10}\left\{\frac{1}{T_0}\int_0^{T_e}\left[\frac{p_A(t)}{p_0}\right]^2 \mathrm{d}t\right\}$$

where : L_{Aeq} = equivalent continuous sound level ,
T_0 = total working period (usually 8 hours)
T_e = exposure period (hours)
$p_A(t)$ = time varying instantaneous A-weighted sound pressure (Pa)
p_0 = 20 µPa
t = time (hours)

Some examples of representative exposure periods are as follows:

Operator of a Band resaw
At machines of this type it is usual to measure over the period needed to cut say four lengths of wood of the average processed. If different lengths of wood are processed (this means that the dominant noise level; i.e. that during cutting will exist for longer periods with long lengths) then there is a need to make an assessment of the average cutting times. In addition, if the operator and his assistant are responsible for moving processed material and replenishing stock to be processed, then these activities need to be included in the assessment period.

Operator of Power Press
At a machine of this type the measurement period should be representative such as to include all activities the operator carries out to process a batch of material; e.g. if the press is oil /automatically fed then a representative cycle can be chosen such as that required to process a coil of material or a portion of it.

If the operator is responsible for replenishing material then this activity should be included in the period of measurement.

Operator at a position on a continuous process line.
At positions such as these the measurement period should cover the time to process a complete batch of material, particularly if stock needs to be replaced.

Under general conditions a period of 10 minutes would normally suffice unless the preliminary tour identified circumstances where longer measurements were necessary.

Varying cycles of operation or transient workers
In situations in which cycles of operation are not repeatable and longer measurement times are necessary, then measurements should be carried out using logging dosimeters, unless the activities can be split into identifiable samples. In addition, if the operator is continually changing his or her movements, then again there may be a need to use logging dosimeters for the measurements. If logging dosimeters are used it may be necessary to select more than one operator (carrying out similar tasks) to support assessment results.

7.3. EXPOSURE EVALUATION

The measurement of the actual noise exposure is the second step in the evaluation procedure presented in Figure 7.3. The measurement strategy is designed, and then measurements are carried out using as a basis the data collected during the preliminary survey.

Depending on the circumstances of the workshop/site to be evaluated; i.e. the size/type, the machines/processes in use and number of persons employed, the system of measurement and the gathering of information needs to organised to achieve the desired results. A strategy needs to be developed, which cannot be done unless, prior to measurements, it is known which workplaces are of interest, which machines are in use and which operator positions and activities need to be included in the assessment. This can only be done after establishing with the workshop manager and operators/machinists that the activities on the day of the assessment are typical of a normal day's work.

7.3.1. Design of the Measurement Strategy

Occupational noise exposure is generally characterised by two factors: a large exposed population, and an exposure duration that can extend over the course of many working days**.** Under these conditions, the measurements can only be carried out for a well-defined sample of workers, during specific exposure intervals (for a given sample), using appropriate materials and techniques. The goal here is to minimise the number of measurements that have to be made to guarantee their representativeness, given the changes in activity and exposure identified in the preliminary survey.

It is essential to draw a plan of the workplace which identifies the machines/processes in use, the operator positions associated with the machines/processes and any other persons engaged in work activities. Information, relating to numbers of employees and their respective duties/tasks should be identified and logged; it is also essential to obtain the hours of exposure of each employee to each task/duty. It would be beneficial here to obtain agreement from each employee and the workshop manager prior to data collection.

Agreement on the information above is essential if the results of the exposure assessment are to be considered as representative of a normal day's activities.

7.3.1.1. Choice of equipment

Having gathered the information detailed above, the appropriate instrumentation needs to be selected (see Chapter 6).

If the system of work is such that operators work at one machine only and do not move about in general then measurements can be taken alongside each operator. In some cases simple sound level meters will suffice, but if the cycle of operation of a machine is variable then there will be a need to use instruments capable of measuring L_{Aeq} (A-weighted equivalent continuous noise level) or tape recorders which will record the noise during each cycle of operation with the tape available to be analysed at a later date in the laboratory/office. However if operator activity is such that they need to move about the workshop continually and these movements bring operators into contact with many noise sources for varying lengths of time, then the most convenient instrumentation will be Noise Dosimeters, which will log each person's noise exposure on a continual basis and indicate an overall exposure level as a percentage dose.

100% dose equates to 90 dB(A) in most countries.

Extreme care is required to ensure that the correct exchange rate is built into the meters. The current exchange rate in most countries is 3 dB; however in some countries a 5 dB exchange rate is used.

With the 3 dB exchange rate a dose of 100% equates to 90 dB(A) and 200% equates to 93 dB(A) where as with the 5 dB exchange rate 200% equates to 95 dB(A)

The personal dosimeter, (or personal sound exposure meter) worn by the subject, is indispensable in instances where the worker's activities include numerous and frequent movements, when work is done in confined spaces, or when the characteristics of the exposure are unpredictable. In other, more regular and more predictable exposure situations, an integrating sound level meter, operated by a technician, is sufficient .

The equipment used must provide two results: the value of the daily noise exposure level, and the number of times the regulatory sound pressure level was exceeded. They should also conform with the technical characteristics specified in standard ISO 9612 :

- Personal-dosimeter conforming to the standard IEC 61252, and equipped with an overload indicator;
- integrating sound level meter, class 2 minimum (IEC 60804).

7.3.1.2. Measurement strategy

Three procedures are available for the use of measuring devices, the characteristics of which are outlined in Figure 7.4.

a) Continuous measurements
Every exposure interval is continuously measured using a dosimeter worn by the subject.

b) Sampling measurements, directed by an operator.
The operator responsible for the measurements chooses when to begin sampling during the measurement process, and carries out the measurements using an integrated sound level meter Each measurement lasts at least a few minutes, but a sufficiently large number of measurements is taken.

c) Random sampling
The random selection of measurement times during the observation intervals is one of the recommended methods of obtaining representative samples. A sufficiently large number of data points is taken (at least 10), and it must be verified that there are no systematic, non-random variations among the measured noise levels.

How does one choose the method that is best adapted to the exposure situation at hand?

Continuous measurements using a personal dosimeter can always be used. It is also the only method adapted to situations where the workers are highly mobile, or when they operate in confined spaces.

Sampling with an integrated sound level meter can be a sufficiently reliable method when exposure situations vary little as a function of time. Guided sampling techniques can be used in situations where the noise exposure has been previously evaluated and where there are some data available that can be used to avoid any bias in the sampling introduced by the operator's selection of measurement times. Random sampling methods can be used for a wide range of applications,

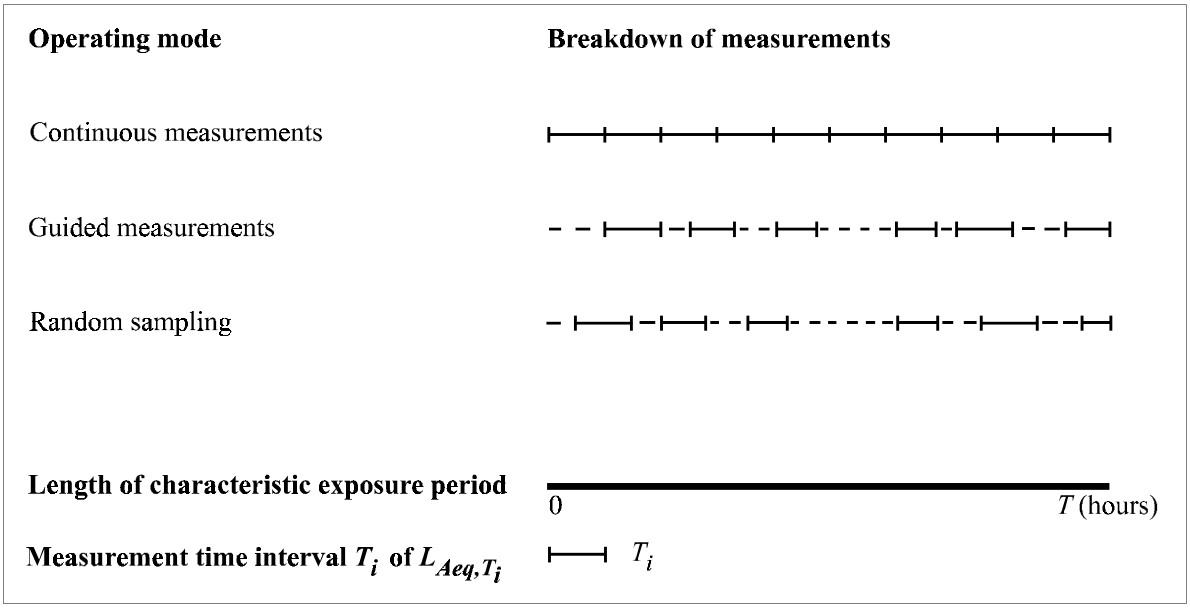

Figure 7.4. The three available operating modes for the measurement of noise exposure.

but are the most difficult to implement.

Noise measurements/surveys are carried out to establish/identify on a workplace basis the type, the nature and the extent of the noise problem. The decision on where and what to measure will be based on the information gathered in relation to Section 7.2.

Some guidelines are outlined in the following paragraphs:

a) Individual operators who work at one machine all day:
Measure alongside the operator as near to the ear as possible without impeding his/her task. The measurement period should be such that any variation in noise level over a full operating cycle of the machine should be included in the measurement period. It is always useful to repeat measurements for confirmation.

b) Operators in a group who carry out similar tasks:
Select a typical operator and measure as in a) above. The measurement period should be such that all activities carried out by the group are included in the period. It would be useful here to carry out repeat measurements but using a different operator.

c) Operators who move about the workshop/process and as a result are affected by many noise sources:
It will be necessary here to use noise dosimeters attached to a person who represents a typical operator in relation to the tasks being performed. The dosimeter should be attached to the person with the microphone clipped to the collar or lapel of their overalls/working clothes. Use two operators as measurement subjects.

7.3.1.3. Sample characteristics

The sample of workers included in the measurement campaign should include the following:

- all of the workers (or work stations) exposed to complex, highly variable, or highly specific conditions, and whose cases should be treated individually;

- a sufficiently large number of workers, selected at random from each of the homogeneous exposure groups defined during the preliminary survey.

Defining the optimal sample size for each homogeneous exposure group *a priori is* a delicate task that depends on several factors: the size of the group itself, the desired precision of the estimate, the predicted amplitude of the fluctuations in the noise level, and the variable to be estimated. An example of this is shown in Table 7.4 (from Leidel et al., 1977), which contains the sample size "n" needed to obtain from an homogeneous exposure group a sample which includes at least one worker among the 20% of the most exposed.

Table 7.4. Sample size "n" needed to ensure (at a 95% level of probability) that the sample will contain at least one worker in the top 20% of the exposed population constituting an Homogeneous Exposure Group (HEG) of N workers.

Size of HEG N	N > 7	7-8	9-11	12-14	15-18	19-26	27-43	44-50	N > 50
Sample size n	n = N	6	7	8	9	10	11	12	14

The working time sampling is based on the position and duration of the time intervals, identified as being representative of the noise exposure of the different tasks identified during the preliminary survey.

When the integration time constant of the measurement devices used is adjustable, it is better to use a smaller value and an increased number of measurements in order to obtain a total specified measurement time since it is easier to detect high exposure levels that last only a very short time. An important point of practical interest to note when carrying out the measurements is that the integration time constant must remain constant from one sample to the next. If **not,** the variances of the measured values cannot be compared.

The sampling itself is necessarily associated with a method for the analysis of the results that includes the validation of the sample. This point will be discussed in detail below (Section 7.4), but the analysis might require an increase of the sample size already analysed, or a modification of the sampling design.

7.3.2. The Measurement Survey

This section details the measurement procedures necessary to complete the exposure evaluation.

7.3.2.1. Preparation

The measurement survey should be carried out with the objectives clearly defined and understood by all parties and maximum cooperation given to the survey team, the resulting report will be beneficial to all concerned and the information gathered can be used for a variety of purposes such as:

- establishing exposures;
- establishing high noise areas;
- ranking of individual noise sources;

- establishing noise contours;
- identifying noise control requirements on an area/machine basis;
- identifying the areas/machines making contributions to the exposures of persons;
- identifying hearing conservation requirements;
- creation of records of noise levels, high noise areas and personal exposure patterns;
- basis for later review.

The calibration of the instrument must be verified (ISO/DIS 9612) on-site, before and after each series of measurements, using an acoustic calibrator that conforms to standardized specifications (CEI 942, class 2 minimum).

If a noise dosimeter is being used, the worker who will be wearing the device should be informed of any precautions related to the use of the device. The microphone attachment should be placed in a stable, non-hindering manner on the individual's shoulder, or on the edge of a protective helmet.

Note: It is recommended that prior to starting measurements the following check-list procedure is followed.

CHECKLIST

- has a site plan been produced?
- are all sections identified?
- are all machines/processes correctly identified and located?
- are all personnel identified and allocated in their respective locations?
- have all areas been classified for type of noise?
- is the appropriate instrumentation available?
- is the instrumentation in good working order?
- are there sufficient batteries?
- is the calibrator functioning properly?
- is the microphone un-damaged?
- have the instruments to be used been checked for calibration /response within the prescribed period?
- is there adequate supply of information sheets for the number of personnel and activities?
- are the conditions in the workplace representative of normal activity?
- have all areas with noise levels above recommended limits been identified?
- has adequate and effective hearing protection been chosen and allocated to personnel on the basis of the results of the preliminary survey?

7.3.2.2. Measurements

Measurement requirements should be known to all survey personnel and data sheets indicating all previously gathered information completed before measurements commence. All data required to be obtained should be known by all personnel with the ultimate objective to obtain accurate and justifiable levels of personal noise exposures. Personnel should also be familiar with national exposure limits; i.e. daily exposures and peak levels and sufficient measurements should be made to facilitate comparison. These comparisons will indicate which personnel are at risk; i.e. likely to be affected by Noise Induced Hearing Loss (NIHL).

The position of the measuring microphone is very important during the exposure evaluation. The microphone must follow the worker under evaluation in all areas where his/her activities take place. This type of immission measurement is different from area measurements, or from emission measurements (ISO 11690-1). The standard states that the microphone of the measuring device be maintained between 10 and 30 cm from the subject's ear (ISO 9612). If an integrating sound level meter is being used, the operator responsible for the measurements must make sure that this distance is respected in order to avoid any systematic errors.

It is possible that peak sound pressure levels will saturate (overload) the measuring device. If this occurs, it is preferable to discard the measurements and begin again with another instrument, or reset the controls (amplifier gains) of the current device in order to avoid saturating it.

Note - Following all measurements there is a need to check the meter response by re-calibrating the instrument. If there is any significant change in the calibration level, then all measurements just completed will need to be repeated and the batteries will need to be replaced.

When using integrating sound level meters the meter should be reset after every measurement,

7.3.2.3. Recordings

All measurements taken should be recorded on data sheets together with information relating to machines, operators, activities, conditions, locations and measurement times. In addition, all equipment used, together with model and type numbers, calibrators used and dates of last calibrations should be noted.

When listing data from measurements, any extra relevant information should also be recorded. This information should be part of the final report and should be made available to all interested personnel.

The detailed information recorded with each measurement should complete the information obtained during the preliminary survey, and should include:

- the identity of the worker and eventually that of his/her homogeneous exposure group,
- the date and time of the measurement, and the measurement time interval,
- the type of work being done,
- any observations that might help explain eventual variations in the noise level,
- the characteristics of the measurement device used (identification, frequency and time weightings),
- the results obtained (equivalent noise level, peak sound pressure level (C-weighted) and number of times the threshold value was exceeded).

The use of a C-weighted peak resolves a long standing problem with measurement of the peak. The term "unweighted peak" is undefined. Without specifying the low end cutoff frequency of the measurement devices, measurements with different devices could vary greatly. For example, an innocuous car door slam might cause a unweighted peak greater than 140 dB on some instruments but not on others. Use of C-weighting defines the frequency response of the instrument and eliminates very low frequency impulses and sounds. The C-weighting discounts such sounds. Thus, the harmless effect from a low-frequency impulse that comes from closing a car door or other such innocuous very low-frequency impulses can be more properly assessed. Infrasound exposures (exposures below 20 Hz) will also be better assessed. Such exposures are rare and, even if they could occur, are not likely to be dangerous, at levels found in industry directly, to a person's hearing or health

7.4. INTERPRETATION AND REPORTING

All information collected, resulting from carrying out the measures outlined in 7.3.1 and 7.3.2 will allow decisions to be made on the aspects discussed in the following sections. The method for the interpretation of the results must validate the measurements carried out; indicate whether or not the limit value was exceeded; and evaluate the hearing hazard created by the noise exposure.

7.4.1. Validation of Results

Before drawing a conclusion relative to the exposed population from data collected in a sample it is necessary to ensure that the statistical hypotheses used in the sampling design were not rejected. To achieve this goal the following statistical tests can be used (Malchaire, 1994).

a) a correlation test to verify the temporal independence of the measured data
b) an analysis of variance, or comparison of the observed distribution to a normal distribution to validate the homogeneity of the exposure group.

The methods of analysis mentioned here are available in a range of statistical software. However, to make them somewhat more accessible in the area of industrial hygiene, new software packages are being made available (e.g. the ALTREX software package presented by Despres et al. 1995).

A statistical analysis can lead the investigator to one of several choices, shown schematically in Figure 7.3:

- the results obtained are conclusive,
- the series of measurements carried out were too scattered to allow a clear conclusion to be drawn.

If it is not possible to decide whether or not there is an over exposure, two solutions can be envisaged:

- continue the series of measurements, or
- redesign the sampling if a new factor could explain a part of the observed variance.

7.4.2. Compliance

In addition to establishing the exposures of all personnel in the workshop and whether they are at risk the information allows the company to assess whether they are complying with national regulations.

Exposure level limits and the actions required to be taken at the various levels differ from country to country; however, whatever levels are set national legislation requires compliance in some form. Take the example of the European Directive 86/188/EEC, this Directive which requires that member countries put in place certain actions if exposure levels are in excess of certain levels. These levels are: "1st action level 85 dB(A) $L_{EX,8}$ (= $L_{EP,d}$, daily personal noise exposure)"; "2nd action level of 90 dB(A) $L_{EP,d}$" and a "peak action level of 200pascals (140 dB(C))". To comply with this Directive, member countries would, following an assessment of exposure levels, take certain actions and would need to implement certain procedures and controls. Where there are no clear regulations in place, ISO/DIS 9612-1995 may be used.

The statistical interpretation of whether or not the regulatory thresholds have been exceeded can be performed as follows:

- there is no over-exposure if the upper confidence limit of the daily noise exposure level is less than the limit value;

- there is over-exposure if the lower confidence limit of the daily noise exposure level is greater than the limit value;
- the results are inconclusive between these two limits. In this case it is preferable to continue with the measurements or modify the sampling design to reduce the width of the confidence interval and to obtain a more conclusive result.

Although there is a general duty requirement to reduce the risk of hearing damage, there is no defined level at which this is to be carried out, as it is considered to be a general duty if a risk is present. Actions to be taken are then associated with various levels of exposure; i.e. if in excess of 85 dB(A), then hearing protection would need to be provided for all personnel so exposed.

Additionally if noise exposure levels were in excess of 90 dB(A) then hearing protection would need to be provided and measures taken to ensure its proper use. Also at this level and in excess of this level, noise control is required with a view to reducing exposures.

The overall aim of legislation is reduce, prevent or control the risk of Noise Induced Hearing Loss (NIHL) to employed people.

7.4.3. Evaluation of the Risk of Hearing Impairment

Again there may be different attitudes to risk of NIHL; however in the UK, research carried out to support the legislation (produced to implement the European directive 86/188/EEC) and also research carried out to assess the effects of the proposed Directive, provided information on percentages of populations likely to suffer varying degrees of hearing loss depending on noise exposure level and length of exposure in years; see for example Tables 7.5 and 7.6.

The risk of hearing loss in a population of workers exposed to a continuous equivalent noise level ($L_{Aeq,8h}$) of between 85 and 100 dB(A) is described in the standard ISO 1999. The description of the risk is given in statistical terms, and varies as a function of the following parameters: age, sex, exposure duration and noise level. In an homogeneous population, the evaluation of the risk of hearing loss supposes that these parameters are known.

It is occasionally necessary to reconstitute a medium-term mean noise exposure level by associating different work stations with specific exposure durations. If each work station "*i*" is exposed to a level $L_{Aeq,Ti}$ in dB(A) for a relative duration D_i (in%), the reconstituted noise level is:

$$L_{Aeq,T} = 10\log_{10}\left(\sum_{i=1}^{n} \frac{D_i}{100} 10^{L_{Aeq,T_i}/10} \right)$$

7.4.4. Evaluation of The Risk of Non-auditory Effects

Exposure to high noise levels may not produce NIHL but high exposure could produce many other effects. Non-auditory effects of noise may be many but some effects have been the subject of studies on the health and well-being of workers in relation to performance ,efficiency and safety.

Noise can contribute to fatigue, loss of concentration and absenteeism, some aspects of these effects are as follows:

- influence on cardiovascular function
- increase in response time
- decrease in speech recognition
- decrease in the quality of work
- influencing the ability to hear warning sounds and resulting effects on safety
- disturbance of sleep-leading to deterioration in health

Research will continue in this area and other non-auditory effects may emerge for consideration.

Table 7.5. Hearing loss expected in a typical unselected mixed male/female population exposed to noise continuously from 20 years of age. (Based on HSE Contract Research Report No2/1988, with extrapolations.)

Level (dB(A))	Exposure duration - years						
	10	15	20	25	30	35	40
115	36+	58+	70+	82+	95+	100+	100+
105	20+	35+	47+	60+	70+	83+	92+
97	8	16	26	35	46	57	70
92	2+	7	13	20	28	37	49
87	0+	1+	4+	9	14	21	31
82	0+	0+	0+	1+	7+	10+	19+
no noise exposure (take as 75dB(A))	0+	0+	0+	1+	7+	10+	19+

1A : % exceeding 30 dB hearing threshold level

Level (dB(A))	Exposure duration - years						
	10	15	20	25	30	35	40
115	11+	16+	38+	46+	54+	64+	73+
105	2+	5+	11+	16+	22+	29+	37+
97	0+	1+	2+	5+	8	11	17
92	0+	0+	0+	1+	3+	6	9
87	0+	0+	0+	0+	0+	1+	4+
82	0+	0+	0+	0+	0+	0+	1+
no noise exposure (take as 75dB(A))	0+	0+	0+	0+	0+	0+	0.5+

1B : % exceeding 50 dB hearing threshold level

Table 7.6. Hearing loss expected in a typical male and female population exposed to noise without protection, continuously from the age 20. (From HSE Contract Research Report No. 29/1991)

		Males[1]		Females	
		No noise exposure[2]	85 dB(A)	No noise exposure	85dB(A)
% reaching 30 dB hearing loss at age:[3]	40(i.e.20 yrs. exposure)	5%	7%	1%+[4]	1%+
	60(i.e.40 yrs. exposure)	28%	35%	10%	15%
% reaching 50 dB hearing loss at age:[5]	40(i.e. 20 yrs. exposure)	1%+	1%+	0%+	0%+
	60(i.e. 40yrs. exposure)	7%	7%	1%+	3%+

[1]*At all ages males tend to have worse hearing than females. There is still scientific debate about how far this reflects real differences in resistance to noise damage and how far it is due to a tendency for males to lead lives more prone to accidental hearing damage.*

[2] *The contract report does not give estimates for less than 5% of the population because the author does not consider scientific data allows for reliable figures to be given. Estimates which might not be to reliable might be made by extrapolation of the figure in the table.*

[3] *This is the level of hearing loss is recognised as the point at which there is impairment of hearing. Compensation by the UK government scheme (DSS) is payable for this amount of loss. At a lower level of loss a civil claim might be possible.*

[4] *+ : indicate values extrapolated from the values in the contract report.*

[5] *A higher level of compensation under the UK scheme (DSS)*

7.4.5. Use of the Information

Information; i.e. noise levels, exposure periods, operator locations machine/process details should be recorded on the data sheets attached (Figures 7.5-7.9) to which a copy of the workplace plan/layout information relating to the $L_{Aeq,8hr}$ levels should be attached.
There are many uses for the information collected as a result of a full assessment and these are

detailed below:

- informs all workers of their exposure pattern/level
- it serves as a record for the employer
- identifies those operators whose exposure level is above nationally agreed limits
- indicates areas of high noise exposure
- identifies machines/processes producing high noise levels
- indicates to employers where noise control is necessary
- indicates areas where ear protection is required prior to noise control being implemented
- indicates those areas where ear protection will still be required after noise control as been applied
- allows identification of the most appropriate location for new machines /processes.

These records should be kept by the employer until a re-assessment is carried out; re-assessments should be carried out when activities change, processes are changed/renewed or when methods of production are changed

7.4.6. Transfer of information

Information gathered as a result of an assessment should be discussed by all parties; i.e. management, employees, unions and any medical personnel. The reasons for this are that all personnel will then be aware of the noise exposure situation; agreements on where to apply control measures can then be made that satisfy all concerned. Priorities and action can be agreed upon and supported by all concerned. Areas where ear protection is required can also be agreed upon and hearing conservation plans can be drawn up with the full cooperation of everyone concerned. An agreed hearing conservation and noise control plan will be more effective if all persons concerned in the operations of the workshop are committed to dealing with the problem.

Training in the use of ear protection can be given by medical staff; if there are no staff on the premises, arrangements can be made for employees to be provided with the training by outside agencies, and appropriate time off arrangements can be agreed upon. Periodic medical checks can also be agreed upon between all parties. Medical records can be established and updated whenever reviews take place.

Workshop plans can also be updated whenever changes to operations, work practices, personnel or machines take place.

After collecting all the information; i.e. noise levels, operator locations, machine/process details and identifying all this on the plan of the workplace and on the various sheets forming the report, a list of operators and their activities should be compiled and the levels of exposure ($L_{Aeq,8\mathrm{hr}}$) allocated accordingly.

Areas identified as having noise exposure levels in excess of 90 dB(A) $L_{eq,8\mathrm{hr}}$ should be designated noise hazard areas and clearly marked with signs indicating the hazard.

Entry into these areas should be restricted unless personnel are equipped with adequate and effective hearing protection.

The areas so identified may need to be the subject of further measurement to establish the frequency spectra of the noise; in these cases instruments capable of measuring noise in OCTAVE BANDS will be necessary. After obtaining frequency data, the selection of hearing protection will need to be based on this information in accordance with Chapter 11. This information is also crucial when considering noise control systems.

7.4.7. Report Format

The report should be compiled and completed by the person in charge of the assessment. Care should be taken to include all information gathered during the exercise and the sheets attached fully completed (see Figures 7.5-7.9). It should be possible from studying the report to obtain information in relation to the following:

- name location and business of the company,
- number of personnel employed names and titles/job descriptions,
- type of work being done,
- any observations that might help explain eventual variations in the noise level,
- characteristics of the measurement device (identification, frequency and time weighting),
- the results obtained (equivalent noise level, peak sound pressure level (dB(C)) and number of times the threshold value was exceeded).

7.5. EXAMPLES OF SURVEYS

Surveys/assessments will vary depending on the circumstances of the workplace; i.e. there will be a variation in size, number and layout of machines/processes, operator positions, number of operators and systems of working.

Two example surveys are outlined below and in each case the method of measurement and assessment is explained.

7.5.1. Survey Example One

A small woodworking premises containing 3 machines, has a layout as shown in Figure 7.10. All information in relation to the **REPORT** sheet is to be completed.

The situation is as follows:

Machine - A is a Band Resaw
B is a Multi-cutter Moulder
C is a Thicknesser

All machines have a dedicated operator and each machine is used for 4 hours each day.

7.5.1.1. Gathering the information

Measurements are taken using an integrating sound level meter set to fast response dB(A) and L_{aeq} , and calibrated before measurements begin. In this case, because all the machines can be in operation at the same time or working alone, it is essential to establish noise exposure levels of operators under all working situations which will indicate if a particular machine makes a contribution to the exposure level of operators at the other machines.

To establish this it is necessary to measure at the operator location of say machine A with that machine in operation only and then to repeat the measurements at machine A with machine B operating, then with machine C operating and with both machine B and machine C operating at the same time. This will then provide four sets of results which will need analysing to establish the exposure levels of each operator under each of the conditions of machine operation, where to concentrate noise control solutions and whether noise control carried out at one machine affects only that operator or whether it also reduces the exposure level of operators at other machines.

REPORT (Figure 7.5)

COMPANY DETAILS NAME ADDRESS	
ACTIVITY / BUSINESS	
NUMBER OF EMPLOYEES	
COMPANY CONTACT	
UNION/EMPLOYEE CONTACT	
AREA TO BE ASSESSED	
NUMBER OF EMPLOYEES	
NUMBER OF MACHINES	
INSTRUMENT DETAILS METER CALIBRATOR RECORDERS ANALYSERS	
DATE OF ASSESSMENT	
SIGNATURE	

ASSESSMENT DETAILS (Figure 7.6)

AREA DETAIL						
MACHINE	PROCESS/ACTIVITY	MEASUREMENT POSITION		LEVELS (dB(A))		
		OPERATOR	OTHER	SPL	PEAK dB(C)	SAMPLE L_{Aeq}

FREQUENCY ANALYSIS (Figure 7.7)

FREQUENCY (Hz)	63	125	250	500	1000	2000	4000	8000
OCTAVE BAND SPL								

FREQUENCY (Hz)	63	125	250	500	1000	2000	4000	8000
OCTAVE BAND SPL								

FREQUENCY (Hz)	63	125	250	500	1000	2000	4000	8000
OCTAVE BAND SPL								

FREQUENCY (Hz)	63	125	250	500	1000	2000	4000	8000
OCTAVE BAND SPL								

EXPOSURE ASSESSMENT (Figure 7.8)

LOCATION	EMPLOYEE	JOB TITLE	NOISE SOURCE	TIME EXPOSED	$L_{Aeq,8h}$
1					
2					
3					
4					
5					
6					
7					

COMMENTS

EMPLOYEE EXPOSED ABOVE THE ACTION/LIMIT LEVELS OF $L_{Aeq,8h}$

NAME	ACTIVITY	TITLE	LEVEL

CONCLUSIONS AND ACTIONS **(Figure 7.9)**

RECOMMENDATIONS AND CONCLUSIONS	
1	
2	
3	
4	
5	
6	
ACTIONS REQUIRED	
1	
2	
3	
4	
5	
6	

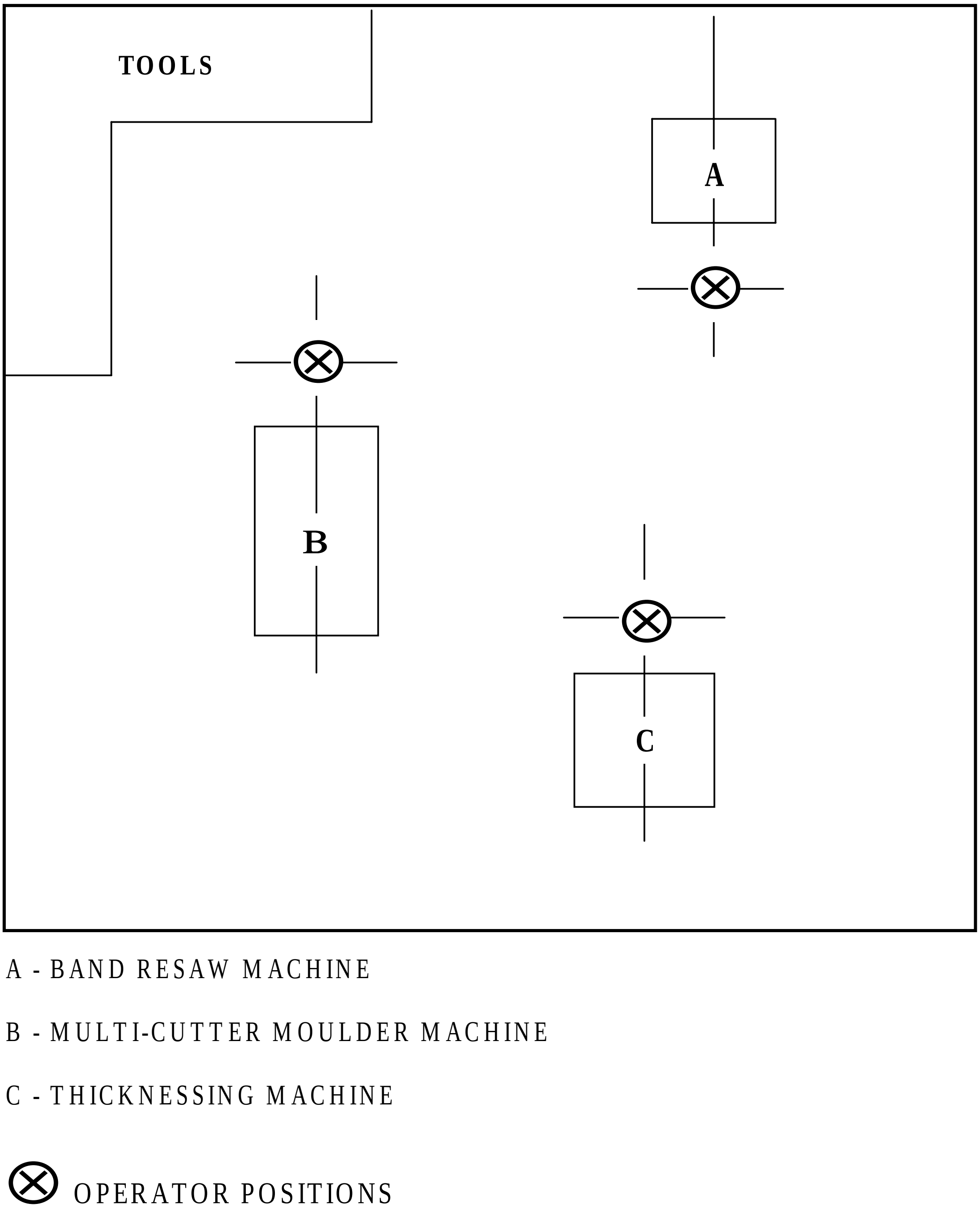

Figure 7.10. Woodworking machine shop - example 1.

STAGE ONE

Machine A- Operating Alone
Before measurement it is advisable to watch and listen to the variation in sound over a representative cycle; i.e. assess the time for the measurement period such that all variations are included in the measurement. Probably the cutting of 3 to 4 lengths of wood would be sufficient.

The resulting level shown by the meter as L_{Aeq} would be sample L_{Aeq} in dB(A) (see Figure 7.6). In this case the level is 96 dB(A).

This information is to be noted on the measurement sheet.

Machine B-Operating Alone

RESET METER

Measure as for machine A, note and record the level. In this case the level is 93 dB(A)

Machine C-Operating Alone

RESET METER

Measure as for machine A, note and record the level. In this case the level 99 dB(A)**.**

RESET METER

STAGE TWO

Machine A-with Machine B Operating At the Same Time
Measure as for machine A, note and record the level. In this case the level is 96 dB(A) (i.e. no change in level). This indicates that the exposure level of operator A is not influenced by noise from machine B. Note that noise at operator A due to machine B is determined by the level of noise produced by machine B, the separation distance from machine A to machine B and the acoustical characteristics of the building.

RESET METER

Machine A-with Machine C Operating At The Same Time
Measure as before, note and record the level. In this case the level remains at 96 dB(A). This indicates that the operator at machine A is not influenced by noise from either machine B or machine C.

RESET METER

Machine B-with Machine A Operating At The Same Time
Measure as before, note and record the level. In this case the level at machine B is 94 dB(A); i.e. an increase of 1 dB(A); this is the contribution of noise from machine A on the operator of machine B. This also indicates that if machine B were not operating but machine A was, the

noise at the operator position of machine B due to machine A would be 87 dB(A) which is calculated using $\{10\log_{10}[10^{94/10}-10^{93/10}]\}$.

RESET METER

Machine B-with Machine C Operating At The Same Time
Measure as before note and record the level In this case the level at machine B is 96 dB(A); i.e. an increase of 3 dB(A). This is the contribution of noise from machine C on the operator of machine B. This also indicates that if machine B were not operating but machine C was, the noise at the operator position of machine B due to machine C would be 93 dB(A) which is calculated using $\{10\log_{10}[10^{96/10}-10^{93/10}]\}$.

RESET METER

Machine C-with Machine A Operating At The Same Time
Measure as before note and record the level. In this case the level at machine C is 99 dB(A); i.e. no measurable change; therefore no significant contribution is made by machine A to the noise level at the operator of machine C.

RESET METER

Machine C-with Machine B Operating At The Same Time

In this case the level is 99 dB(A); i.e. no measurable change, this indicates that machine B makes no significant contribution to the noise level at the operator of machine C.

RESET METER

STAGE THREE (note:- after each measurement reset meter)

Machine A-with Both Machines B And C Operating

Measure at machine A with machines B and C operating at the same time. In this case the level is 96 dB(A); i.e. no measurable change. this indicates that machine C and machine B make no significant contribution to the level of exposure at the operator of machine A.

Machine B-with Machines A and C Operating

Measure at machine B with both B and C operating at the same time. In this case the level is 97 dB(A) which indicates that both machines A and C make a contribution to the noise exposure level of operator B.

Machine C-with Both Machines A and B Operating

Measure at machine C with both machines A and B operating at the same time. In this case the level is 99 dB(A); i.e. no measurable change. This indicates that the noise from both machines A and B make no significant contribution to the exposure of operator C.

Assessment of $L_{Aeq,8h}$ levels. ($L_{EP,d}$, Daily personal noise exposure)

$L_{Aeq,8h}$ and exposure levels can be obtained as follows.

OPERATOR- A
The measurements indicated that the noise level in terms of sample L_{Aeq} was 96 dB(A) during the representative cycle but information indicates that the machine is in use for 4 hours per day. Therefore using the formula:

$$f = \frac{T}{8} 10^{(L_{Aeq} - 90)/10} = 1.99$$

$$L_{EP,d} = 10 \log_{10} f + 90 = 92.99 \approx 93\,\mathrm{dB(A)} = L_{Aeq,8h}$$

OPERATOR-B
The measurements indicated that the noise level in terms of sample L_{Aeq} at machine B from machine B was 93 dB(A) but that the noise at this position due to machine A was 87 dB(A) and the noise from machine C was 93 dB(A). To obtain the total noise level for operator B we need to add all three contributions,

$$L_{Aeq} = 10 \log_{10}\left[10^{87/10} + 10^{93/10} + 10^{93/10}\right] = 97\,\mathrm{dB(A)}$$

Again the exposure period is 4hours per day; therefore from the above formula, $L_{Aeq,8h}$ = 94 dB(A).

OPERATOR-C
This measurement indicated that the sample L_{Aeq} level was 99 dB(A) and again the period of exposure was 4 hours per day. Therefore, using the previous formulae, $L_{Aeq,8h}$ = 96 dB(A)

In relation to noise control which is to be applied over a period of time it is advisable to analyse the above information to target control in the area which will give the optimum benefit and in this case the machine to deal with first is machine C. The reason is that operator C receives 96 dB(A) from machine C and machine C makes a contribution to the exposure of operator B. So reducing the noise from machine C would benefit both operators of machines C and B.

As an example, assume noise from machine C is reduced by 10 dB(A) by providing a noise enclosure. Then the exposure of operator C would be reduced to 86 dB(A) and the exposure of operator B would be as follows:

Previously the exposure was made up of contributions from all machines as follows 87 + 93 + 93 = 97 dB(A) and because use of the machine was 4 hours the exposure was 94 dB(A). Now because of reducing the effect of C down to 83 dB(A), the new L_{Aeq} level for operator B is

$$L_{Aeq} = 10\log_{10}\left[10^{87/10} + 10^{93/10} + 10^{83/10}\right] = 94\,\mathrm{dB(A)}$$

As before, use is 4 hours; therefore for operator B, the new $L_{EP,d}$ =$L_{Aeq,\mathrm{8h}}$= 91 dB(A), a reduction of3 dB(A).

7.5.2. Survey Example Two

In this example, the premises involved is an Auto-Lathe workshop, which houses 20 lathes, the operation of which is carried out by four setter/operators. The preliminary discussions and tour of the workshop indicated that each setter/operator carries out similar duties. This needs to be confirmed by all involved, and if this is agreed we need only establish the exposure of one setter/operator as an example and we can then assume that the other three will have similar exposure levels.

Again all details of the report sheets should be completed and below is an explanation of the system to use to establish $L_{EP,d}$ = $L_{aeq,8h}$.

Obtain a copy or draw a plan of the workshop and identify the areas of work of one of the setter-operators. The plan of the workshop is shown in Figure 7.11.

Preliminary observations indicate that the size of the workshop is also important in this case (this is generally the case with Autolathe workshops) because the workshop is small, compact and all surfaces are hard reflecting surfaces; i.e. concrete floor, concrete walls or corrugated steel sheet walls, windows and corrugated steel sheet ceilings. Therefore other information to be collected during the survey should include the following:

- a measurement of the reverberation time (to establish the acoustic nature of the room),
- `an octave band frequency analysis to assist selection of hearing protection.

7.5.2.1. Gathering the information

Discuss with all operators their normal activities on a typical day, identify on the plan the areas where noise level measurements are required. Following discussions, the operator chosen indicated he would carry out the following activities:-

A- setting machines- 2 hours-stationed at the machine head.
B-replenishing stock bars-2 hours-stationed at the stock feed of machines
C-selecting tools and sharpening-2 hours-stationed at the work-bench area
D-organising removal of finished goods-2 hours-stationed at the exit of the workshop.

This information should be confirmed by all operators

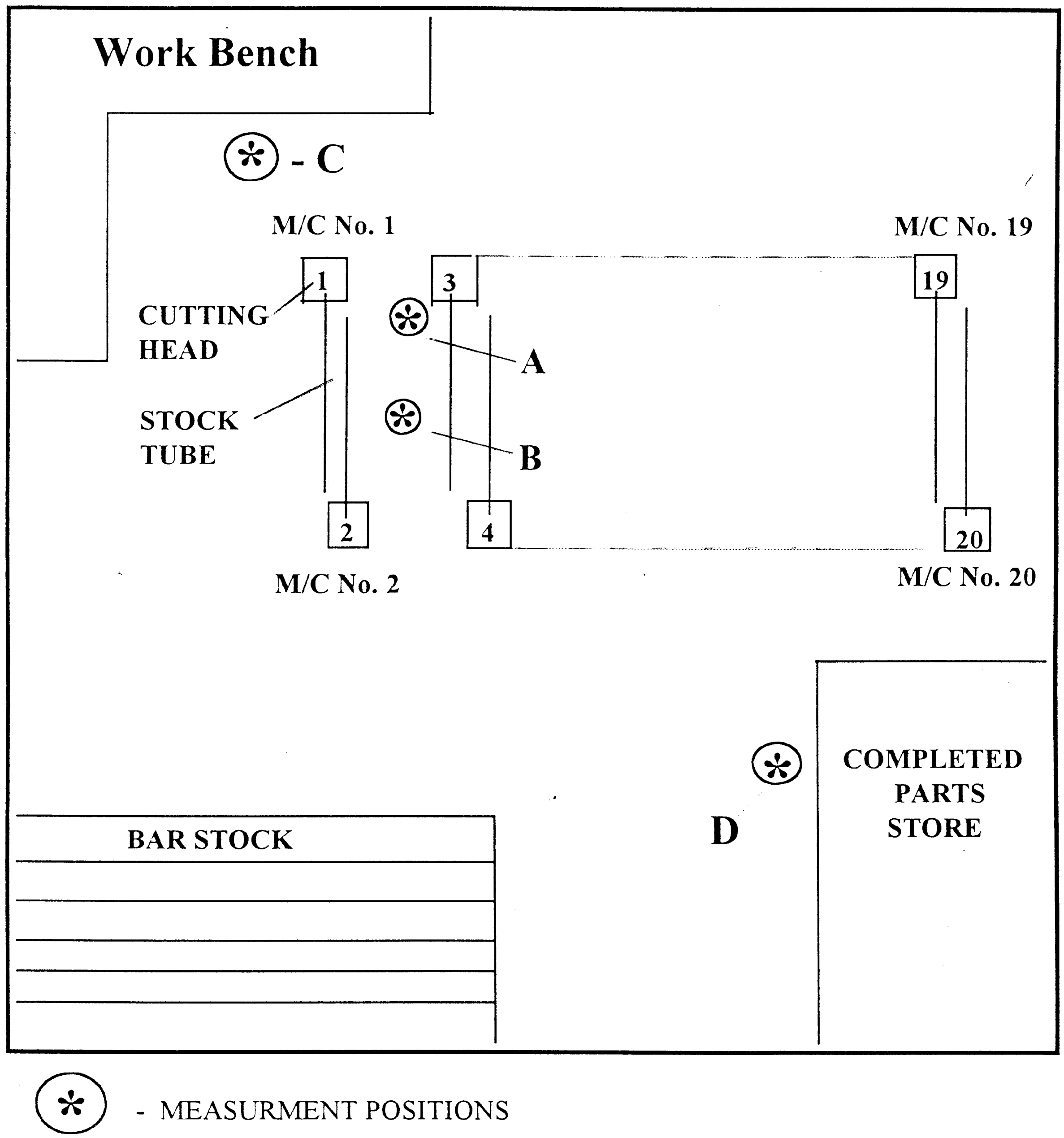

Figure 7.11. Autolathe workshop

Following a measurement survey using the integrating sound level meter and using the knowledge gained from observing the operator and discussions with the operator; i.e. the information above, the following levels were established:

A- At a typical machine head the noise level was 97 dB(A)
B- At a typical stock feed the noise level was 96 dB(A).
C- At the work-bench the noise level was 94 dB(A)
D- At the exit to the workshop the noise level was 93 dB(A).

Example 2.

Information should also be obtained regarding the nature and type of work being carried out by each machine; i.e. the material being used: steel, brass aluminium or copper ? and the type of material; e.g. round bar, square bar or hexagon bar ?. Previous experience indicates that square and hexagon steel bar produce the highest noise levels in the stock tubes and the cutting heads. Using the previous formulae, the exposures for activities A, B, C and D are as follows:-

A-fractional exposure is 1.3	f = 1.252
B-fractional exposure is 1.0	f = 0.995
C-fractional exposure is 0.7	f = 0.63
D-fractional exposure is 0.50	f = 0.5
	Total = 3.5

To obtain the total exposure and $L_{EP,d}$ for 8 hours we use the 3.50 figure above for *f* and use our previous formula to calculate $L_{EP,d}$ and $L_{Aeq,8\mathrm{h}}$ = 95.5 dB(A) which is rounded to 96 dB(A). It can be said that under typical working conditions all four setter/operators have an exposure level of 96 dB(A)

An alternative system would be to use a noise dosimeter. After calibrating the instrument, it is attached to a setter-operator, the microphone being clipped to the lapel of the overalls. The dosimeter is then set to run and the operator carries out his/her normal tasks. At the end of the 8 hour period the instrument is then interrogated to establish the dose level- a dose of 100% equates to an level of 90 dB(A) averaged over 8 hours. With an exchange rate of a 3 dB increase being equivalent to a doubling of exposure time, a noise exposure level of 96 dB(A) would read as 400% noise dose.

For the example considered, the major activities making up the exposure levels were at locations A and B. The exposure levels at both places are due to the noise from the lathes at both the machining heads and the tail stocks. Thus, any noise control should be directed at the lathes. However the noise at both the other two positions, C and D, is also mainly due to the noise from the autolathes and the reflected sound from the floor, ceiling and walls.

7.5.2.2. Noise control options

Because there are 20 lathes, noise control has to be considered carefully. If all machines were to produce similar noise levels then applying noise control to 10 machines would only reduce the noise in the workshop by 3 dB(A). In addition the noise at the locations C and D would only be marginally affected.

Using the information gathered during the frequency analysis select the most appropriate form of ear protection to be used.

Identification of those machines used predominantly for machining steel square or hexagon bar should be carried out first and a list made. These machines should be fitted with liners in the stock tubes, which will restrict noise from the action of the stock bar on the casing of the tubes. If all machines can be considered for this treatment, then the degree of noise reduction will depend on the performance of the liners in reducing impact noise.

Investigate the possibility of fixing acoustic absorption material to the ceiling of the workshop to reduce reflected noise; this will have most effect at locations C and D.

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INTERNATIONAL STANDARDS

Titles of the following standards related to or referred to in this chapter one will find together with information on availability in chapter 12:

ISO 1999, ISO 9612,
IEC 60804, IEC 60942, IEC 61252.

8

HEARING MEASUREMENT

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8.1. INTRODUCTION (RATIONALE FOR AUDIOMETRY)

The audiogram is a picture of how a person hears at a given place and time under given conditions. The audiogram may be used to describe the hearing of a person for the various frequencies tested. It may be used to calculate the amount of hearing handicap a person has. And, it may be used as a tool to determine the cause of a person's hearing loss. Audiograms may be obtained in many ways; e.g., by using pure tones via air conduction or bone conduction for behavioral testing or by using tone pips to generate auditory brainstem responses.

The audiogram is a most unusual biometric test. It is often incorrectly compared to a vision test. In the audiogram, the goal is to determine the lowest signal level a person can hear. In the case of a vision test, the person reads the smallest size of print that he or she can see, the auditory equivalent of identifying the least perceptible difference between two sounds. In most occupational and medical settings, this requires the listener to respond to very low levels of sounds that he or she does not hear in normal day-to-day life. A vision test analogous to an audiogram would require a person to sit in a totally darkened room and be tested for the lowest luminosity light of various colors, red to blue, that can be seen.

The most basic audiogram is a screening test such as is used in the schools. A series of tones at fixed levels are present and the listener indicates which he or she can hear. The levels are set so that those who hear them should have hearing within normal limits and those who don't are referred for a threshold audiogram. The threshold audiogram produces a picture of how a person hears air-conducted signals, such as pure tones. A person sits in a quiet environment, listens for pure-tone pulses (beeps), signaling when they are heard. The test consists of presenting these beeps as varying intensities for different test frequencies, recording at each frequency the lowest intensity at which there are responses from the listener. At no other time during day-to-day life are people presented with perceptual tasks of similar demand.

8.1.1. Audiometry for Monitoring/Compliance

The same type of threshold audiometry is used to monitor the individual worker's response to noise exposure. A baseline audiogram is obtained before the worker is exposed to potentially hazardous noise, periodically during the exposure times, and at the end of the worker's exposures. Permissible exposure levels, the amount of time a worker may be exposed to noise without the necessity of engineering controls to reduce the noise, removing of the worker from the noise, or requiring that the worker use hearing protection, are founded on the maximum acceptable excess risk level of developing hearing impairment. These risk estimates are based on pure-tone air-conduction audiograms. As an example, based on available data, the National Institute for Occupational Safety and Health (NIOSH 1996) calculates that 15% of workers exposed to noise levels of 85 dB(A) $L_{Aeq,8h}$ will develop hearing impairment over their lives.

Table 8.1. Comparable American National Standards Institutes and International Standards audiometric standards.

Topic Area	ANSI Standard	ISO Standard
Audiometer Calibration	S3.6-1996 Specifications for Audiometers	ISO 8253 Audiometric Test Methods - Part 1 (1989): Basic Pure Tone and Bone Conduction Audiometry; Part 2 (1991): Sound Field Audiometry; Part 3 (199x): Speech Audiometry ISO 389-1985: Acoustics - Standard reference zero for the calibration of pure tone air conduction audiometers and Addendums 1, 2, and 3 IEC 60645-Part 1 (1987) Pure Tone Audiometers: Part 2 (199x) Equipment for speech audiometry, Part 3 (199x) Specifications of reference audiometric test signals of short duration, Part 4 (199x) Equipment for extended high frequency audiometry
Test Room Noise Levels	S3.1-1991 Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms	ISO 8253(1) 1989 Audiometric Test Methods - Part 1: Basic Pure Tone Air and Bone Conduction Audiometry ISO 6189-1983 Acoustics-Pure Tone Air Conduction Threshold Audiometry for Hearing Conservation Purposes
Sound Level Meters	S1.4-1983 (1990) American National Standard Specification for Sound Level Meters; S1.4A-1985 Amendment to ANSI S1.4-1983; S1.25 American National Standard for Personal Noise Dosimeters; S1.43-1997 American National Standard Specification for Integrating-Averaging Sound Level Meters	IEC 60651 (1979) IEC 60804 (1985)
Estimation of Noise-Induced Hearing Loss	S3.44-1997	ISO-1999 (1992)

($L_{Aeq,8h}$ is the equivalent noise level for an 8-hour exposure when the exchange rate is 3 dB. 88 dB(A) for four hours equals 85 dB(A) $L_{Aeq,8h}$ while 91 dB(A) for two hours is the same as 85 dB(A) $L_{Aeq,8h}$.) NIOSH defines hearing impairment as a pure-tone average in either ear for the audiometric test frequencies of 1000, 2000, 3000, and 4000 Hz that exceed 25 dB HTL (Hearing Threshold Level or Hearing Loss) re ANSI S3.6-1996, *Specifications for Audiometers*. See Table 8.1 for a listing of ANSI standards and comparable ISO and IEC standards.

In the United States, the Hearing Conservation Amendment of the Noise Standard of the Occupational Safety and Health Administration (OSHA 1983) requires employers to obtain baseline audiograms for all workers exposed to noise levels at or above the time-weighted average for eight hours (TWA_8) of 85 dB(A). (OSHA's TWA_8 is based on a 5 dB exchange rate with 90 dB(A) for four hours equal to a TWA_8 of 90 dB(A) and with 100 dB(A) for two hours equal to a TWA_8 of 90 dB(A). OSHA further requires that all exposed workers receive audiometry once per year for the duration of their work life in noise of 85 dB(A) TWA_8. Each worker's annual audiogram is compared to his or her baseline audiogram to check for changes in hearing that might have been related to the noise exposure. OSHA sets no time limit from administering the annual hearing test to comparing the results to the baseline audiogram (allowing up to a year in cases where mobile hearing services are used). OSHA requires that if a change of hearing of sufficient magnitude has occurred, the employer must take certain actions to avoid further worsening of hearing for the worker. This type of hearing testing program; i.e., regimental application of baseline and annual hearing tests according to the requirements of the OSHA, is referred to as monitoring audiometry for the purposes of compliance.

8.1.2. Audiometry for Intervention/Prevention

NIOSH recommends a more assertive use audiometry; e.g., one that is driven less by monitoring for hearing loss and driven more by hearing loss prevention. NIOSH recommends that all workers exposed to noise levels at or above 85 dB(A) $L_{Aeq,8h}$ receive audiometry. (NIOSH 1996). In addition to the baseline audiogram, which is preceded by a 12-hour period of no exposure to loud occupational or other noise, NIOSH recommends an annual test for workers whose exposure levels are less than 100 dB(A) $L_{Aeq,8h}$ and testing every six months for those workers who exposure levels are equal to or greater than 100 dB(A) $L_{Aeq,8h}$.

While OSHA requires that the baseline audiogram be administered following a quiet period, there is no regulatory guidance about quiet periods preceding annual audiograms. NIOSH recommends that annual audiograms be obtained during the work shift, preferably at the end of the work shift, to observe any temporary threshold shift the worker may have. NIOSH recommends immediate retesting of employees who do show a shift in order to validate the audiogram. If the change in threshold remains on the retest audiogram, NIOSH recommends providing a confirmation test which is preceded by quiet. For workers whose threshold shift was determined to be temporary by the confirmation audiogram, NIOSH encourages interventions that reconsider the exposure conditions, the adequacy of the hearing protection, and the worker's training. For workers whose threshold shift was determined to be permanent, NIOSH recommends ruling out etiologies other than noise and if the threshold shift is noise related, removing the worker to a quieter work environment or, at a minimum, one-on-one training in the fitting and use of hearing protectors.

Because the frequency of periodic audiograms is dependent upon the noise exposure level, and the testing paradigms are designed to identify and respond to temporary threshold shift, this type of audiometry is referred to as prevention driven. In an effective program, each worker at risk of developing permanent threshold shift would be identified early by responding to the situation that produced a temporary threshold shift with the goal being to prevent any future temporary threshold shift. Elimination of temporary threshold shifts prevents permanent threshold shift, and thus prevents hearing loss due to noise exposure.

The rest of this discussion of hearing measurement will be based upon a prevention, rather than compliance, model.

8.2. ELEMENTS OF AUDIOMETRY

8.2.1. The Test Environment

Because audiometry requires determination of the lowest signal level that a person can hear, the audiometric test environment is very important. The audiometric test environment includes the space in which the test is administered, the instruments used to administer the test, and conditions under which the test is administered.

8.2.1.1. Noise levels

In a perfect hearing test, the lowest signal level to which a person responds will reflect only the limitations of his or her own auditory system. In many cases, however, auditory thresholds actually reflect the lowest signal that the person can hear against the background noise that is present in the test environment.

Every audiometer calibration standard either includes or references a corresponding standard for maximum permissible ambient noise levels for testing to audiometric zero. In the United States, the standard for audiometric zero is ANSI S3.6-1996 and the standard for maximum permissible ambient noise level is ANSI S3.1-1991. Audiometers calibrated according the ANSI standards or the corresponding ISO standards will make it possible to test to 0 dB HTL for persons whose hearing is that sensitive. The maximum permissible ambient noise levels for ANSI S3.1-1991 are displayed in Table 8.2.

Table 8.2. Maximum permissible background noise level during audiometric testing: Accordance with ANSI S3.1-1991, OSHA table D-2 (1981), and OSHA table D-1 (1983). Levels shown are octave-band sound pressure levels (dB re 20 µPa) for ears covered with standard MX41/AR cushions.

Octave-Band Center Frequency	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
ANSI S3.1-1991 (Rounded to the nearest whole decibel)	22	30	34	42	45
OSHA Table D-2	27	30	32	42	45
OSHA Table D-1	40	40	47	57	62

It is important to note that the levels in Table 8.2 represent conditions when the earphone cushions that are specified by the standards are used. Also displayed in Table 8.2 are the maximum permissible ambient levels specified by the OSHA Hearing Conservation Amendment

(OSHA 1983). The OSHA levels are much higher, being based on audiometers calibrated to much older American Standards Association (American National Standard Specification for Audiometers for General Diagnostic Purposes, Z24.5-1951). OSHA had initially proposed that these higher levels from Table D-1 of the Hearing Conservation Amendment be used for two years until industry came into compliance with the Hearing Conservation Amendment, afterwards switching to the levels from ANSI S3.1-1991 with a 5 dB adjustment at 500 Hz (OSHA 1981). After successive stays and issuances of the regulation, only the levels in Table 8.2 remain. Audiometry that relies upon OSHA's specifications will be unable to test to levels below 15 dB HTL (Franks, Engel, and Themann 1992)

8.2.1.2. Controlling the test environment

There are many ways to control the test environment. The optimal test environment is quiet and free of distractions. There should be no activity outside the test room that the listener can see or hear. A person with normal hearing may be able to follow a conversation outside the test room even if the ambient noise levels meet the level specified by ANSI S3.1-1991. While audible speech would not mask the test tones, it would distract the listener, making a difficult test more difficult yet. There is no such thing as a "soundproof" test room; i.e., a room which no outside sound can penetrate. It is important that rooms are designed to attenuate nominal outside noise to the point where it won't mask the test signals, and it is just as important to not have unnecessary noise generating activities in the area of the test room.

8.2.1.2.1. Single-person test rooms. In most audiometric testing situations, the listener will be seated in a small sound-treated room just large enough to accommodate him or her. The room will have a door, a window through which the listener may be observed, as well as lighting and ventilation systems. These rooms are often prefabricated and either are delivered assembled to a test site or are assembled at the test site. Figure 8.1 displays a single-person test room along with the typical floor plans..

The standard "mini" booth usually arrives preassembled and has wheels so that it may be moved within a test site. The "mini" booth usually has a folding shelf attached under the observation window on which the audiometer and other items may be placed. The booth is referred to as "mini" because of its small interior: 0.72 m x 0.66 m x 1.50 m. It is fabricated from 5 cm- thick panels. The typical attenuation provided by a "mini" booth is shown in Table 8.3.

There is also a transportable "mini" booth which can be set up at one test site and, after testing is completed, taken down and moved to a new test site set up. This room also uses 5 cm-thick panels and has a window and a shelf as well as lighting and ventilation. It even comes with a carrying case that can be placed in the back of a station wagon or small truck. However, because of its set-up/take-down features, its attenuation is less than that of the standard "mini" booth. This booth was designed at the request of the airlines so that the hearing conservationist could fly to one airport, set up the booth, test airline personnel, take down the booth, and load it back on an airplane for transport to the next airport where testing was to be done.

Another type of single-station test room is the standard stationary booth that is assembled from 7.5 cm or 10 cm-thick panels. As with the mini booth, there is an observation window as well as ventilation and lighting. The interior is larger than the mini booth, 0.80 m x 1.0 m x 1.7 m. Because it is built of thicker and heavier panels, the attenuation is greater, as is shown

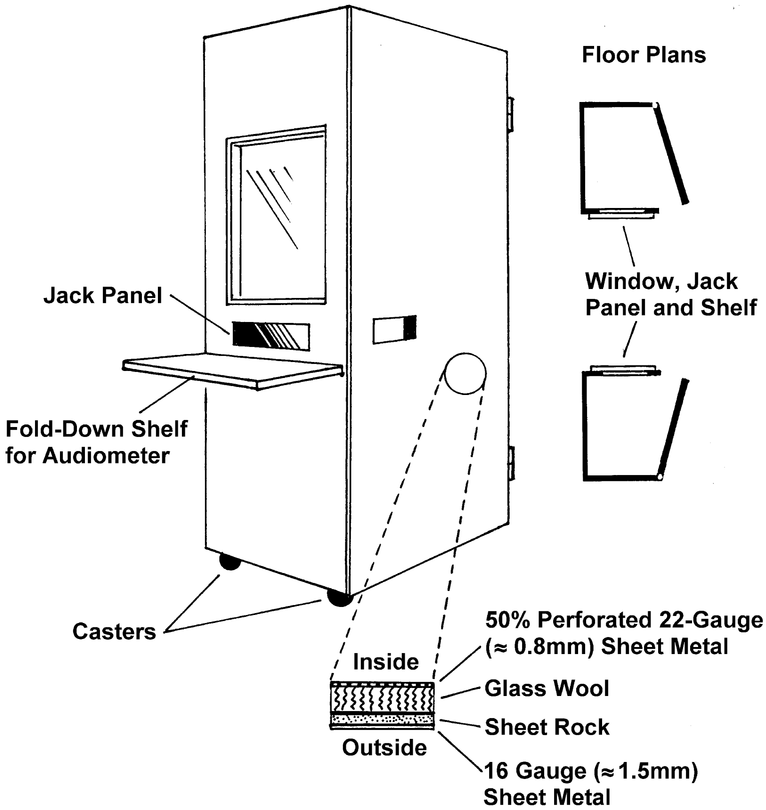


Figure 8.1. A typical "mini" sound booth.

in Table 8.3. In the stationary single booth, the ambient noise levels should be low enough to allow bone conduction testing with unoccluded ears as is specified in ANSI S3.1-1991. Stationary booths are quite rugged and have a use life of more than 30 years so long as the door gaskets and ventilation fans are replaced every four to five years. If there is significant vibration from the floor, the vibration isolators should also be replaced every four to five years.

Table 8.3. Representative noise reduction data of various thickness panel construction for audiometry testing rooms (dB).

	1/1 octave-band center frequency						
Panel thickness	125	250	500	1000	2000	4000	8000
10 cm panel	28	36	48	57	61	61	57
7.5 cm panel	24	31	71	46	55	55	52
5 cm panel	15	31	34	42	49	50	51
Transportable	12	26	27	27	30	35	35
Double walled	47	62	83	91	99	97	>91

8.2.1.2.2. Multiple-person test rooms. It is sometimes necessary to test more than one person at time. In some settings this may be accomplished by installing more than one test booth. In others, one larger booth may be set up capable of supporting multiple testing stations. Such booths may be large enough to accommodate testing as many as twelve persons at a time. Most, however, are built to accommodate six to eight persons simultaneously. These booths are most often constructed of 10 cm-thick panels. In the United States the most common users of multiple-station test booths are the military and mobile hearing conservation test providers. The multiple-station test booths are often built into trailers or trucks.

The drawback to multiple-station test booths is the potential distraction of listeners by those around them and the increased ambient noise levels created by having several persons in a small enclosure. Sometimes, persons with normal hearing can hear the high intensity test signals being presented to those with substantive hearing loss, making it difficult to determine to which tone they should respond. It is also difficult for the audiometrist to detect testing problems when they occur and it is difficult to intervene for one listener having trouble while others are completing their hearing test. Also, the time it takes to complete a hearing test when microprocessor audiometry is used will be different for each person, so it is necessary to have people who have completed the test remain seated and quiet while others are finishing.

The addition of curtains or panels to separate listeners in a multiple-person test booth would appear to be beneficial by reducing distractions. However, it also makes the space seem smaller and blocks the audiometrist's view of the listeners. When self-recording audiometry has been used in multiple-person test rooms, there have been cases when a person with a hearing loss enlisted the support of a "buddy" with good hearing to sit at an adjacent station. The "buddy" would press his own response switch and that of the person next to him, pressing both buttons when he heard the signals. As a result, his neighbor's audiogram showed good hearing when in fact that person had a severe high-frequency hearing loss. An open booth with good lighting set up so that the audiometrist and listeners have good two-way visual contact can inhibit such behaviors when multiple-person test booths are used.

8.2.1.2.3. Selecting the test area and the test booth. While an area with little traffic may seem to be the obvious location for a test booth, it is necessary to measure the ambient sound levels in the space before selecting a booth configuration. It will be necessary to choose a test booth with adequate noise reduction to ensure that the ambient noise levels are below those specified in ANSI S3.1-1991, as shown in Table 8.2. The best way to determine the booth specifications is to subtract the values for each panel thickness in Table 8.3 from the ambient noise levels measured where the booth will be used. The ambient noise levels in the areas intended for the booth should be measured when there is normal traffic and building activity. If the calculated values are below those in ANSI S3.1-1991, the booth should be adequate. If the calculated levels are higher than those in ANSI S3.1-1991, the booth will not be adequate and a thicker-walled structure will be needed.

In some unusual settings a double-walled booth may be needed. This is a "booth within a booth" with both booths constructed from 10 cm-thick panels. Because these structures are very heavy, the floor of the building where they will be assembled must be rated for loads of 45 kilograms or higher. Typical noise reductions for a double-walled room is shown in Table 8.3.

8.2.1.3. Noise-reducing earphone enclosures

The standard earphone assembly in the United States uses an MX41/AR supra-aural earphone cushion. “Supra-aural” means that the cushion sits on the pinna. Compared to a circum-aural cushion, the MX41/AR cushion has many leaks and is not a good attenuator of external sounds. Nevertheless, the maximum permissible noise levels of ANSI S3.1-1991 and the calibration values of ANSI S3.6-1996 are based on the use of the MX41/AR cushion. Changing to a different cushion or placing a shell around cushion changes both the attenuation and calibration of the earphone assembly. Therefore, NIOSH recommends that noise-reducing earphone enclosures not be used. OSHA will issue a deminimus citation when they are used in a test booth with ambient noise levels that meet the OSHA maximum allowable ambient noise levels or a serious citation when they are used in place of a test booth that meets OSHA’s ambient noise limits.

In spite of all the reasons against using noise-reducing earphone enclosures, they are fairly common. There are three enclosures in use at present. They are the Aural Dome, the Amplivox Audiocup, and the Madsen/Peltor Audiomate. All three accommodate the Telephonics TDH series earphones and MX41/AR cushion. They replace the earphone assembly headband and provide an outer earcup with a circumaural cushion that seals around the ear much as a noise reducing circumaural earmuff provides a seal around the ear. Since these devices essentially place the standard earphone/cushion inside an earmuff, it would seem that they ought to reduce ambient noise levels, making a quieter situation for testing at low hearing levels while not changing calibrations. Unfortunately, they don’t effectively reduce ambient noise and they do affect calibration.

Studies by Franks, Merry and Engel (1989) found that Audiocups have insufficient attenuation in the low frequencies where test booth noise levels are usually the highest. Frank and Williams (1993a) found that if one is using the OSHA maximum permissible ambient noise levels, the real-ear attenuation at threshold of the Audiocup is insufficient to enable testing down to 0 dB HL. Other studies have found that while the earphone may be calibrated while in the enclosure, use of the enclosure has an effect on hearing thresholds at 3000 and 6000 Hz (Frank and Williams, 1993b). Flottorp (1995) studied placement of the earphone cushion, finding large changes in hearing thresholds at 3000 and 6000 Hz for placements common in occupational hearing conservation test settings. Because noise-reducing earphone enclosures cover the earphone and cushion, it is not possible to ascertain the exact placement of the earphone and cushion and the exact alignment of the earphone and the ear canal opening when noise-reducing earphone enclosures are used.

New active noise-reducing earphones that have pass throughs for communication and warning signals are presently being studied. It is conceivable that the noise-reducing circuitry can be used to reduce low-frequency (< 1000 Hz) noise levels. However, none of the active noise reduction headsets are able to employ the MX41/AR cushion, and so a great deal of laboratory work would be necessary before these systems could be found to be suitable for use in hearing testing.

8.2.1.4. Documenting ambient noise levels in the test booth

Test room ambient noise levels should be measured during the normal course of business in the audiometric testing area. For example, if the testing area is in an occupational health setting, ambient noise levels should be measured while other normal activities of the setting are underway with the exception of having a person inside the test booth. The booth ventilation and lighting systems should be turned on as well. Most modern sound level meters meeting the specificationsof type II (ANSI S1.4-1983) should be capable of measuring these noise levels. It may be easier to mount the sound level meter on a tripod than to hold it while taking readings.

Noise levels should be measured in octave bands. It is not sufficient to take an A-scale or C-scale reading. Octave band filters should meet the Class II requirements of ANSI S1.11-1966 1971), *Specifications for Octave, Half-Octave, and Third-Octave Band Filter Sets*. Once the octave-band levels have been measured, the C-scale measurement may be taken and used to monitor the ambient noise levels as any change in the octave-band levels will be reflected in the C-scale reading.

For a fixed facility, although there is no regulatory guidance, it should be adequate to measure the test room ambient noise levels annually. For mobile facilities, ambient noise levels should be taken daily or whenever the facility is relocated, whichever is most frequent (NHCA 1996). The noise levels should be kept as part of the record keeping system and should also be recorded on each audiogram. Additionally, the make, model and serial numbers of the sound level meter, octave-band filter set, and calibrator should be kept along with the calibration date of each instrument.

Sometimes, it may be necessary to perform audiometry even when the test room ambient noise levels are higher than specified by the standards. At such times, it will not be possible to test to audiometric zero at the frequencies for which the noise levels are too high. The audiometrist should make certain to annotate each audiogram with a statement that the minimum test hearing level could not have been zero. For example, if the octave-band ambient noise level at 1000 Hz was 40 dB SPL instead of the 30 dB SPL specified by the standard, the note would say that hearing thresholds of less than 10 dB HL at 1000 Hz were unreliable.

8.3. PURE-TONE AUDIOMETRY: AUDIOMETERS AND METHODS

The pure-tone air-conduction audiogram allows determination of the lowest sound levels a person can hear at given test frequencies. The entire auditory system, from ear canal to auditory cortex, is tested. There are various testing methods and instrument types for determining these levels. The methods are all based on presenting to the listener sound levels from just audible to just inaudible. The listener's threshold is somewhere between these two levels. When a testing program is established, a method is selected and an audiometer for applying that method is chosen.

There are three main testing methods: manual audiometry, self-recording audiometry, and microprocessor-controlled audiometry. Each method has its own instrumentation requirement so that a manual audiometer cannot be used for self-recording, just as a self-recording audiometer cannot be used for manual or microprocessor-controlled audiometry. Thus, once a testing method has been selected, the choice of audiometer to use will be limited to the set of instruments which perform that test method. Most microprocessor-controlled audiometers may be used for manual testing.

There are differences in thresholds determined by the various testing methods. It is very important that once a method is selected for a test site or for a group of workers, the method be used consistently. If one were to test a group of workers one year by microprocessor-controlled audiometry, by manual audiometry the next year, and by self-recording audiometry the following year, there would be apparent changes in the workers' hearing that actually were due to the change of testing methods. Thus, it would be more difficult to detect true changes in workers' hearing due to noise exposure.

8.3.1. Manual Audiometry - The Benchmark

Manual audiometry is the standard for clinical testing. The signal frequency, intensity, and presentation are controlled by the tester. The tester follows a standard procedure for presenting the test signals. By observing intensities to which the listener responds and those intensities for which there is no response, the tester determines the signal intensity at threshold for each test frequency and records it on an audiogram chart or table.

8.3.1.1. Instruments

A typical manual audiometer, such as the one shown in Figure 8.2, permits the selection of the test frequency, the intensity, right or left earphone, continuous or pulsed tones, and presentation of the signal. Most modern manual audiometers also have a listener response button and a light or other indicator on the audiometer to show that the response button has been pressed. A type 4 audiometer as defined by ANSI S3.6-1996 will have an intensity range from 0 to 90 dB HL for all test frequencies. A manual audiometer may also support other testing such as bone conduction, masking, speech threshold and intelligibility, but those tests are seldom used in the occupational setting.

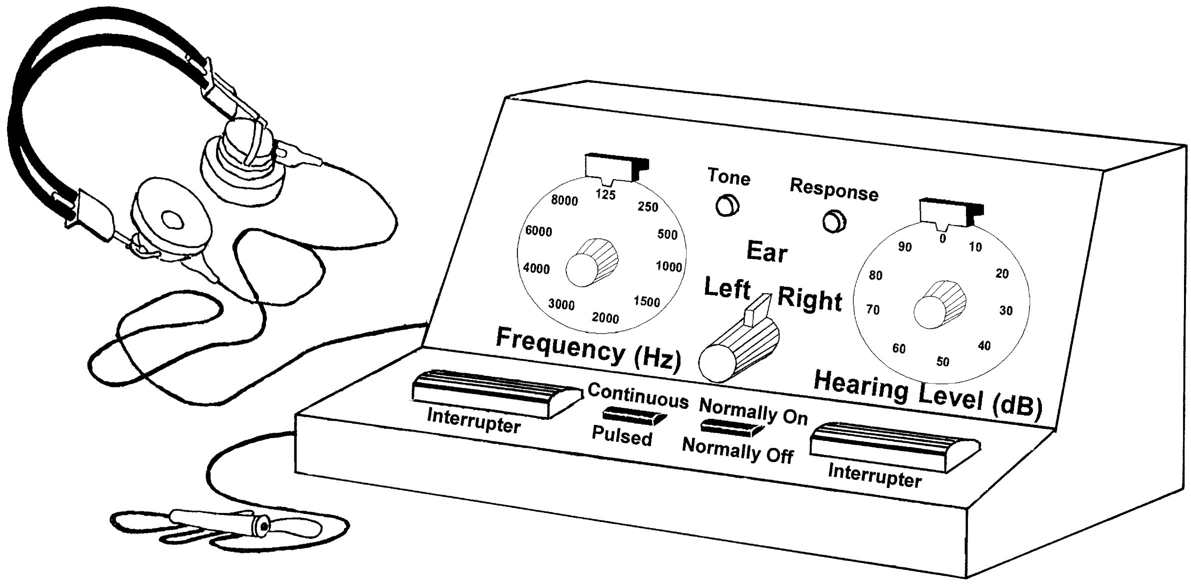


Figure 8.2. Manual audiometer

8.3.1.2. Methods

There are three basic methods that may be used to test hearing: the method of constant stimuli, method of limits, and method of adjustment. In the method of constant stimuli, the listener is presented with a series of tones at each intensity and the number responses for each intensity is recorded. The intensity at which the number of responses equals half the number of presentations is defined as threshold (the 50% point). In the method of limits, various intensities are presented and how the listener responds at each intensity is recorded. The lowest intensity to which the listener responds at least 50% of the time is recorded as threshold. In the method of adjustment, the listener has control of the signal intensity and sets it to a level so that the signal is just-barely heard, such that if it were less intense it could not be heard at all. This intensity setting is recorded as threshold.

There is a trade off between time to administer these three methods and the accuracy of the threshold determination. While the most accurate, the method of constant stimuli takes the longest amount of time. The method of adjustment takes the least amount of time, but is the most inaccurate. That leaves the method of limits as the method upon which manual audiometry is based.

The version of the method of limits used in manual audiometry is referred to as the modified Hughson-Westlake procedure (Carhart and Jerger, 1959). This procedure is detailed in ANSI S3.21-1978 (R-1992). In this procedure the signal intensity is first presented at a level the listener can hear clearly. Then the intensity is reduced in fixed-size decrements until the listener no longer responds. The intensity is then increased in smaller fixed-size increments until the listener responds again. From this point on, whenever the listener responds, the signal is decremented and whenever the listener fails to respond the signal is incremented. The intensity, when the signal is being incremented, to which the listener responds two out of three times is recorded as threshold. Figure 8.3 displays a flow chart for administering the modified Hughson-Westlake procedure (after Martin, 1986).

There are other variations on the method of limits. If the signal is presented at a level the listener cannot hear, incremented until there is a response, decremented until there is no response and then incremented until there is a response again, the level at which there are two responses for three presentations may be lower than for the modified Hughson-Westlake method. But, the task will be much more difficult for the listener and will take more time to administer. If the Modified Hughson-Westlake method were used, but the threshold level was determined on all responses to signals, increasing or decreasing, there would be many inconsistencies, making it much more difficult to assign threshold to any intensity.

When hearing is tested for clinical purposes, thresholds are found for octave frequencies from 125 to 8000 Hz, and sometimes including the half-octave frequencies of 750, 1500, 3000, and 6000 Hz. When hearing is tested for occupational haring loss prevention programs, only the frequencies 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz are tested. In the United States, the OSHA Hearing Conservation Amendment (OSHA 1983) does not require testing at 8000 Hz. However, since a notch in the audiogram shape at 4000 and/or 6000 Hz with recovery to better hearing at 8000 Hz is the signature of a noise-induced hearing loss, having a threshold for 8000 Hz is important for the professional reviewer to sort out hearing loss most likely due to noise from hearing loss due to some other cause.

When beginning a hearing test it is important to start with the listener's better ear. If the listener notices no difference between the right and left ears, the right ear should be the default starting ear. An effective way to sequence the ears and test frequencies is to start with the determination of threshold in the better/right ear at 1000 Hz. Then threshold is determined at 500 Hz, followed by a retest of threshold at 1000 Hz. If the first and second thresholds at 1000 Hz agree within 5 dB, testing may continue for 2000, 3000, 4000, 6000, and 8000 Hz. Then testing is started for the worse/left ear with the frequency sequence of 1000, 500, 2000, 3000, 4000, 6000, and 8000 Hz. A pulsing tone with on/off times of no less than 200 msec duration should be used if the audiometer has the feature.

If the first and second thresholds for the better/right ear at 1000 Hz do not agree within 5 dB, it will be necessary to stop testing, refit the earphones, and re-instruct the listener. Then 1000 Hz would be tested again, followed by 500 Hz with a return to 1000 Hz. If the thresholds at 1000 Hz agree this time within 5 dB, the rest of the test may be completed. If not, the listener

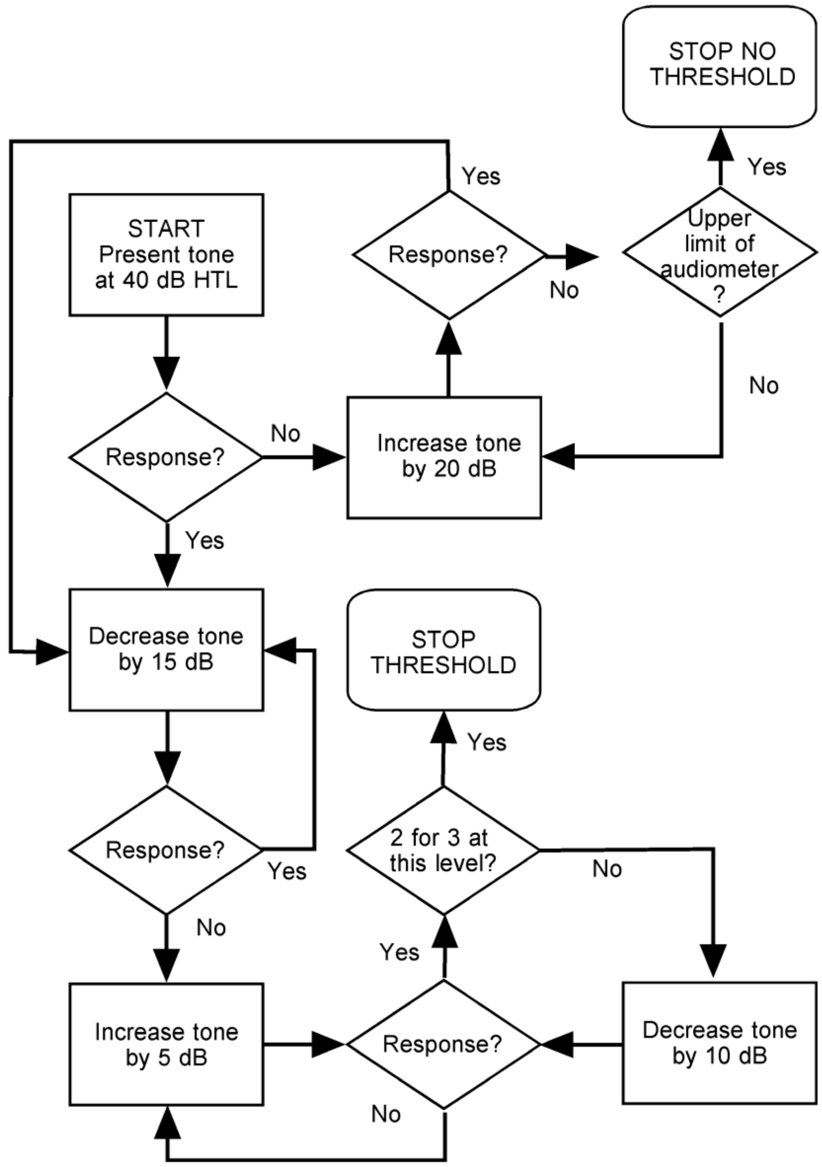


Figure 8.3. Modified Hughson-Westlake flow chart. (Adapted from Martin 1983)

should be referred to a clinical setting for testing. It is not necessary to do the 1000 Hz retest for the worse/left ear since the retest is a confirmation that the listener is responding consistently. Once that is determined, it is not necessary to reconfirm it.

8.3.1.3. Recording of Results

Thresholds of hearing may be recorded on a graph or in a table. Typically, the graphic form is used in clinical settings and is referred to as an audiogram. Audiograms are very helpful in explaining results because the listener can easily envision the test outcome. The procedure for graphing audiometric thresholds is specified in ANSI S3.21-1978 and an example graphical audiogram is displayed in Figure 8.4. Thresholds for the right ear are recorded with an O while thresholds for the left ear are recorded with an X. If working with colored pencils or pens, the right-ear O is written in red ink while the left-ear X is written in blue ink. Lines are drawn to connect the symbols. Since hearing levels typically are determined to the nearest 5 dB, the symbols should be aligned at the 5 dB points.

Audiogram shows frequency in Hz increasing from left to right as a logarithmic scale while intensity in decibels increases downward in a linear scale. The preferred aspect ratio is 20 dB per octave or 50 dB per decade of frequency. Thresholds for the right ear are drawn as circles, in red, and are connected with red solid lines, while thresholds for the left ear are drawn as X's, in blue, and are connected with blue solid lines. (ANSI S3.21-1978 (R-1992))

The graphic audiogram is plotted so that poorer hearing thresholds are plotted near the bottom of the chart and normal thresholds are plotted near the top. The graphic audiogram also has some other characteristics. The distance between each octave plotted along the abscissa (x axis) corresponds to the same distance represented by a 20 dB range on the ordinate (y axis). Frequency is plotted logarithmically so that there is equal distance between the octaves.

The audiogram form can be traced back to the 1920's when Western Electric developed the first electronic audiometer. In the absence of a calibration standard, it was decided that the average hearing of a group of company employees who should have had normal hearing would be 0 dB Hearing Loss. Anyone else tested would be compared to the normative employee group and their hearing loss would be plotted on the chart going down to represent decreased hearing (rather than going up on the chart to represent increased intensity of the signal at threshold). At that time, signal levels were measured in terms of voltage applied to the earphone rather than acoustic output from the earphone. Until the 1950's, each audiometer manufacturer had its own reference group of normal hearers so that 0 dB Hearing Loss was not necessarily the same signal level for competing brands of audiometers.

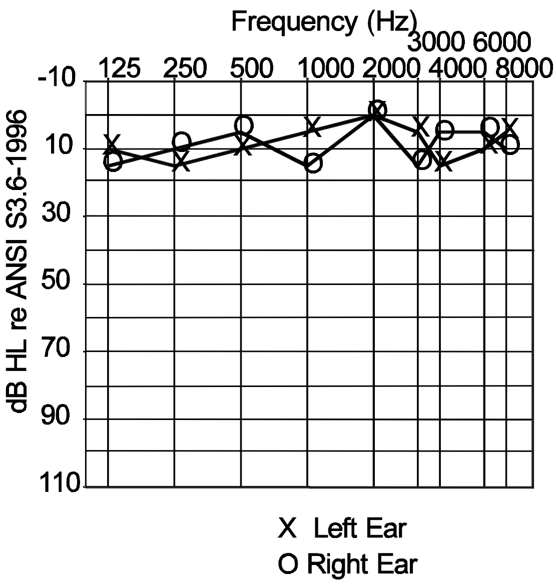


Figure 8.4. Typical graphic audiogram.

Hearing threshold levels may also be presented in a tabular format, referred to as the tabular audiogram. Table 8.4 displays an example. The advantage of the tabular audiogram is that it does not require drawing on a chart or having to read a chart or worry about colors of the lines and symbols to interpret the audiogram. The disadvantage is that is not readable at a glance as is the graphic audiogram and it does not provide much assistance for counseling listeners about their test results. Another advantage of a tabular audiogram is that one sheet of paper may contain multiple audiograms, effectively holding a record of all the tests a person may have had over a 20 to 40-year range.

Table 8.4. Tabular audiogram. Hearing thresholds are entered for each frequency. Multiple tables may be placed on single page to show hearing tests results in a serial audiogram form.

Frequency (Hz)	500	1000	2000	3000	4000	6000	8000
Right Ear (dB)	5	10	0	15	5	5	10
Left Ear (dB)	10	5	0	5	15	10	5

There is some concern that if the tester has access to a serial audiogram form with past audiometric data, there will be less care in performing the hearing test and hearing levels may be more likely to be consistent with the prior audiograms. However, a conscientious tester can avoid being influenced by prior test results. Additionally, by having access to prior tests, calculations can be made immediately to see if the changes in hearing are large enough to be considered a significant threshold shift.

Testers should make sure to record the following on the audiogram: audiometer make model, and serial number; the dates of its most recent functional and exhaustive calibrations; identification of the tester; identification of the reviewer; acceptability of the audiogram (good, fair, poor); any audiogram classification codes employed; and additional comments that might be relevant to the hearing test. This applies to both graphic and tabular audiograms.

8.3.1.4. Pitfalls

The disadvantage of manual audiometry is that the tester can make mistakes that won't be reflected in the audiogram. With several control switches to manipulate in the course of the hearing test, it is possible to make an error. Failing to change the earphone selector can result in testing the same ear twice. The threshold may be recorded on the wrong place on the graph or in the table. The tester must evaluate each listener response, make presentation level decisions accordingly, and determine which hearing level is threshold. Many testers tend to develop their own method after a time. This alone will introduce error into the audiogram.

8.3.2. Self-Recording Audiometry

Self-recording audiometry (also known as Bekesy audiometry) was introduced by George von Békésy in 1947 as an improvement over manual audiometry. Self-recording audiometry employs the use of a recording attenuator to perform the hearing test. The attenuator can either increase or decrease the signal intensity at a fixed rate of so many decibels per second (dB/sec). The listener has control of the attenuator action. By pressing the response switch, the listener will cause the signal intensity to be decreased. Upon release of the response switch, the signal intensity will be increased. The listener's threshold is somewhere between the point of pressing and the point of releasing the switch.

8.3.2.1. Instruments

Figure 8.5 shows a self-recording audiometer. These are no longer manufactured or repaired by the manufacturers in the United States, although through the middle of the 1980's they accounted for 70% of the audiometers in use in occupational settings. The audiometer records the listener's responses directly on the card. The card is marked for test ear, test frequency, and signal intensity. A pen attached to the recording attenuator draws the tracings on the card that correspond to the attenuator's setting, moving down the card as the signal level increased (no button press) and up the card as the signal level decreased (button pressed). In some cases the card is immobile and the pen not only moves in keeping with the attenuator's actions, but also moves to the from left to right at a selected rate of so much time per frequency; usually 30 seconds. In other cases, such as is shown in Figure 8.5, the card mounts on a table that moves at a fixed rate underneath the pen as the pen moves up and down in keeping with the attenuator's actions.

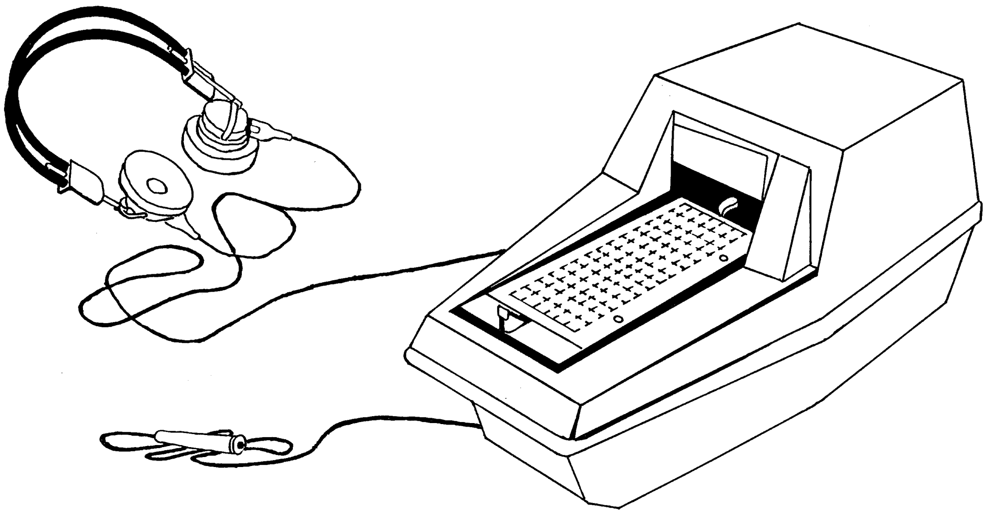


Figure 8.5. Self recording, Békésy, audiometer.

One of the reasons for the popularity of self-recording audiometers was that they could be used in multiple-person testing situations. Many audiometers could be placed in a rack, each with earphone and response switch wired to a test station in the test booth. Once instructions were given and earphones were fitted to each listener the test could be started for everyone at once. Because the test took 7.5 minutes to administer, testing for everyone would be finished at the same time. OSHA requires that self-recording audiometers to present a pulsing 200 msec-duration tone with a 50% duty cycle (200 msec on, 200 msec off) (OSHA 1983).

Figure 8.6 shows a typical audiogram card for a self-recording audiometer. There is a section for each frequency that is wide enough to contain 30 seconds of tracings. The frequencies are laid out on the card in the order that they are presented by the audiometer. The tracings provide a graph of hearing for each ear that is comparable to the audiogram graph for manual hearing testing. Once the audiogram is scored, the chart can be used as an effective counseling tool to explain the test results to the listener.

Note that the 1000 Hz retest in this case is at the end of the frequency sequence for the first test ear. It may seem that this method of testing needs no attention once started. However, it is important that the retest tracings obtained 3.5 minutes into the test (i.e., at the 1000 Hz retest) be monitored so that the test may be stopped if the retest threshold is not within 5 dB of the first 1000 Hz threshold. Of course, when the audiometry is conducted in a multiple-person test booth, it is not practical to stop testing for one person, so the test would be allowed to continue.

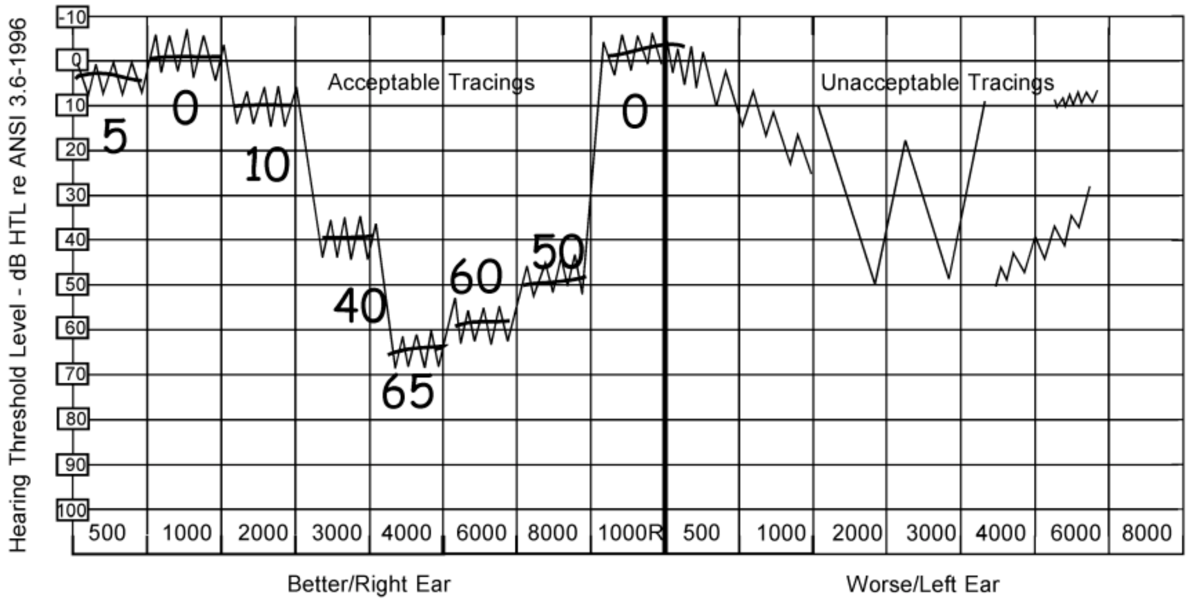


Figure 8.6. Example of audiogram from self-recording audiometer with examples of acceptable and unacceptable tracings.

Figure 8.6 shows an acceptable audiogram for the better/right ear. The tracings are consistent over the range of each test frequency such that it is easy to draw a line through the center of the tracings to determine a threshold. As a rule of thumb, a good tracing also has excursions of no less than 3 dB and no wider than 13 dB.

The chart for the worse/left ear shows some examples of unacceptable tracings.

- In the first case, the tracings may indicate a person who didn't understand the instruction and is pressing and releasing the button without regard to the tones. It may also indicate a person who is searching for a loudness range to trace rather than an audibility range.
- The second case may happen when a person presses the button only when sure of hearing the signal and releases it when sure that the signal can't be heard. With tracings this wide, it is impossible to determine where threshold is.
- The tight trace on the chart occurs when a person is quickly pressing and releasing the button. It is not possible for a person to make decisions about audibility/inaudibility so quickly when the attenuation rate is 5 dB/second.
- The rising trace occurs when the listener hears the tone and presses the button, releases the button because the signal has gotten fainter, discovers that the signal is still audible, presses the button again, and so on.

In all cases producing tracings such as these, the test should be stopped, the person should be reinstructed and testing should be started over.

8.3.2.2. Methods for scoring

Scoring the audiogram to obtain hearing thresholds is fairly simple for audiograms with acceptable tracings. A tracing to be scored should have at least six crossings. That is, there should be at least 3 excursions from button press to button release and 3 from button release to button press. The first step in scoring is to draw a line across the center of the tracings. The second step is to determine the hearing threshold level for the line. The third is to the round the hearing threshold level to the nearest 5 dB. That value should then be written above or below the tracing for each frequency. The audiogram for the better/right ear in Figure 8.6 shows the horizontal line drawn for each test frequency and the value of the assigned hearing threshold level.

In the United States, OSHA requires the following from Appendix C(2)(E) of the Hearing Conservation Amendment (OSHA 1983): *It must be possible at each test frequency to place a horizontal line segment parallel to the time axis on the audiogram, such that the audiometric tracing crosses the line segment at least six times at that test frequency. At each test frequency the threshold shall be the average of the midpoints of the tracing excursions.*

Some audiologists have adopted the practice of determining the mid point for each excursion to the nearest decibel, calculating the average for all of the excursions, and then recording the hearing threshold in 1 dB rather than 5 dB increments. While this may be appropriate for a trained listener in a laboratory setting, the gains from this type of precision for occupational hearing loss prevention purposes are minimal.

8.3.2.3. Recording of results

While it is necessary to maintain the audiogram cards for the record, when multiple years of test results are available, it will be helpful to transfer the threshold levels to a tabular form. Thus, while the card is the legal record and should not be destroyed, the tabular transfer record can be used more easily to review the chronology of test results to determine if there has been a significant threshold shift since the baseline audiogram.

Testers should make sure to record the following on the audiogram: audiometer make model, and serial number; the dates of its most recent functional and exhaustive calibrations; identification of the tester; identification of the reviewer; acceptability of the audiogram (good, fair, poor); any audiogram classification codes employed; and additional comments that might be relevant to the hearing test.

8.3.2.4. Pitfalls

There were two primary reasons for the initial popularity of self-recording audiometry. The first was that it did not require ongoing decisions from the tester as did manual audiometry and so should be free from tester bias and tester error. The second was that it worked well in group audiometry settings. However, unless the tester was careful to inspect each audiogram, audiograms with unscoreable tracings could become the permanent record.

There are people who simply cannot perform the listening task necessary for self-recording audiometry. Experience has shown that about one in seven persons will need to be reinstructed and retested. Of those about half will not be able to provide acceptable tracings for the retest. Those persons must be tested some other way, such as with a manual audiometer.

As stated earlier, self-recording audiometers are no longer manufactured in the United

States. However, there is a resale market of used U.S. manufactured audiometers and there are European manufacturers. Because the self-recording audiometer draws an audiogram, it will be necessary to have access to consumable supplies such as audiogram cards and marking pens. Without the proper card or pen, the unit can't be used.

8.3.3. Computer-Administered (Microprocessor) Audiometry

The first commercial microprocessor audiometer was the MAICO 26 introduced in 1975 and advertised as the 'unBekesy" audiometer. The microprocessor audiometer employed the modified Hughson-Westlake procedure in its code. When the test was completed, the audiometer printed out a tabular audiogram that contained additional information including the listener's identification number, the time and date of the test, and pure-tone averages over 500, 1000, and 2000 Hz, 1000, 2000, and 3000 Hz, and 2000, 3000, 4000 Hz, all of which could be used for calculations not related directly to obtaining a hearing test.

8.3.3.1. Instruments

Figure 8.7 shows a stand-alone microprocessor audiometer. Instead of dials for selecting frequency and intensity, and switches for selecting ears and presenting tones, it has a multifunction keypad. The keypad may be set up in the 10-key fashion of a calculator and numeric data such as the listener's identification number, date and time of test, and tester's identification number may be entered. These numbers will appear on the printout of the audiogram and all but the tester's identification number will be maintained for subsequent tests unless changed. Some microprocessors accept entry of the listener's baseline audiogram and at the completion of the test perform the calculation for significant threshold shift.

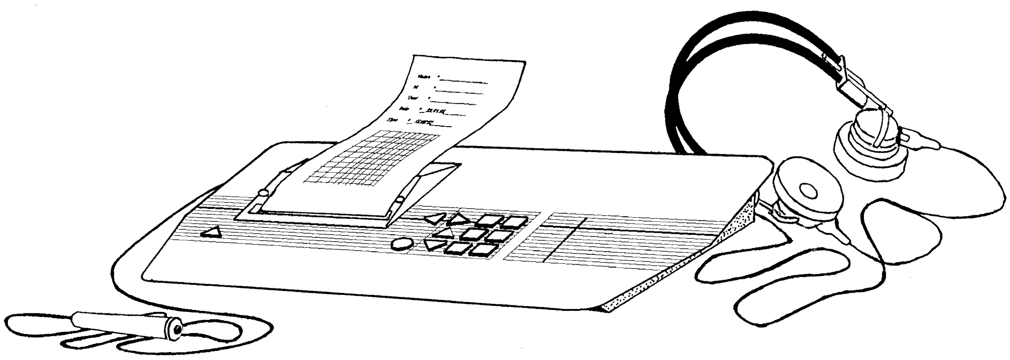


Figure 8.7. Microprocessor audiometer.

The numeric keypad has other functions such as selecting the initial test ear, scrolling through menu items seen on the audiometer's display panel, and performing manual audiometry. Finally, the keypad may be used to display the audiogram plus any stored audiograms and to direct the output of the audiogram to a printer or to a computer.

The microprocessor audiometer offers significant advantages over manual and self-recording audiometers. Since it follows a program for sequencing test frequencies and test ears, it is not possible to skip a test frequency or fail to switch ears as can happen with manual audiometry. Its program also determines how tones will be presented, how intensity will be changed in relation to listener responses, and how threshold will be defined. Thus, it provides a continuity from test to test, and when used in a multiple-person test setting, from audiometer to audiometer, that may be difficult to achieve with manual audiometry. Because there are no moving parts other than a printer, if included, it is more rugged than a self-recording audiometer.

Most microprocessor audiometers available today present the test tones to the listeners as a sequence of three 200 msec tone pulses (a tone triad). There usually is no provision for any other mode of tone presentation. The tone triad is easy to recognize and makes the testing process easier for the listeners.

8.3.3.2. Fault conditions

A simple computer program can be written to test hearing following the modified Hughson-Westlake method as is displayed in Figure 8.3. However, that procedure does not take into account listeners who press the response button when no tone has been presented. It also does not account for the listener who can't respond consistently at any presentation level or who keeps the response button pressed all of the time. Most microprocessor audiometers have rules for these occurrences in their programming. Repeated presses of the response button when no tone is present will cause the audiometer to stop testing and alert the tester of the program, providing the option to continue testing after the listener has been reinstructed or abort the test. If the listener doesn't respond consistently enough for a threshold to be determined, many of the microprocessor audiometers will move on the next ear-frequency condition and then return to the problem ear-frequency at the end of the test. If threshold still cannot be determined, the audiometer will alert the tester of the problem and provide the options of continuing after reinstruction or stopping the test. Some microprocessor audiometers will allow the problem ear-frequency conditions to be tested manually and will integrate the manually-determined threshold with the others already determined. Others will not allow a return to microprocessor audiometry once manual audiometry has started, requiring the rest of the test to be performed manually.

8.3.3.3. Recording of results

As with self-recording audiometers, the microprocessor audiometer provides its own record of the results. In this case the record is tabular. An example of such a record is shown in Figure 8.8 from a microprocessor audiometer with a built-in printer. In addition to the hearing thresholds for each ear-frequency condition, the record may provide a detailed summary of presentations and responses for each ear-frequency condition as well. The averages for key frequencies that are useful for calculating significant threshold shift and percent hearing handicap may also appear. In many cases, the listener can sign the tape with the audiogram as verification that this displays the results of his or her test.

As with self-recording audiometer charts, it is best to transcribe the audiogram to some other record keeping system as well. That system may be the serial-audiogram form. However, to do that would be to fail to take advantage of the microprocessor's ability to transfer audiometric data into a computerized database without the possibility of transcription error. For this purpose, there are commercial hearing conservation database programs that work with every microprocessor audiometer available and there are programs that audiometer manufacturers have developed for their systems.

While some microprocessor audiometers have the capability of holding up to 200 audiograms in memory so that they may be batch uploaded into the computer database at the end

Name: John Doe
ID Number 111-22-3333
Test Date 11223333
Test Time 11:22:33

Audiogram

Frequency	Left Ear	Right Ear
500	10	10
1000	10	10
2000	10	10
3000	10	10
4000	10	10
6000	10	10
8000	10	10
Ave 512	10	10
Ave 123	10	10
Ave 234	10	10
Ave 5123	10	10
Ave 1234	10	10

Tester ID
Signature
Audiometer Serial Number
Date of Calibration
Test Room Noise Level dB(A)

Figure 8.8. Microprocessor audiogram printout.

of a testing day, a week or whatever, this is not a good practice. It is better to have direct, live access to the computer with the database or at least to that portion of the database relevant to testing. This allows immediate comparison to baseline audiograms and other information while the person is being tested. Thus, rational, realistic, and practical decisions can be made on the spot instead of days or weeks later when the opportunity to follow up with the person has been lost. It is possible to transfer the baseline audiograms of each person to be tested into the audiometer's memory so that it may perform the calculations for significant threshold shift, but it is less cumbersome to have the audiometer connected to the database and let the computer do the calculations.

Testers should make sure to record the following on the audiogram: audiometer make model, and serial number; the dates of its most recent functional and exhaustive calibrations; identification of the tester; identification of the reviewer; acceptability of the audiogram (good, fair, poor); any audiogram classification codes employed; and additional comments that might be relevant to the hearing test.

8.3.3.4. Pitfalls

The microprocessor audiometer has taken the place of the self-recording audiometer in the multiple-person testing environment. It is attractive because at face value it performs the equivalent of the manual test. Once instructions are given and earphones are fitted, all audiometers may be started at once.

However, the tests will not all end at the same time. Some persons with good hearing or with lack of tinnitus may finish very quickly while others with poorer hearing or tinnitus who are uncertain of what they are hearing will require many more presentations and will finish later. For those with many false positives or for whom the audiometer is not able to resolve threshold at one or more frequencies, the audiometer will have stopped, awaiting intervention by the tester. The tester must be able to intervene in these cases without disrupting the test sequence for those whose hearing tests are not complicated.

Some microprocessor audiometers have a talk-through circuit so that the tester can tell those with tests that have halted what to do or what to expect next. The talk-through circuit can be used to tell those whose tests are completed to not remove their earphones and to sit and wait quietly until the tester comes into the test booth. The tester could also provide reinstruction for some and then resume the test. However, talk-through circuits only enable one-way communication, so it is not possible for the listener to tell the tester what the problem may be.

In the United States, the Hearing Conservation Amendment, 29 CFR 1910.95(g)(3) states that *a technician who operates microprocessor audiometer does not need to be certified.* This is a poor exemption. A technician operating a microprocessor audiometer must know the ins and outs of microprocessor audiometry and of manual audiometry since he or she will be called to perform manual audiometry for those whose audiograms the microprocessor audiometer can't complete. Those who think of a computerized audiometer as an expert system capable of responding to all contingencies clearly have little experience with administering audiograms in an occupational setting.

While all microprocessor audiometers available in the United States employ the modified Hughson-Westlake procedure, no two manufacturers implement the procedure in precisely the same way. Thus, there will be differences between audiograms obtained on audiometers from two different manufacturers. The manufacturers have not been willing to share the code for their testing procedures with anyone, including the American National Standards Institute working group on computerized audiometry (S3/WG76). Thus, it is not possible to determine what and why differences occur between audiometer types.

8.3.4. Test-Retest Reliability and Differences Within and Across Procedures

8.3.4.1. test-retest reliability and differences within methods

Whenever any type of psychometric measurement is made, there will be variation from time to time as the test is readministered. This applies to tests of intelligence as well as to tests of hearing. There are systematic and random error sources in audiometry that affect the results (Hétu 1979). They are:

- audiometer calibration error or drift
- excessive background noise levels in the test room
- interfering signals from the test equipment
- earphone placement
- tester bias and examination procedure bias
- improvement in performance due to familiarity with the examination procedure
- residual temporary threshold shift at the time of the examination
- partial or complete obstruction of the external auditory canal
- presence of tinnitus
- functional hearing loss
- fluctuation in the subjective criterion of audibility by the subject.

Many of these error sources can be minimized by careful control of the testing environment. Careful calibration and day-to-day monitoring of the audiometer, test room, and other equipment can reduce the effects of audiometer miscalibration, excessive background noise, and spurious instrument noises. Errors due to earphone placement inconsistencies can be reduced by having only the tester fit the earphones before the start of each test. Insufficient earphone headband force can be managed by having the tester remove the earphones at the completion of each test and place them on a mounting block that has cups for the earphone cushions; a bioacoustic simulator provides a perfect place for earphones when not used for testing in addition to providing a means of managing the day-to-day calibration check of the audiometer.

Tester bias and improvements in performance due to familiarity with the test procedure can be controlled by the tester. In the first case for manual audiometry, if the tester follows the same protocol test after test, test bias can all but be eliminated. In the second case, if complete test instructions are given at the beginning of each hearing test, no matter how many hearing tests a person has had previously, listeners will always begin at the same point and familiarity should not have an effect on the audiogram.

Instructions also have bearing on the listener's criterion for responding that a tone was heard. Most people, upon being told to signal when they hear a tone will wait until they are sure that they clearly heard a tone; they will have a strict response criterion. A few people will respond whenever they perceive a tone regardless of their certainty level; they have a lax criterion. The instructions presented for each of the test methods later in this chapter (sections 8.8.3.1 through 8.8.3.4) are designed to shift the response criteria to a middle level criterion for those who normally start a hearing test with a strict criterion. The instructions should have little effect on those with a lax criterion and it may be necessary, after testing has begun if there are more than three false positive responses–responses with no signal presented–to advise these listeners to respond only when they are sure that they hear a tone to move them to a moderate criterion.

An alert tester can also reduce error due to tinnitus and obstruction of the ear canal. Listeners should be asked prior to testing if they have ringing in the ears or other head noises that become more audible in quiet. If the listener indicates tinnitus or head noises, the tester should remind the listener that the tones will be pulsed and even presented in triads for microprocessor-controlled audiometry. Adding to the listener's criteria for response the necessity of hearing pulsing tones can help most listeners with tinnitus. A cursory otoscopic examination should precede all hearing tests; thus obstructions can be noted and listeners can even be referred for cerumen removal.

Residual temporary threshold shift is a curse and a blessing for the tester. It is a curse when performing baseline, confirmation, or exit audiometry; for those are the occasions when it is necessary to obtain the best measures of how a person hears. Consequently, care must be taken to ensure that a quiet period (exposure to no loud sounds) of 12 to 14 hours precedes the hearing test. Earmuffs or other forms of hearing protection should not be used to obtain the quiet period. For the annual or periodic audiogram, residual temporary threshold shift is a blessing. It is a blessing if temporary threshold shift is identified during the periodic audiometry, because then interventions can be employed to prevent temporary threshold shift before it becomes permanent threshold shift. Thus, it is recommended that periodic audiometry be performed during and toward the end of work shifts so that any temporary threshold shift due to work place noise can be identified.

The listener with a functional hearing loss, responding only to signal levels that are clearly audible often using a loudness rather than a threshold criterion, presents a difficult challenge.

Most listeners will not conceive of "cheating" on a hearing test by not following the instructions. However, a few of those with something to gain from exaggerated hearing loss may adopt a loudness-based rather than a just-detectable-based criterion for responding. There are many ways to detect such responses and to resolve the functional hearing loss, but they are beyond the scope of this chapter as they involve more than pure-tone air-conduction audiometry.

8.3.4.2. Manual versus Békésy

Manual audiometry will usually provide slightly higher thresholds than Békésy audiometry. This is not because Békésy audiometry is more sensitive than manual. It is related to the range of signal levels presented to the listener. In manual audiometry, the listener is presented signals and responds to those he or she hears. If a person responds, for example, at 10 dB HL and not at 5 dB HL, the threshold will be recorded as 10 dB HL. In Békésy audiometry the listener responds by pressing the response button when the tones are audible and by releasing the response button when the tones become in audible. Given the time it takes to make a decision and respond and the rate of attenuation, the point at which the listener releases the response switch will be a few decibels below the signal level the listener can actually hear. At an attenuation rate of 5 dB/second with a respond latency of 0.5 seconds, the listener will release the response switch when the signal level is at least 2 dB below his or her threshold. The same applies to pressing the response switch in response to hearing the tones. The signal level will be 2 or more decibels above the point of audibility when the response is made. This would seem to even out so that there should be no difference between manual and Békésy methods.

However, given the example of the listener with a 10 dB HL manual threshold, the actual threshold may be 6 dB HL, a level not tested by manual audiometry. So the listener responds by pressing the response button at 9 dB HL, 3 dB above the point of audibility, and by releasing the button at 3 dB HL, 3 dB below threshold, providing a tracing that is 6 dB wide with a mid-point at 6 dB HL. The 6 dB HL threshold would be rounded to the nearest 5 dB and recorded as 5 dB HL, 5 dB less than the 10 dB HL threshold from manual audiometry for the same person. So, in general, Békésy thresholds should be 3 to 4 dB lower than thresholds from manual audiometry. This is consistent with the findings of Harris (1980).

A 6 dB trace width is very good and usually provided only by experienced listeners. Most will provide a wider trace width, pressing the button when they first hear the tones and releasing the button when they are sure they don't hear the tones, thus providing a lower estimate of threshold of hearing than would be obtained with manual audiometry.

8.3.4.3. Manual versus microprocessor

Since the microprocessor-controlled audiometry procedure is an emulation of the modified Hughson-Westlake procedure, there are no apparent reasons for differences between the two procedures. In fact, Jerlvall, Dryselius and Arlinger (1983) and Cook and Creech (1983) have demonstrated that to the extent that the microprocessor method duplicates a manual method, there will be no differences.

8.3.4.4. Differences in Microprocessors

There is no standard method for microprocessor controlled audiometry. As noted above, manufacturers of microprocessor controlled audiometers have not been forthcoming with the details of their methods and their criteria for threshold assignment. Harris (1980) found that differences of 3.5 dB could be demonstrated just by changing the instructions to the listener. Requiring the listener to press the response button upon hearing the tone and releasing it after the tone was discontinued resulted in higher thresholds than simply requiring the listener to press and release the response button when a tone was thought to have been heard.

8.4. AUDIOMETER CALIBRATION

For audiograms to have any value at all, the audiometers must be in calibration. Thus, it is necessary to check the audiometer calibration no less than daily before use. In addition, records of calibrations must be maintained and dates of calibrations should become part of the permanent audiometric record.

8.4.1. Functional Checks

A functional check is just that, a check to make sure the audiometer's functions are operative. This is often called a listening check because functional checks are performed by listening to the audiometer while checking its functions and state of readiness. The goal of the functional check is to make sure that the audiometer is able to generate tones, gate tones, change levels, switch ears, and work with the response switch without introducing distortions, clicks, and drop outs.

Most audiometer manufacturers will provide a guide for performing a functional check. A suggested procedure follows:

A. Set the audiometer to 70 dB HTL, 1000 Hz, output to right ear.

B. Turn the tone selector to continuous on or, if not possible, for a train of pulses either automatically or by repeated pressing the presentation switch.

C. Listen to the tone; it should sound clear. If pulsing, there should be no noticeable click at the beginning or end of the tone pulse.

D. Wiggle the earphone cords. There should be no noise on the line nor should there be any interruption of the tone. Gently pull on the earphone cords where they enter the earphones and as they come from the back of the audiometer or test room jack panel. There should be no noise on the line nor should there be any interruption of the tone.

E. Switch the signal from right to left ear. The tones should be equally as loud.

F. Press the response button. There should be no clicking in the earphone for either the press or release of the button.

G. Change the signal intensity up and then down. There should be no clicking as the level is changed.

H. Change the frequency dial. The tones should start with no clicking noise and the tone should not seem to ramp up or down in frequency.

I. Set the intensity back to 70 dB HTL. Unplug the left earphone and listen through the right while selecting each test frequency. No tones should be audible. Repeat by sending the signal to the unplugged right earphone and listening to the reconnected left earphone.

8.4.2 Acoustic Output Checks

In the United States, OSHA requires a functional check that includes testing the hearing of someone with known hearing (29 CFR 1910.95(h)(5)(i)): *The functional operation of the audiometer shall be checked before each day's use by testing a person with known, stable hearing thresholds, and by listening to the audiometer's output to make sure that the output is free from distorted or unwanted sounds. Deviations of 10 decibels or greater require an acoustic calibration*. For the purposes here, OSHA is describing both a functional and daily threshold check.

8.4.2.1. Daily threshold check

The daily threshold check is a confirmation that the calibration of the audiometer remains unchanged. Each day before use, or each time an audiometer is relocated, a hearing test is administered to a person with known, stable hearing. It is not necessary for the person tested to have normal hearing. While being tested, the listener should also listen for artifacts that might have been missed during the functional check. The person being tested should not be the tester self-administering the hearing test, for response decisions may be made on what is expected rather than on what is heard. Changes of 10 dB or more require the audiometer to be acoustically calibrated before it is used.

8.4.2.2. Bioacoustic simulators

It may not always to be possible to have the same person or persons with known hearing available for the daily threshold check. It is also difficult to perform a daily threshold check on a bank of 8, 10, or 12 audiometers used in a multiple-person test booth. The bioacoustic simulator can take the place of the person with known hearing.

Figure 8.9 displays a typical bioacoustic simulator. The simulator uses acoustic couplers designed to accept the full-size MX41/AR cushion and earphone mounted on the headband. Microphones are located within the couplers. An electronic circuit closes a switch when the signal level exceeds a preset threshold and opens the switch when the signal level is below the threshold, thus simulating a listener. It may be used with any manual audiometer with a response switch and indicator lamp as well as with a Békésy or microprocessor-controlled audiometer . Because the electronic switch responds faster than a listener and doesn't have the signal uncertainty problems of a listener, the Békésy tracings will be very tight, of the order of a couple of decibels. The simulators cannot be used with microprocessor audiometers requiring unusual response patterns such as holding the response switch until the signal stops or counting pulses before responding.

Each simulator has its own characteristic "audiogram," so the same simulator must be used with a given audiometer, day in and day out. Each unit will be set to respond around 65 dB HL for the test frequencies, but as the microphones are not laboratory quality, there can be variations of as much as 15 dB between units and thus each unit is supplied with its own reference audiogram. As with the daily threshold test, changes of 10 dB or more require acoustic calibration of the audiometer before it is used. The nature of the simulator microphones and electronic circuits is such that they work properly or not at all, so they do not require periodic calibration as they will not drift.

Some simulators have circuitry to measure ambient noise levels. Whenever the background noise levels in the test booth exceed a preset threshold, a lamp associated with the octave-band center frequency lights to alert the tester. Obviously, these lamps will light when there is any activity in the test booth such as giving the listener instructions, but they should not light when the test booth door is closed and testing is underway. While these units may be used to monitor ambient test booth noise, they may not be a substitute for using a sound level meter to measure and document test room ambient noise levels.

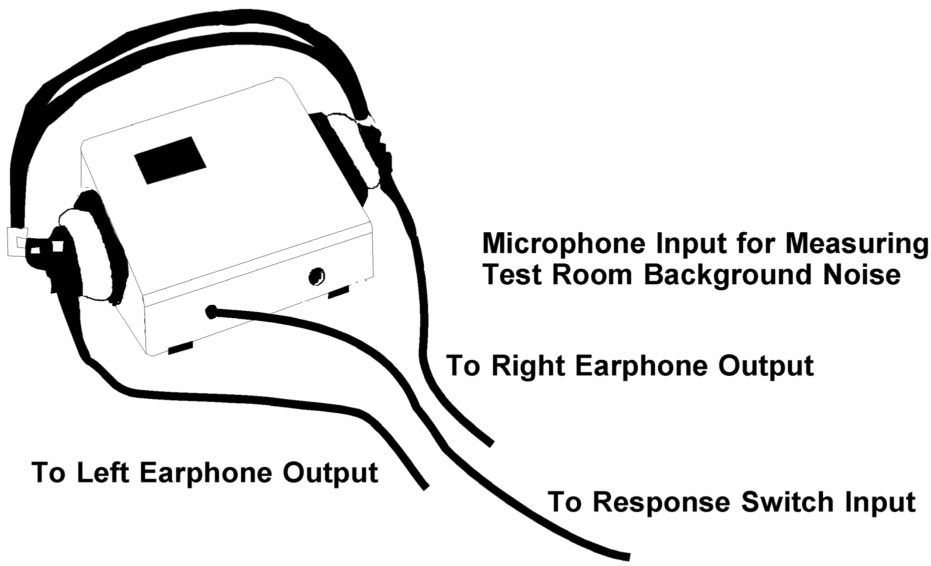


Figure 8.9. Bioacoustic simulator.

In the United States the default pre-set simulator criteria levels are those of OSHA's Appendix D, Table D-1 (see Table 8.2) rather than those of ANSI S3.1-1996 for ears covered. One model of simulators (Quest Technologies BA 210-25) may be set to the criteria levels of Appendix D, Table D-1 (see Table 8.2) of the 1981 OSHA Hearing Conservation Amendment (OSHA 1981). These are the same levels as recommended by the National Hearing Conservation Association for mobile test vans (NHCA 1996).

8.4.3. Acoustic and Exhaustive Calibrations

If the daily threshold check shows that there has been a change of 10 dB or more, it is necessary to take the audiometer out of service and use a sound level meter to determine its output levels. The output level will be noted in terms of its deviation from the level specified by the audiometer reference standard. This is referred to as an acoustic calibration check. During an exhaustive calibration, the output levels are actually set to meet those specified by the audiometer standard (e.g., ANSI S3.6-1996).

8.4.3.1. Acoustic calibration check

The acoustic calibration check requires a sound level meter, an acoustic coupler, and a set of octave-band filters. In the United States the meter must meet type II specification re ANSI S1.4-

1983. The coupler must be an NBS-9A or equivalent with an effective volume of 6 ml (the effective volume is the combined actual volume of the coupler and the equivalent volume of the sound level meter microphone and the earphone - the coupler is often referred to as a 6-cc coupler). The earphone in its cushion is placed on the coupler so that the plane of the earphone diaphragm is parallel to the diaphragm of the microphone and so that there are no leaks between the earphone cushion and coupler lip. The earphone is weighted with a 500-gram weight that effectively compresses the earphone cushion to the coupler. Morrill (1986) suggests that with the proper equipment and training the tester can perform the acoustic calibration, thus avoiding having to ship the unit for calibration which alone can have effects on the outcome.

It is important to note that audiometers are calibrated with specific earphones. Replacing the earphones of an audiometer with those of another will result in both audiometers being out of calibration. This is true even when the earphones are the same type and model. The calibration is for the earphones and the audiometer as an integral set. If an audiometer is taken out of service for any reason, the earphones used with that audiometer should also be taken out of service. Likewise, when an audiometer is sent away for calibration, its earphones must be sent with it.

8.4.3.1.1. Coupling the earphone. The goal of this part is to ensure that the earphone is well coupled to the sound level meter and that there are no leaks that would cause inaccurate sound pressure level readings. The earphone and weight should be placed on the coupler. The audiometer should be set to produce a continuous signal at 70 dB HTL at the lowest test frequency (125 Hz on clinical audiometers, 250 or 500 Hz on type 3 or 4 pure-tone air-conduction audiometers). The earphone is then adjusted on the coupler to produce the highest sound pressure level reading on the sound level meter. Then the earphone and weight are removed and the process is repeated. The same reading should be obtained. If so, the earphone should remain on the coupler for the rest of its calibration. If not, the earphone and weight should be removed and the process should be repeated until a sound pressure level reading is duplicated on successive placements and adjustments.

8.4.3.1.2. Measuring output for comparison to the standard. The following steps are adapted from Appendix E of the OSHA Hearing Conservation Amendment (OSHA 1983). The procedures are valid regardless of the earphone or calibration standard used. There are three parts: sound pressure output check, linearity check, and tolerances.

Sound pressure output check

A. Place the earphone on the coupler as described in Section 8.4.3.1.1.
B. Set the audiometer's hearing threshold level (HTL) dial to 70 dB.
C. Measure the sound pressure level of the tones at each test frequency from 500 Hz through 8000 Hz for each earphone.
D. At each frequency the readout on the sound level meter should correspond to the levels in Table 8.5 for the type of earphone, in the column entitled "sound level meter reading." There is a debate as to whether or not the Telephonics TDH 39 earphone had a calibration artifact at 6000 Hz. Many advocate making a correction for the artifact, others do not. In the United States, OSHA has not addressed the matter.

Table 8.5 Reference threshold levels for Telephonics -TDH-39/49

Frequency (Hz)	Reference threshold for TDH-39 earphones	Sound level meter reading at 70 dB HTL for TDH-39 earphones	Reference threshold for TDH-49/51 earphones	Sound level meter reading at 70 dB HTL for TDH-49/51 earphones
500	11.5	81.5	13.5	83.5
1000	7	77	7.5	77.5
2000	9	79	11	81
3000	10	80	9.5	79.5
4000	9.5	79.5	10.5	80.5
6000	15.5	85.5	13.5	83.5
8000	13	83	13	83

Linearity check

A. With the earphone still in place on the coupler, set the audiometer frequency to 1000 Hz, the HTL dial on the audiometer to 70 dB and the frequency band on the sound level meter octave band filter to 1000 Hz.

B. Measure the sound levels in the coupler at each 10 dB decrement from 70 dB to 10 dB, noting the sound level meter reading at each setting.

C. For each 10 dB decrement on the audiometer the sound level meter should indicate a corresponding 10 dB decrease.

D. Alternatively, this measurement may be made electrically with a voltmeter connected to the earphone terminals. The dynamic earphone is also a very efficient microphone and care must be taken when performing electrical measurements that the signal being measured is from the audiometer, not from the earphone that is picking up environmental sounds.

Tolerances. When any of the measured sound levels deviate from the levels in 8.5 by + or - 3 dB at any test frequency between 500 and 3000 Hz, 4 dB at 4000 Hz, or 5 dB at 6000 and 8000 Hz, an exhaustive calibration is advised. ANSI S3.6-1996 requires that each change of 5 dB in HTL have a corresponding change in sound pressure level of ± 1.5 dB.

8.4.3.2. Exhaustive calibration

An exhaustive calibration requires the use of a sound level meter, octave band filters, an acoustic coupler and other instrumentation. Exhaustive audiometer calibrations should be performed by trained personnel who are familiar with the operations of audiometers, who have the necessary equipment, and who may adjust the audiometer to bring it back into calibration where necessary. Thus, it is often necessary to send the audiometer away for exhaustive calibration. If such is the case, an acoustic calibration should be performed upon its return. Also, if a bioacoustic simulator is used for daily threshold checks, it is important to perform a simulator test with the newly calibrated audiometer to obtain new reference levels.

NIOSH recommends and OSHA requires that audiometers receive an exhaustive calibration every two years in accordance with relevant sections of ANSI S3.6-1996. These include measuring output levels and output frequencies with comparison to tolerances of the standard, evaluating distortion of the test signals, checking for channel crosstalk and any other unwanted sounds in the earphone, and measuring duty cycle and rise/fall time of the signal when gated on and off. If the measurements for the audiometer are outside of specified tolerances, repairs or adjustment in calibration must be made before the audiometer may be placed back into service.

Since every audiometer will receive an exhaustive calibration at least every two years (more frequently if a substantial problem arises), it is important that instructions for resetting the output level of the audiometer be given to the technician performing the exhaustive calibration. Over time, the output levels of audiometers may drift away from the specified levels, but will remain within the tolerance range. If this is the case, it is important to tell the calibrating technician to not adjust the output level to bring it back to the exact specified level. Resetting the output level back to the exact specified level in the standard every two years will introduce a new source of variability into the hearing conservation database (see Section 8.3.4) and may result in a sudden increase in the number of workers identified as having a significant threshold shift.

There are not universal standards for certifying calibration technicians. In the United States, only Texas licenses audiometer calibration technicians who are required to pass an examination. Massachusetts requires that all audiometers used in the public schools to screen school children be sent to the state facility every summer for calibration. In the absence of calibration technician certification standards, it is best to have an audiometer calibrated by the firm that sold it or by a firm that is recognized by the manufacturer as an authorized repair facility for its audiometers. A few audiometers must be sent to the manufacturer for calibration and, except for damage that may be encountered during shipment, the likelihood that correct procedures will be used is good.

8.4.4. Calibration Records

At a minimum, calibration records should be kept with the audiometer as long as it is in service. A better practice would be to maintain the audiometer calibration records as long as there are persons currently receiving hearing tests who were tested at any time in the past with the audiometer in question. Ambient test-booth noise levels should be recorded on the audiograms and maintained separately for as long as the booth is in service. These records are important when workers' compensation claims are filed and when regulatory agencies are reviewing the hearing loss prevention program.

It is also important to place the biological or functional calibration and the exhaustive calibration dates on the audiogram. In the United States, state compensation claims for hearing loss are often filed at the termination of employment or at retirement (Gasaway 1985). When the employer cannot produce records of ambient noise levels and audiometer calibrations, there is very little protection level against the claim if it should reach litigation.

8.5. THRESHOLD SHIFT

In the United States, OSHA and the Mine Safety and Health Administration (MSHA), presently have definitions different from NIOSH of the amount of change in hearing indicated by repeat audiometry that should trigger additional audiometric testing and related follow up. OSHA and MSHA use the term Standard Threshold Shift (STS) to describe and average change in hearing from the baseline levels of 10 dB or more at the frequencies 2000, 3000, and 4000 Hz. Upon finding OSHA/MSHA STS, certain actions are mandated including retest, evaluation of the adequacy of hearing protectors or requiring their use if not used prior to the STS event, and revision of the baseline audiogram. NIOSH uses the term Significant Threshold Shift to describe a change from baseline levels of 15 dB or more at any single test frequency 500 through 6000 Hz that is also present on an retest for the same ear-frequency condition. The NIOSH Significant Threshold Shift, called the 15 dB twice, same-ear, same-frequency method, can only be calculated and subsequently employed if the baseline audiogram is available for comparison at the time of the annual audiometric test. OSHA and MSHA do not require immediate check for Standard Threshold Shift. As a result, it may be days, weeks, or even months before the Standard Threshold Shift is documented and subsequent follow-up actions commence.

8.6. TYPES OF AUDIOGRAMS

Audiometric monitoring is critical to the success of a hearing loss prevention program in that it is the only way to determine whether occupational hearing loss is being prevented. When the comparison of audiograms shows temporary threshold shift (a temporary hearing loss due to noise exposure), early permanent threshold shift, or progressive hearing loss, it is time to take swift action to halt the hearing loss before additional deterioration occurs. Because occupational hearing loss occurs insidiously and is not accompanied by pain or other symptoms, the affected worker will not notice the change until a large threshold shift has accumulated. The results of audiometric tests can trigger changes in the hearing loss prevention program more promptly, initiating protective measures before the hearing loss becomes handicapping, and motivating employees to prevent further hearing loss.

8.6.1. Baseline Audiogram

The baseline audiogram is the audiogram obtained when someone is initially hired to work in a situation where potentially hazardous noise exists. NIOSH recommends that the baseline audiogram be obtained prior to employment or placement into hazardous noise. In order for the baseline to represent the best hearing that a person has prior to noise exposure, it is important that the period of time prior to the hearing test be free from exposure to high-level noise. If the person has not been exposed to high-level noise(defined as noise above 80 dB(A), occupational and non-occupational) for between 12 to 14 hours prior to the test, then the baseline audiogram should represent best hearing (i.e., be uncontaminated by temporary threshold shift). This is analogous to requiring a fasting period before tests are made of blood cholesterol levels. The goal is the same, baseline levels with no prior activity that would raise levels. (While OSHA requires a 14-hour pretest quiet period, NIOSH recommends 12 hours since the amount of recovery from temporary threshold shift for 12 versus 14 hours is negligible. A 12-hour is easier to manage for those employees with compressed work schedules such as four 10-hour days)

Many have suggested that in lieu of actual quiet, hearing protectors may be used prior to the baseline audiogram to achieve the pretest quiet period. While this makes management easier for the employer, it does not guarantee that the worker has actually had a quiet period. Research has shown that the noise reduction labels for hearing protectors over-predict the amount of actual noise reduction by as much as 2000% (Berger, Franks, and Lindgren 1996). Thus, an audiogram that at face value is supposed to provide best hearing levels may, in fact, have a temporary threshold shift overlay. The best approach is to keep the employee from all known occupational noise exposures and to provide advice on how to avoid non-occupational hazardous noise. The following advice may be used as a practical guideline for helping the employee to know when noise is too loud: *if talking with someone in a background of noise requires raising one's voice to be heard at a distance of 1 m, the noise may be hazardous and should be avoided*. This same advice should also be given to a person to be seen for a baseline audiogram as part of a pre-employment evaluation.

8.6.2. Periodic-annual audiogram

In the United States, OSHA requires annual hearing testing for those exposed to noise levels equal or greater than 50% of the permissible exposure limit of 90 dB(A) eight-hour time-weighted average (TWA_8). The TWA_8 is based on a 5 dB exchange rate, so workers with exposures of 85 dB(A) TWA_8 are enrolled in the hearing conservation program and receive annual hearing testing. NIOSH, on the other hand, recommends that all employees exposed at or above the recommended exposure limit of 85 dB(A) $L_{Aeq,8h}$ receive annual hearing testing. NIOSH further recommends that the hearing tests be administered from the middle to the end of the work shift so that those employees who are experiencing temporary threshold shift may be identified. OSHA has no similar requirement or recommendation.

*Editors‘ note**:** Appropiate procedures for baseline and periodic audiograms should be adopted in line with national practice and guidance. But one should have in mind that practising different procedures for baseline and periodic audiograms as expressed in this chapter has its implications, e.g. identification of the temporary threshold shift depends on the execution of a strict timetable related to the immediate daily noise impact, which is for various reasons impossible to manage properly in most cases.*

For many companies that must use an outside provider of hearing tests, such as mobile audiometry testing services, it is most effective to test the hearing of all workers once a year over a few-day period. For companies that have on-site facilities for hearing testing, it is often convenient to test an employee at the same time every year, such as on a birthday or anniversary of employment. It is not always possible to ensure that all workers are tested exactly on the anniversary of the previous audiogram, so an acceptable window of time would be from 9 months to 15 months after the previous audiogram.

Noise-induced hearing loss can develop rapidly in workers exposed to relatively high noise levels on a daily basis. For example, the most susceptible 3 percent of a population exposed to average unprotected noise levels of 100 dB(A) $L_{Aeq,8h}$ could be expected to develop significant hearing threshold shifts before the end of one year (ANSI S3.44-1997). Thus, it may be good practice to provide audiometry twice a year to workers exposed to noise levels that equal or exceed 100 dB(A) $L_{Aeq,8h}$.

8.6.3. Immediate Retest Audiogram

In order to determine if a significant threshold shift exists, it is necessary to have access to the baseline audiogram. If the audiometry is done remotely from where the hearing loss prevention program's records are kept, it will not be possible to do the determination at the time of the periodic audiogram while the worker is still accessible to the tester and test facility. When this is the case, a confirmation audiogram must be rescheduled for every worker with a significant threshold shift.

However, when the baseline audiograms are immediately accessible, a check for significant threshold shift may be made as soon as the hearing test is complete. If the condition for significant threshold shift is met, the worker can be reinstructed, the earphones can be refitted, and the hearing test may be administered again. Experience of some vendors finds that as many as 70% of those showing significant threshold shift on the periodic audiogram will not substantiate the shift on the immediate retest.

There are many reasons for this, the most common reason being familiarization with the threshold task of responding to low-level signals after a portion of the test has been completed, lack of concentration on the first test, or poor placement of earphones. When instructions are given again and the earphones are refitted, all of these situations may resolve and the immediate retest audiogram will show hearing levels not significantly different from those of the baseline audiogram.

8.6.4. Confirmation Audiogram

The confirmation audiogram is scheduled for all persons whose periodic audiogram or immediate retest audiogram indicated significant threshold shift. Those audiograms are considered to show pending significant threshold shift. If no confirmation audiogram were scheduled, those audiograms would automatically become confirmed significant threshold shift and thus the new reference audiogram (revised baseline audiogram) at the time of the next periodic audiogram.

As with the baseline audiogram, the confirmation audiogram should be preceded by at least a 12 to 14-hour quiet period, a period with no exposure to high-level occupational or non-occupational noise. As with the baseline audiogram, hearing protection should not be used to achieve the quiet. If the confirmation audiogram affirms the significant threshold shift, some follow-up actions are necessary. The first action involves assessing the worker's noise exposure, the adequacy of the worker's hearing protection and his or her ability to wear them correctly, and the training the worker has received about noise effects on hearing, protector use, and avoidance of hazardous noise at and away from work. The second action involves a determination that the threshold shift was not due to a factor other than exposure to noise. While this determination is not the purview of the occupational hearing conservationist, there are guidelines for making referrals to physicians for the purpose of establishing threshold etiologies (AAO 1983). More often than not, exposure to noise will be the default etiology in the absence of any other explanation. A third action might be recording the standard threshold shift as an occupational hearing loss on the OSHA Form 300 log or similar form.

If the confirmation audiogram fails to confirm the significant threshold shift and, if an immediate retest audiogram were performed, then the shift can be considered as a temporary threshold shift. OSHA gives no guidance regarding the management of those with temporary threshold shift. NIOSH recommends that the same actions be followed as for the worker with a confirmed threshold shift, other than referring the worker for a medical evaluation. In fact, this is a case where intervention with a better selection of hearing protectors and further training in recognizing noise hazards for best self-protective behaviors has a chance at preventing a permanent threshold shift. Successful intervention for the worker with temporary threshold shift makes the periodic audiometry program a tool for hearing loss prevention instead of a tool for hearing loss documentation.

8.6.5. Exit Audiogram

It is good practice to obtain an audiogram for those workers leaving a place or position with exposure to hazardous noise, whether because of transfer, cessation of employment, or retirement. The exit audiogram should be preceded by a period of quiet just as the baseline and confirmation audiograms. The audiogram will provide the best estimate of the worker's hearing at the termination of exposure to workplace noise for this employment situation.

The exit audiogram has more value for the employer than the employee, because it specifies the amount of hearing loss incurred while employed in this situation. In states where employers pay workers' compensation for only the amount of hearing loss acquired while the worker was on the payroll, the exit audiogram can limit employer liability.

8.6.6. Considerations for All Audiograms

Adherence to the following practices will ensure the best possible quality of audiograms:

- The audiograms should be administered using properly calibrated audiometers in a sound-treated room with acceptable ambient noise levels during testing. Circumaural earphone enclosures (earphones inside earmuffs), which are purported to reduce external noise, should not be substituted for a sound-treated room, and generally should not be used because of inherent problems with calibration and earphone placement.

- The same type of audiometer (and preferably the same instrument) should be used from year to year. This may help prevent measurement variations caused by subtle differences among instrument models/types or by the type of responses required from the person being tested.

- The training of audiometric technicians should meet as a minimum, in the United States and Canada, the current requirements of the Council for Accreditation in Occupational Hearing Conservation and any state requirements for audiometrists. Use of microprocessor-controlled or computer-based audiometric equipment should not exempt a technician from receiving training.

- All audiometric technicians should use the same testing methods for all of the company's employees.

- All testing should be done under the supervision of an audiologist or a physician knowledgeable about hearing loss prevention.

8.7. TRAINING AND SUPERVISION OF AUDIOMETRIC TESTING PERSONNEL

There is a tendency for the training of audiometric testing personnel to be dismissed as not really important. After all, this is only a pure-tone audiogram, not a diagnostic clinical test. In fact, the importance of the test itself is often diminished by referring to it as a "screening test." So, it is not uncommon to encounter the attitude that "anyone can do a hearing test."

In reality, the well administered pure-tone audiogram is the tool that signals the need for intervention by identifying temporary threshold shift so that interventions can be employed to prevent permanent threshold shift. Thus, technicians must be well trained and be responsible to an audiologist or physician knowledgeable in the prevention of occupational hearing loss. *(See Editors' note in section 8.6.2)*

8.7.1. Occupational Hearing Conservationists

In the United States, certification of audiometric technicians dates back to 1965 when the Intersociety Committee was started by the American Association of Industrial Health Nurses, the American Industrial Hygiene Association, the Industrial Medicine Association, and the American Speech and Hearing Association. In 1966 the Intersociety Committee published the Guide for the Training of Industrial Audiometry Technicians (Intersociety Committee on Industrial Audiometric Technician Training 1966).

In 1972, the Intersociety changed its name to the Council for Accreditation in Occupational Hearing Conservation (CAOHC) and added additional representatives from the American Council for Otolaryngology, the Academy of Occupational and environmental Medicine, the National Safety Council, and the National Hearing Conservation Association as well as from the founding organizations and their successors. CAOHC is the only professional group involved in the development, review, and approval of course work that leads to a recognized certification. Each course director, who must be separately certified by CAOHC, must submit an occupational hearing conservation training course outline and faculty list to CAOHC before the course is taught and must use approved training materials. Those technicians completing the course are eligible for a five-year certificate in Occupational Hearing Conservation. The certificate may be renewed by taking a refresher course every five years.

The American Speech-Language-Hearing Association (ASHA), the certification body for audiologists in the United States, does not certify audiometric technicians or hearing conservationists. ASHA is one of the professional organizations with representation in CAOHC and so has influence in its certification processes and standards. Some states that licence audiologists are now beginning to require that audiometric technicians be registered by the state and supervised by an audiologist licensed by the state. This has resulted in situations where a national hearing testing company may have to allay with a local audiologist licensed by the state and register the company's technicians as under the supervision of that audiologist. Presently, California, Indiana, New York, and Ohio have such requirements.

8.7.2. Audiologist and Physicians

OSHA requires an audiologist, otolaryngologist, or a physician, to perform or supervise hearing testing and to provide general program overview including the supervision of audiometric technicians.

Audiologists are universally certified by ASHA once they have obtained the necessary academic and clinical training and pass a nationally administered examination. Those states that license audiologists have standards that are very similar to those of ASHA. In some states a person must be a licenced audiologist, hearing aid dispenser, or physician to even perform a hearing test. If an audiometric technician, one must be working under the direct supervision of an audiologist or physician licensed in the state. The definition of supervision varies from state to state.

Otolaryngologists are physicians who specialize in the practice of otology (ear diseases), and laryngology (throat disease). Most often the otolaryngologist's practice will focus on the diagnosis, evaluation, and treatment of ear disease, while relying upon the audiologist to perform the hearing testing and assessment. However, some otolaryngologists who are particularly interested in occupational hearing loss may perform the actual testing as well as the training and supervision of technicians.

There is no mandated course of training for audiologists or otolaryngologists in the area of occupational hearing loss prevention. While a few graduate training programs have formal course work in occupational hearing loss prevention, most don't. The situation is similar for the otolaryngologists. Thus, those who work in the area do so because of interest, opportunity, or both. They are members of organizations such as the National Hearing Conservation Association where they meet with others of similar interest to exchange information. ASHA may eventually offer speciality certification in occupational hearing loss prevention.

8.8. PREPARING EMPLOYEES FOR AUDIOMETRIC TESTING

The most important part of an audiometric test is its beginning. If employees are not sure of the importance of the audiogram they are not likely to work as hard as they need to during the audiogram. Employees should be told that the hearing test is "hard work" and requires a measure of concentration and effort on their part. If there is no care as to the placement of the earphones prior to the test, there is great likelihood that there will be unsupportable threshold shift. If excellent instructions about how to listen and respond during the test are not given, the results may be inconsistent, frequency to frequency, ear to ear.

An example of the worst case scenario is one where employees are told that the purpose of the hearing test is to have a hearing test and their instructions run something like, "Put the blue phone on your left ear, and the red on your right, press the button when you hear the tone."

8.8.1. Pre-Test Information for Employees for Valid Tests

The employee needs to be informed of the purpose of the hearing test. If it is the baseline audiogram, its importance as the reference against which all future audiograms will be compared should be explained. If it is the periodic audiogram, it is important in identifying temporary threshold shift or confirming no change in hearing and thus needs explanation. The immediate retest needs to be explained in the light of substantiating a threshold shift. If the shift is not substantiated, the employee should be told that a vast majority of retests actually confirm the better hearing of the baseline. Similarly, the importance of the confirmation audiogram and the need for a 12 to 14-hour quiet period before the test should be explained. When exit audiograms are given, their importance in documenting the employees' hearing at the end of their exposure to potentially hazardous noise requires explanation. *(See Editors' note in section 8.6.2.)*

8.8.2. Earphone Placement

Figure 8.10 depicts the technician placing the earphones on the employee. This is critical. The audiometric earphone, cushion, and headband were not designed for comfort. If the employee places the earphones for most comfortable fitting, it will most likely not be the correct placement for audiometry. The correct placement is for the opening of the ear canal to be centered under the cutout in the earphone cushion for the earphone diaphragm. There should be no hair under the earphone cushion and eyeglasses and earrings need to be removed for testing.

Figure 8.10. Technician placing earphones on listener in an audiometric test booth

Care must be taken to place the left earphone over the left ear and the right earphone over the right ear. In many occupational settings, the earphone case will have a colored plastic cap, blue for left and red for right. Nonetheless, reversing the earphones is the most common mistake made in testing hearing, whether for occupational or clinical purposes.

On occasion the earphone placement will cause the tragus to close over the ear canal opening or cause the pinna to shift so that the ear canal collapses, thus closing off the path to the eardrum and raising hearing thresholds in the higher frequencies. When this happens, the technician has several options. The most common remedy is to place an otoscope specula or an insert tube specifically designed for that purpose in the ear canal and then gently place the earphone over it. In some cases, insert earphones are available for use in cases such as collapsed ear canals.

8.8.3. Instructions

The pure-tone hearing test, as stated at the beginning of this chapter, is an unusual test. The employee encounters nothing similar in his daily life. Therefore, good instructions are essential for getting good results. Good instructions should resolve all uncertainties about the test, doing everything possible to make the test easy for the employee up to the point of pressing the response button.

8.8.3.1. Manual audiometry

A suggested instruction set for manual audiometry follows:

> *Do you hear better out of one ear than the other? (If yes, ask which ear. If no, then start with the right ear.) You will be hearing some faint tones, first in your <better or right> ear and then in your <other or left> ear. The tones will be pulsing so that you will hear a chain of beeps and then silence. Listen for the beeps and when you hear them <press this button or raise your hand> to signal that, -Yes, I hear them. The beeps will generally get fainter and fainter each time they are presented. <Press this button or raise your hand> whenever you think you hear the beeps. The pitch of the tones will change, first going lower in pitch and then going higher in pitch. The test of your <other or left> ear will not begin until your <better or right> ear has been tested for all of the frequencies. If you are certain that you hear the beeps, you don't have to wait for the beeping to stop to <press this button or raise your hand>. And, you don't have to <hold the button down or hold your hand up> for as long as you hear the beeps. A simple <press and release or hand raise and fall> will do. So, if you haven't any questions, I will put the earphones on and we can start the test. (Answer any questions.) Please wait for me to remove the earphones when the test is over.*

8.8.3.2. Self-recording audiometry

A suggested instruction set for self-recording (automatic) follows:

> *Do you hear better out of one ear than the other? (If yes, ask which ear. If no, then start with the right ear.) You will be hearing some faint tones, first in your <better or right> ear and then in your <other or left> ear. The tones will be pulsing so that you will hear a beep-beep-beep-beep sequence. Listen for the beeps and when you hear them press and hold down this button. Press this button as soon as you think you hear the beeping. As you hold the button, the beeps will get fainter and fainter until you can no longer hear them. Hold the button down for as long as you hear the beeping and then release it as soon as you think that you can no longer hear the beeping. You will be pressing the button when you hear the beeps and releasing the button when you don't hear the beeps. After about one-half minute the pitch of the tones will change, first going to a lower-pitched tone and then going higher pitched tones. Once your <better or right> ear has been tested for all of the frequencies, the test of your <worse or left> ear will begin. So, if you haven't any questions, I will put the earphones on and we can start the test.(Answer any questions.) Please wait for me to remove the earphones when the test is over.*

8.8.3.3. Microprocessor-controlled audiometry

A suggested instruction set for microprocessor-controlled audiometry follows:

> *Do you hear better out of one ear than the other? (If yes, ask which ear. If no, then start with the right ear.) You will be hearing some faint tones, first in your <better or right> ear and then in your <other or left> ear. The tones will be pulsing so that you will hear three beeps and then silence. Listen for the beeps and when you hear them press this button to signal that, -Yes, I hear them. The beeps will get fainter and fainter each time they are presented until you don't hear them and then they will increase so that you can just hear them. They will never get very loud. Press this button whenever you think you hear the*

beeps. The pitch of the tones will change, first going to a lower tone and then going to higher and higher tones. The test of your <other or left> ear will not begin until your <better or right> ear has been tested for all of the frequencies. If you are certain that you hear the beeps, you don't have to wait for all three to press this button. And, you don't have to hold the button down for as long as you hear the beeps. A simple press and release will do. So, if you haven't any questions, I will put the earphones on and we can start the test. (Answer any questions.) Please wait for me to remove the earphones when the test is over.

8.8.4. Employees with Testing Problems

Various problems may be encountered during audiometric testing. The following is adapted from Morrill (1986).

8.8.4.1. Physiological Problems

A. Tinnitus (head noises) that become more noticeable in the quiet test environment when earphones are worn. In some cases the tinnitus may be confused with the test tones. In rare cases, test tones can initiate tinnitus, even beeping tinnitus. Persons with tinnitus that interferes with testing should be referred for clinical testing.

B. Ear-hand coordination (latency in the response such as pressing the response button) may make the administration of self-recording or microprocessor-controlled audiometry impossible. An technician experienced with manual audiometry will know to allow adequate time for the person to respond after a tone sequence is presented.

C. Fatigue that causes the listener to fall asleep in the quiet and darkened test booth. If often helps to have the listener take a walk before retesting.

D. Ear disease and or wax impaction will complicate testing hearing. Ear disease may have accompanying drainage, which will not be a hygiene problem if disposable polypropylene earphone covers are used. While the tympanic membrane may not be visible due to obstruction by wax, as long as there is the smallest airway, hearing thresholds should not be affected.

E. Existing hearing loss may make the start of audiometry more difficult because the listener will require a higher initial signal level. It may also happen that the listener is not able to hear signals at some frequencies at the maximum output levels of the audiometer.

F. Unilateral hearing loss may be sufficient that it is not possible to know without contralateral masking if the thresholds for the worse ear are actually valid or if the crossover signal was heard in the better ear. In some settings insert earphones will be available, increasing the interaural attenuation from the 40 dB for earphones to as much as 60 dB or more, allowing a better assessment of the hearing in the poorer ear. In any case, when a unilateral hearing loss is observed for the first time, the employee should be referred to a clinical a setting for a complete hearing test.

8.8.4.2. Response problems

A. Intelligence and comprehension may have an effect on the employee's ability to respond appropriately to the test signals. Arrangements should be made to provide detailed test instructions in a language other than English, if the employees do not have a functional ability to understand English. Do not, however, assume that written instructions in English or another language will suffice, since many persons may not be literate in the language in which they converse.

B. Persons under the influence of prescription or non-prescription drugs or alcohol may often be drowsy, have drug-induced tinnitus, and may have problems following instructions. If a reliable audiogram can't be obtained, then referral for clinical testing may be necessary.

C. Anxiety, fear, or confusion can make taking a hearing test very difficult. Some employees may have test anxiety. Be aware also that some employees may have claustrophobia that prevents them from remaining in a test booth for the duration of the hearing test. Referral to a clinical facility with a larger test booth may help alleviate claustrophobia.

8.8.4.3. Malicious Intent

A. Labor relations problems.

B. Malingering to either inflate or deflate thresholds. It is just as common to find an employee trying to hide a hearing loss as it is to find an employee trying to fake a hearing loss.

C. Clowning behavior that makes administration of the test difficult and is especially disruptive of group hearing testing environments.

D. Compensation problems may make the employee hesitant to provide adequate historic information.

8.9. SUPPORTIVE INFORMATION

An audiogram or a collection of audiograms is of diminished value in the absence of collateral supportive information. While audiograms alone are sufficient for calculation of threshold shift, they are insufficient when it comes to planning interventions for employees with threshold shift or for understanding employees who don't experience threshold shift. Similarly, without collateral information it is difficult to substantiate test results for workers' compensation or litiginous cases.

8.9.1. Employee Demographics

Figure 8.11 displays an audiometric and identification information form. This form presents the minimum data that should be collected for an employee. It supports recording the audiogram and has a place for recording the baseline audiogram as well. This audiogram can be partially filled out prior to testing, such as recording identification information and the baseline audiogram if

Audiometric and Identification Information

Name ____

Soc. Sec. # ____ -__-____ Birth Date __/__/__ Gender M F (Circle)

Empl No: _____________ Job Code ___________ Dept No ___________

Test Date __/__/__ Time __;__ Test Type _____ Time since last exposure ____ h

Exposure Level ___ dBA

Hearing Protector Activity

Yes ____ No ____

Issue ____

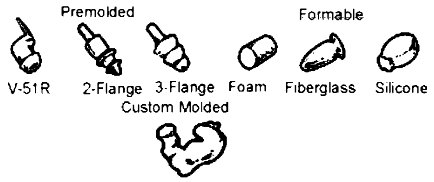
Reissue ____

Training ____

Retraining _____

Hearing Protector Used (Circle)

EARPLUGS



EAR CANAL CAPS

Unknown

EARMUFFS

Self-Reported Employee Histories

(Y/N) Medical History	(Y/N) Hobby & Military History	(Y/N) Additional Information
____Diabetes	____ Hunt/Shoot	____Noisy 2nd Job
____Ear Surgery	____ Car racing	____Noisy Past Job
____Head Injury	____ Motorcycles	____Exposure to Solvents
____High Fever	____ Other Loud Vehicles	____Exposure to Metals
____Measles	____ Loud Music/Band	____Difficulty Hearing
____Mumps	____ Power Tools	____Hearing Aid
____Hypertension	____ Other Noisy Hobbies	____Recent Change in Hearing
____Ringing in Ears	____ Military Service	____See Physician About Ears
____Ear Infection	____ Fire Weapon	____See Prior Histories
____Other	____ Other	____Other

Audiogram

Baseline Thresholds

Test Frequency

	500	1000	2000	3000	4000	6000	8000
Right Ear							
Left Ear							

Audiometer ______________________

Exhaustive Cal. Date __/__/__

Tester Identificaiton ___-__-____

Review Identification ___-__-____

Serial Number ______________________

Biological Cal. Date __/__/__

Test Reliability (Good, Fair, Poor) __

Audiogram Classification Code __ __ __

Comments

Figure 8.11. Sample audiogram and collateral information form

one exists, and then be completed at the time of the hearing test. It can also be used to counsel the employee at the end of the test.

The top of the form collects personal information such as name, identification number, birth date, gender, job code, department number, test date, test time, test type, time since last exposure to occupational noise, and occupational noise exposure level. The baseline audiogram values can be placed in the grey boxes. This is very basic information, but more than many hearing conservation programs collect. In the United States, information about race is either not collected or its provision is optional at the discretion of the employee, but it is useful information to have if possible as expected hearing levels vary by race.

8.9.2. Employee Hearing Protector Use History

This form contains information about whether hearing protection is used at work, whether it is issued or reissued at the time of the hearing test, and whether or not training or retraining has occurred. The form provides sketches of various types of earplugs, ear canal caps, and earmuffs, asking that the type used be circled. In the ideal hearing loss prevention program, the style, make, and model of the hearing protector used would be provided and the attenuation actually received by the worker would be tested and recorded.

8.9.3. Hearing and Related Health

There are conditions of the ear and overall health that are positively correlated with hearing loss or susceptibility to noise-induced hearing loss. Previous studies have shown that persons with histories of diabetes, head injury resulting in concussion, prolonged high fevers, post adolescent measles and mumps, and hypertension are at greater risk of noise-induced hearing loss (Franks, Davis, and Krieg 1989). Other ear conditions such as prior ear surgery, ringing in the ears, and ear infection can cause hearing loss independent of noise exposure. Interestingly, hearing losses due to middle ear disorders are protective against noise-induced hearing loss.

8.9.4 Noisy Hobbies and Military History

Not all exposure to noise comes at work. People may have non-occupational activities that expose them to hazardous noise such as hunting or shooting, using power and hand tools, riding snowmobiles or motorcycles, and listening to loud music. NIOSH has determined that personal stereos are capable of delivering music levels that are just as potentially hazardous to hearing as many occupational noises (Tubbs, Sizemore, and Franks 1997). As well, many persons, particularly males, will have been in the military and may have been exposed to weapons fire, artillery, or heavy equipment noises. These exposures, if they occurred in the past, may account for hearing loss that pre-dated employment; or, if the exposures are continuing into the present, may combine with noises at work to increase the employee's daily noise burden.

8.9.5. Additional Information

There are other instances that can contribute to hearing loss that is observed in a hearing loss prevention program. Persons with noisy past jobs may have pre-existing hearing loss. Some people may have a noisy second job, a job that is as noisy or noisier than the present job which contributes to their noise-induced hearing loss. Research has shown that exposures to solvents such as toluene and styrene and metals such as lead and mercury can cause hearing loss and, that when there are combined solvent-noise or metal-noise exposures, the risk of hearing loss is higher than for exposures to the agents alone (Morata and Franks 1996, 1997).

8.10. REVIEW AND TREATMENT OF AUDIOGRAMS

An audiogram is a medical record, regardless of the conditions under which it was obtained. The pure-tone air-conduction audiogram obtained as part of an occupational hearing conservation program is no less a medical record than a complete audiogram obtained in a hospital, clinic, or private practice office. As such it should be treated as any other medical record, including a quick interpretation, development of successive management strategies, and the protection of the privacy of the person.

Unfortunately in the United States, audiograms are often treated as if they were tax forms with handling avoided until the last possible moment. As much as a year may go by before the employee is advised through his employer about the results of the last test, how they related to the previous test, and whether any additional hearing protective actions need to be taken. Workers may assume falsely that if they receive no information about their hearing test, there is not a problem.

Each audiogram should be compared to the baseline audiogram to determine if there has been a significant threshold shift. *Even when there has not been a shift*, the worker should be told so and given positive reinforcement that present hearing protective measures are working. If there has been a shift, actions should be taken to discover why and appropriate interventions should be initiated with the informed worker as the centerpiece.

8.10.1. Definition of Problem Audiograms

Sometimes circumstances make it difficult to have an audiologist or physician review every hearing test. This may be true whether testing is done on-site by the company at its health station or by a mobile occupational health testing service. Therefore, some rules need to be developed that will identify those audiograms that must be seen by a professional from those that may be reviewed by the tester.

8.10.1.1. Hearing impairment

Figure 8.12 displays both a graphic and tabular audiogram. The lightest shaded area of the graphic audiogram in Figure 8.12 is the range of normal hearing. In most cases, when the hearing level at any frequency for either ear is 25 dB HTL or greater, hearing at the frequency is considered to be impaired. The first frequency to cross the 25 dB HTL fence for most noise-exposed people will be 4000 or 6000 Hz. For the audiogram to indicate that a person is hearing-impaired; however, the average hearing loss for a set of adjacent frequencies must exceed 25 dB HTL. NIOSH recommends that those frequencies be 1000, 2000, 3000, and 4000 Hz and that the binaural average equal or exceed 25 dB HTL.

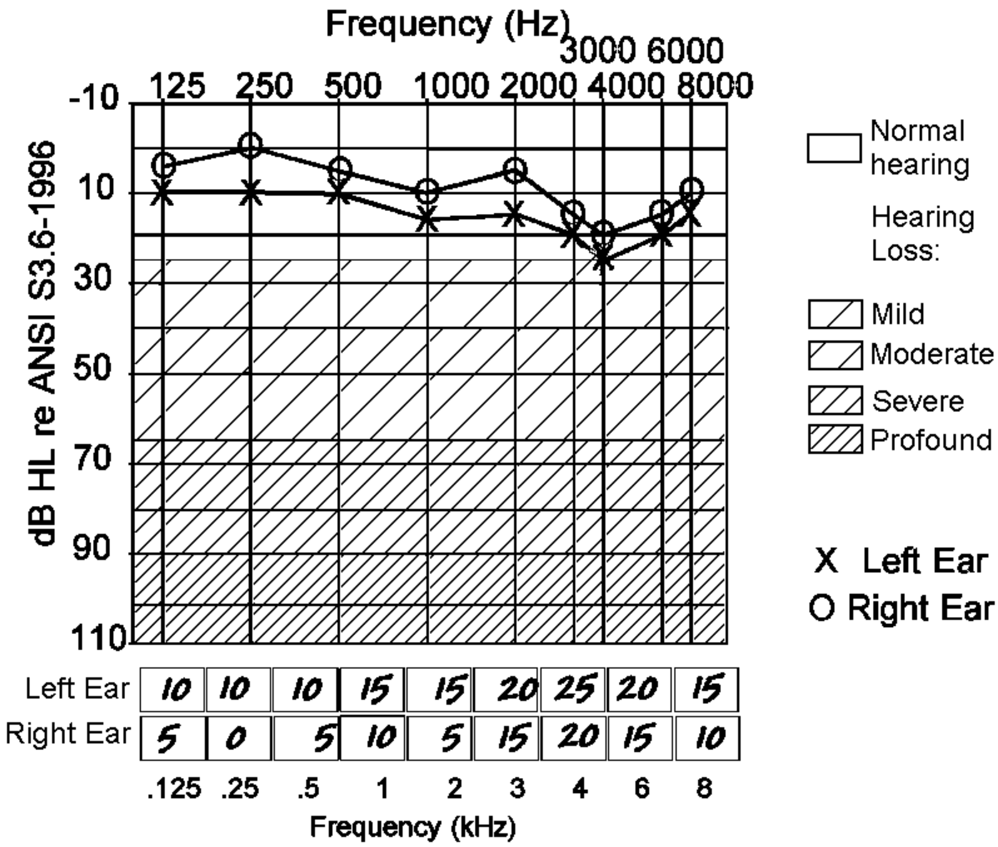


Figure 8.12. Graphic audiogram showing ranges of hearing from normal to profound hearing loss. Normal audiogram is plotted and values are entered in table below audiogram as well.

The first time an employee’s audiogram shows impaired hearing, it should be seen by a professional reviewer. Many workers with prior noise exposure at other facilities will show impaired hearing on the baseline audiogram. It is necessary for the reviewer to determine if the hearing loss is noise-induced or possibly due ear disease or some other factor such as systemic infection, physical trauma, or familial tendency to develop early-onset age-related hearing loss. Often this will require that arrangements be made for an evaluation by an audiologist, a physician, or both.

Any time a periodic audiogram shows hearing thresholds that are poor enough to meet the definition of impaired hearing, the audiogram should be seen by the reviewing professional. It is possible that a person’s hearing will worsen to the point where it is described as impaired, but not sufficiently to qualify for a significant threshold shift, especially for the worker whose baseline hearing thresholds are at the upper boundary of normal hearing.

Once a person with hearing-impairment is identified and a probable etiology is established, it will usually not be necessary for subsequent review and referrals if the hearing stays the same on subsequent tests. Of course, the reviewing professional may wish to see all future hearing tests for that person; the managing audiologist or physician may wish to actually conduct the subsequent examinations as well.

It is tester's role to identify hearing impairment according to established criteria set by the professional reviewer. It is also the tester's role to compare the current audiogram to the baseline audiogram to identify significant threshold shift. Threshold shift is not related to hearing impairment. A threshold that shifts from 0 to 15 dB is as important as one that shifts from 35 to 50 dB and should evoke the same subsequent actions.

8.10.1.2. Interaural difference

Sometimes the audiogram will document a difference between the hearing sensitivity of left and right ears. It is not normal to have exactly the same hearing threshold levels in both ears at all test frequencies. However, in the absence of ear disease or other insult, the differences between the two ears will be small, typically 15 dB or less. The reviewing professional should set rules for when the interaural difference is sufficient to require referral for professional review.

Figure 8.13 displays a graphic and tabular audiogram showing normal hearing for the right ear and a hearing loss for the left. When the difference between left and right hearing thresholds

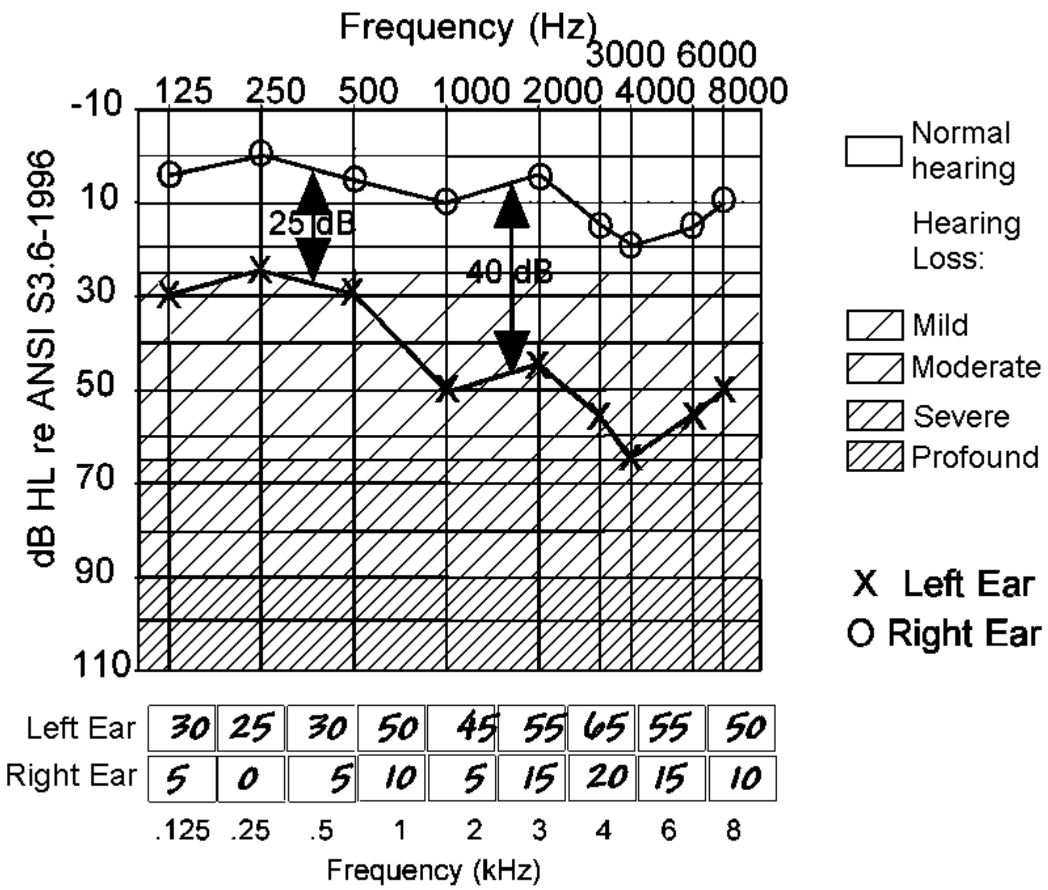


Figure 8.13. Maximum differences between ears for reliable air-conduction thresholds. Shown are hearing thresholds for right an left ears (values also shown in table) to demonstrate maximum frequency-dependent interaural differences. The right ear shows a 4000-Hz notch, but normal hearing sensitivity, while the left ear shows a moderate high-frequency loss with 4000-Hz notch.

equals or exceeds 25 dB in the lower frequencies (500 Hz or less) there is the possibility that the apparent thresholds for the poorer ear actually represent crossover responses for the non-test ear. Crossover thresholds may occur for frequencies at or above 1000 Hz when the interaural difference is 40 dB or more.

The only sure way to determine the hearing thresholds for the poorer ear is to use masking noise for the better ear while testing the poorer ear. Masking is usually not available with audiometers used for testing in occupational hearing loss prevention programs and most testers are not trained to obtain masked thresholds.

Figure 8.14 displays audiometric results for which there is an interaural difference, but where the difference is not greater than 25 dB at 500 Hz and below nor greater than 40 dB at 1000 Hz or above. Instead, the shape of the audiogram, the audiometric contour, is not the same for both ears. The right ear has a notch at 4000 Hz and recovery at 8000 Hz such as would be expected for a person exposed to noise. The left ear also has impaired hearing at 4000 Hz, but the hearing does not recover at 8000 Hz as it does for the right ear. This type of asymmetry of contour may be medically significant and is another reason for the audiogram to be referred to the reviewing professional.

8.10.1.3. Change since last hearing test

Just as no person's left ear will have exactly the same hearing levels at the same frequencies as the right, no person's audiogram will be exactly the same for each successive hearing test. There will be variations due to placement of the earphones, time of day, fatigue level of the person, and other factors. The problem, then, is how much change between successive audiograms should be attributed to normal variation and how much change should trigger referring the audiogram to the reviewing professional.

In many cases in the United States, the criteria for change sufficient to trigger referral is the same as the definition of OSHA Standard Threshold Shift; an average change of 10 dB or more for the frequencies 2000, 3000, and 4000 Hz in either ear compared to the baseline audiogram. Following this rule might trigger an audiogram for review if the hearing at all three frequencies worsened by 10 dB (which is within the scope of normal test-retest variation). However, at the other extreme, the hearing at 4000 Hz can worsen by 30 dB while the hearing at 2000 and 3000 Hz remains unchanged (or more than 30 dB at 4000 Hz if the hearing at either 2000 or 3000 Hz improves by 5 dB). Royster (1996) recommends that the OSHA Standard Threshold Shift not be used as the sole criteria for change sufficient to trigger referral to the reviewing professional. She suggests that "sub-OSHA" threshold shifts also be used to identify a person before a Standard Threshold Shift occurs.

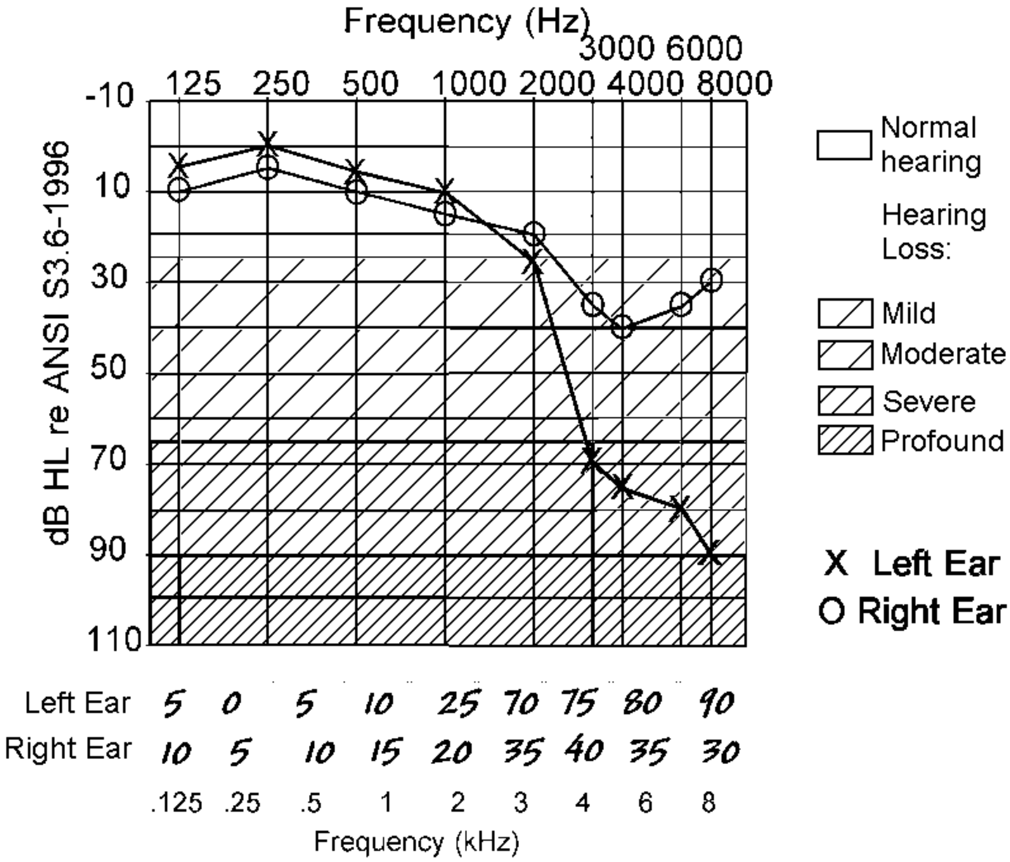


Figure 8.14. Audiogram asymmetric depicting high-frequency hearing loss. The right ear shows a mild high-frequency loss with notch at 4000 Hz. The left ear shows a severe-to-profound high-frequency hearing loss with no notch. Audiograms showing this type of asymmetry usually trigger a referral for clinical evaluation.

NIOSH defines a significant threshold shift as a change in hearing of 15 dB or more as compared to the baseline audiogram at any single frequency, 500 through 6000 Hz. The NIOSH recommendation takes into account that normal time-to-time variations in hearing thresholds may be as large as 10 dB, thus reducing the likelihood of referring an audiogram for review that is just showing normal variation. In order for the threshold shift to be significant, the 15 dB or more change must appear on a subsequent audiogram for the same ear and the same frequency. If that subsequent audiogram is the immediate retest, the shift is considered to be pending and a confirmation audiogram should be scheduled. The confirmation audiogram is preceded by a quiet period of 12 to 14 hours. If the confirmation audiogram affirms the 15 dB or greater threshold shift for the same ear and frequency, the shift is considered to be confirmed.

A pending threshold shift that is not confirmed is most likely to be a temporary threshold shift that resolved when the person had an adequate time away from the noise. It is important that the events that led to the temporary threshold shift be identified so that the person will experience no further temporary shifts as he or she continues to work in hazardous noise. Except in cases of acoustic trauma, where hearing loss is caused by one event such as blast overpressure, permanent threshold shifts may be preceded by hundreds or thousands of temporary threshold shifts. Preventing temporary threshold shift prevents permanent threshold shifts.

A pending threshold shift that is confirmed also requires actions to make sure that the person's hearing does not further degrade. In addition, the confirmation audiogram also becomes the revised baseline audiogram to which all future subsequent hearing tests are compared. Thus, subsequent referral of a person's audiogram for review would not occur unless and until the criteria for significant threshold shift were met again.

8.11. SUMMARY

A very common occurrence in occupational hearing loss prevention programs is the underestimation of the difficulty inherent in the measurement of hearing in the occupational setting. There must be a continuous quality assurance process in place to assure that each audiogram reflects to the extent possible, the worker's hearing at the time of the test. Without continuous quality assurance, unreliable, unrepeatable audiograms become part of the record. NIOSH has analyzed large audiometric databases for the purpose of identifying invalid audiograms. In many cases, only a few audiograms were found to be invalid. However, in other cases, almost half of the hearing tests were invalid (Franks 1996, 1997). It becomes impossible to evaluate the program's success in preventing hearing loss when it becomes impossible to track accurately the progress of each individual worker in the program. The quality assurance steps should involve the evaluation of each audiogram in light of those audiograms that preceded it with acceptance of the new audiogram once all changes in hearing have been assigned a reason.

Morrill (1986) lists testing problems such as excessive ambient noise levels in the test booth, poor instructions, poor testing techniques, instrument calibration errors, employee response problems, inappropriate hearing protection, and medically referable conditions as other reasons for test variability (see Section 8.8.4). A quality assurance program should identify these and have established steps to be taken in case of each of these.

Workers enrolled in an effective hearing loss prevention program should be able to complete their careers without incurring an occupational hearing loss. Accurate audiometry is the key to spotting and responding to temporary threshold shifts in order to prevent workers from developing permanent threshold shifts and eventually handicapping noise-induced hearing loss.

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INTERNATIONAL STANDARDS

Titles of the following standards related to or referred to in this chapter one will find together with information on availibility in chapter 12:

ISO 389, ISO 645, ISO1999, ISO 6189, ISO 8253
IEC 60651, IEC 60804

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9

HAZARD PREVENTION AND CONTROL PROGRAMMES

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9.1. GENERAL CONSIDERATIONS

Noise-induced hearing loss is, at present, incurable and irreversible, however, it is definitely preventable, therefore the implementation of adequate preventive programmes is essential.

Specific measures for the prevention and control of exposure to noise are discussed in detail elsewhere in this document; however, it is important to keep in mind that such measures should not be implemented in an *ad hoc* manner but as part of a comprehensive strategy.

The objective of this chapter is to discuss basic principles for hazard prevention and control programmes and their management, relating them to the prevention of noise exposure and associated effects, whenever relevant.

A programme to protect workers from the effects of hazardous noise exposure in the workplace is often called a "hearing conservation programme". However, rather than an isolated effort, this should preferably be integrated into the overall hazard prevention and control programme of the workplace in question.

Hazard prevention and control programmes should be designed to meet the specific needs of each situation, in view of the existing hazards and of the many other factors that characterize a workplace; furthermore, programmes should be adaptable to new scientific and technological developments, as well as to eventual changes in the socio-economic context.

As previously seen, noise control programmes are often mentioned or defined by national legislation or international standardization. For example, the ISO 11690-1 states that:

"In order to reduce noise as a hazard in the workplace, individual countries have produced national legislation. Generally, national legislation requires the implementation of noise control measures in order to achieve the lowest reasonable levels of noise emission and exposure, taking into account:
- known/available measures;
- the state of the art regarding technical progress;
- possibilities for noise reduction at the source;
- appropriate planning, procurement and installation of machines and equipment."

Another example is the European Directive 86/188/EEC on noise at work which requires appropriate hearing conservation and noise control programmes whenever a workplace falls into the "noisy" category (according to the EU definition).

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9.2. REQUIREMENTS FOR EFFICIENT PROGRAMMES

Hazard prevention and control programmes require:

- political will and decision-making;
- commitment from top management, with a clear and well circulated policy basis;
- commitment from workers;
- well defined goals and objectives;
- adequate human and financial resources;
- technical knowledge and experience;
- adequate implementation and competent management of programmes;
- establishment of multidisciplinary teams;
- mechanisms for communication;
- monitoring mechanisms (indicators);
- continuous improvement of the programme.

Political will and motivation require awareness and understanding of the problems caused by hazardous exposure, in this case to harmful noise levels, as well as of the available prevention and control solutions and of the benefits resulting from their application.

At the workplace level, the decision-making process starts with the awareness and acceptance that there is a problem; for example, a noise problem. This is followed by the recognition and localization of the noise sources and the conditions of exposure (e.g., duration). If there is obvious overexposure, a decision is already possible after this first step and the next stage will be the planning of a preventive strategy. If a decision is not possible, the next stage will require quantitative exposure assessments; for example, noise measurements.

The "decision-making ladder" can be used to analyze the decision-making process concerning hazard control in workplaces, as well as to pinpoint where blockages occurred, or are likely to occur, with a view to avoiding them (Antonsson, 1991). The "steps" in the ladder are:

1. Be aware of the problem
2. Accept the problem
3. Know the cause
4. Learn of possible solutions
5. Accept a solution
6. Know the supplier (of solution)
7. Finance
8. Implement solutions
9. Evaluate

So that efficient hazard prevention and control programmes may be implemented, concern for workers' health should be included in the priorities of top management alongside productivity and quality. A clear policy, discussed, agreed upon and understandable by the stakeholders is essential. The objectives of the programme, the steps to be followed and the available mechanisms for implementation should be clearly defined and presented to all concerned, who must know what to expect and hope for; unrealistic and unattainable goals are very frustrating.

The design and implementation of hazard prevention and control programmes require involvement and commitment not only from management, but from production personnel, workers and occupational health professionals.

9.3. PROGRAMME COMPONENTS

9.3.1. Recognition of the Problem

Complaints of hearing difficulties among workers is too late an indicator that a noise problem exists; however, should this happen, control action must be immediately triggered. The recognition of a noise problem should take place much earlier, whenever noise levels exceed acceptable limits, or simply whenever there is a feeling that the workplace is just too noisy, particularly if there is any interference with verbal communication. In fact, the best approach is to foresee problems and avoid them; for example, by selecting quieter equipment and processes, whenever possible.

The recognition that a noise problem exists is followed by a qualitative assessment of the situation, which includes identifying and localizing noise sources, defining noise exposure patterns, including which are normal and which are unusual exposure conditions. In view of their experience with tasks, work processes, equipment and machinery, workers can provide valuable assistance in gathering such information, which is needed to design an adequate strategy for any subsequent quantitative evaluations, in this case, noise surveys.

9.3.2. Exposure Assessment Issues

Although “strategies for noise surveys”, including measurements and instruments, are presented in detail in Chapter 7, some aspects are hereby summarized so that they may be put into perspective as important elements of an overall noise prevention and control programme.

If hazards are obvious and serious - for example, a workplace where people close to each other have to shout to be understood, the recognition of the problem must be followed by control; quantitative evaluations will come later, in order to verify the efficacy of the control system. It may sometimes be necessary to change the classical concept of "recognition-evaluation-control" to "recognition-control-evaluation". Decision-making as to control actions may have to rely on professional judgement and common sense, particularly if measuring equipment is not available. Impossibility to carry out noise measurements should never be a blockage to correcting obviously hazardous situations.

Measurements must be carried out in the most usual conditions; appreciable fluctuations should be fully appreciated. In fact, as discussed in chapter 7, particularly if there are appreciable noise level fluctuations or workers move around, noise dosimeters offer the best monitoring solution. In order to study noise sources and their relative importance as contributor to exposure, as well as to check the efficiency of implemented noise control measures, the best approach is to use integrating sound level meters, adequately positioned (e.g., at the operators’ ear position).

The initial noise survey constitutes a decision-making tool, and also provides base line data which, together with results from subsequent surveys, may serve as an indicator for future evaluations of any implemented control strategy.

Noise surveys to assess workers’ exposure should be carried out by specialized professionals, for example, occupational hygienists or other occupational health professionals with specific training in noise measurements. Occupational hygiene technicians, if specially trained for this purpose, provide valuable support. Workers’ collaboration is essential.

9.3.2.1. Selection of Measuring Instruments

The type of hazard to be evaluated and the purpose of the survey will determine the type and the required "reliability" of the measuring equipment; for example, sound level meters. If qualitative, or semi-quantitative measurements are sufficient, or if preliminary surveys are a priority, it is useless to spend money on very expensive and sophisticated equipment.

Even if funds are available, equipment should only be purchased, if and when a real need has been established, and, operational capabilities have been ensured, including competent personnel to properly operate, calibrate and maintain the equipment.

If a new programme is being developed, only basic equipment should be purchased initially, more items being added, as the need arises and personnel competencies are developed. When selecting any occupational hygiene equipment, in addition to performance characteristics, practical aspects should also be considered, including:

- portability
- source of energy needed
- calibration and maintenance requirements
- availability of expendable supplies
- conditions of use (including infra-structure and climate)

If the above requirements are overlooked, and unfortunately they often are, the result may be that expensive equipment is inadequately utilized, or not utilized at all. The importance of routine calibration cannot be over emphasized.

All steps of the noise evaluation must be equally well planned and carried out; the complete procedure must be considered as one, since "no chain is stronger than its weaker link". It would be a waste of resources to allow for unequal quality in the different steps of a same noise evaluation. For example, results obtained with a very accurate and precise integrating sound level meter might not be reliable if it had not been properly calibrated, or, the results might be far from representative of the workers' exposure, if the measuring strategy had not been adequately designed and followed.

9.3.3. Control Strategies and Measures

Any hazard prevention and control programme involves measures related to the work environment and measures related to the workers. Efficient control strategies usually rely on a combination of engineering (technical) control measures (e.g., quieter equipment and enclosures) and health/personal measures (e.g., work practices).

Noise prevention and control strategies usually involve elements from the following groups of measures, that is, measures which relate to:

- the work process (including tools and machinery), for example: quieter equipment, good maintenance;
- the workplace, for example: noise enclosures or acoustic treatment, and,
- the workers, for example: work practices and other administrative controls , audiometry, hearing protection and workers' education.

Control measures should be realistically designed so as to meet the needs of each particular situation and the different options should be considered in view of factors such as effectiveness, cost, technical feasibility, socio-cultural aspects.

The control hierarchy should be the following:

control of the noise source ➜ control of the noise propagation ➜ control at the worker level

The standard ISO 11690 (part 1) provides more details on this hierarchy, in its clause on the concept of noise reduction, as follows:

"Noise control can be implemented using various technical measures (see ISO 11690-2) and there may be several ways to solve a noise problem. These measures are noise reduction at the source (e.g., machines, work processes), noise reduction by preventing/attenuating its propagation (e.g., using enclosures, barriers, absorbing materials), noise reduction at specific positions (e.g., cabins). Technical measures for noise control should be applied in order to implement the state of the art with regard to noise control. For this purpose, it is necessary to compare and determine the effectiveness of these measures. Acoustical quantities are used for this purpose, which describe the acoustical features of the sources, the noise reduction attained in workplaces, especially at work stations, when noise sources are operating and control measures have been implemented."

The first priority is to reduce noise through technical measures. When engineering controls are not applicable or not sufficient, noise exposure may be reduced through measures such as:

- hearing protection (adequately selected, worn and maintained);
- administrative controls, which are changes in the work schedule or in the order of operations and tasks, for example, limitation of time spent in a noisy environment (then wearing hearing protection), performing noisy operations outside the normal shift, or during a shift with very few workers (wearing hearing protection), or, in a distant location, if at all possible.

Very often solutions are sought among the most known measures, such as noise enclosures and personal protective equipment; however, the former may be too expensive or unfeasible, and the latter is not always efficient or acceptable to the workers, particularly in hot jobs and hot climates. Approaches to prevention should be broadened, with proper consideration of other control options, particularly of source control through, for example, substitution of materials and process modification, as well as good work practices (as seen in chapters 5 and 10).

Both personal measures and engineering controls should be discussed with the workers, so that they understand their importance, contribute to their design and learn how to best contribute to their continued efficiency. In view of their knowledge and experience with work processes, operations and machinery, workers can make valuable contributions to the design of control strategies. Workers may contribute to, or decrease, the efficacy of engineering measures; for example, by closing or not closing doors of acoustical enclosures when machines are operating. Personal experience with tasks is indispensable for the design of adequate work practices, particularly when different ways of performing them (e.g., the manner to operate tools and machinery) influences the resulting noise levels.

Workers' education and training, as well as audiometric examinations, are essential components of hearing conservation programmes.

9.3.4. Hazard Communication, Education and Training Programmes

Successful hazard prevention and control programmes should include hazard communication, as well as education and training for workers, supervisors and all other persons involved. If a programme is to be successful, all stakeholders must be aware of its importance and motivated to collaborate.

Workers should be clearly informed of any known, suspected or potential hazards associated with their work, for example, noise levels to which they are or may be exposed, and, of the possible harmful consequences, for example, hearing loss or accidents due to impossibility of hearing warnings. Workers should also be informed on the best available means for prevention and control, and on how they can contribute to their implementation. This information should be linked to the purpose and proper use of any noise control system, be it based on engineering controls, work practices or personal protection.

Persons involved with prevention and control should have opportunities to continuously update their knowledge and should:

- be alert to new developments concerning effects of overexposure to noise, as well as new guidelines and new standards which may be applicable;
- keep well informed on current developments concerning hazard recognition and control, which may be applicable to the work processes and operations in question.

9.3.5 Health Promotion

According to the concept spelled out in the Ottawa Charter and accepted by WHO, "health promotion is the process of enabling people to increase control over, and to improve, their health”. In the same context, it is considered that “...in order to reach a stage of complete physical, mental and social well-being, an individual or group must be able to identify and to realize aspirations, to satisfy needs, and to change or cope with the environment...”.

In view of the multiplicity and diversity of health determinants, global and dynamic approaches are needed to protect and promote health in a comprehensive manner. Although the different health determinants will not have the same relative importance in different settings, all must be considered. For example, efforts to control noise may be wiped out by “off-the-job” activities, such as shooting, if practiced without adequate hearing protection. Workers should be encouraged to carry over their good hearing conservation practices to off-the-job situations, whenever relevant.

9.4. IMPLEMENTATION OF PROGRAMMES - PROGRAMME MANAGEMENT

Timely and realistic planning is essential for the establishment of any programme, and a plan of work must be elaborated, according to the real needs and accounting for the available resources. Other factors to be considered include legal requirements (legislation, standards), infrastructure and support services (including for equipment maintenance).

It should be always kept in mind that **anticipated prevention** is the best approach; for example, to achieve noise reduction in already installed and operational workplaces is very difficult and very costly.

Programmes must be efficient and sustainable; continuity must be ensured, as well as the possibility to eventually adapt to new needs and circumstances which may arise in the long run.

9.4.1. Management

Management involves decision-making concerning the goals to be achieved and the actions required to efficiently achieve them, through active participation from all concerned; it also involves foreseeing and avoiding (or recognizing and solving) problems which may create obstacles.

Good management should be able to make the difference between "work done" and "work well done". The importance of implementing and enforcing correct procedures cannot be overemphasized. Moreover, the real objective, not the intermediate steps, should serve as a yardstick to measure success; for example, the efficiency of a hearing conservation programme should not be evaluated by the number of noise surveys or audiometric tests carried out, but rather by the number of successful preventive actions which they triggered.

Furthermore, a distinction should always be made between what is "impressive" and what is "important". A very detailed noise survey with very accurate and precise sound measuring equipment, including 1/3 octave-band frequency analysis, may be very impressive but what is really important is that its results are adequately used for a fully justified and relevant purpose.

Management tools needed to efficiently implement a policy include, for example: transparent organization, clear working procedures (for standard operation as well as for maintenance, inspection and abnormal situations), adoption of standards and guidelines, human resources programme (selection, education and training, information, maintenance of staff competence), effective of lines of communication, development of performance indicators (environmental and health parameters, e.g., results from audiometric tests), and establishment of evaluation mechanisms.

Good communication within and outside the programme is essential for well coordinated team work, sharing of information and enhanced collaboration.

9.4.2. Team Work

The initial step should be the creation of a multidisciplinary team and the elaboration of mechanisms for efficient team work. The multidisciplinary team in charge of hazard prevention and control programmes should include the required occupational health and safety professionals, as well as representatives from management, production managers/engineers and workers. Moreover, all persons concerned should be somehow involved. The team should include, or have access to, professionals with competence in occupational hygiene, occupational medicine and occupational nursing, ergonomics, work psychology, and, in the case of noise control, also acoustical engineering and audiology. In all cases, workers' participation is indispensable.

Persons assigned to the hazard prevention and control team should have, in addition to the required knowledge and experience, also enthusiasm, commitment, spirit of collaboration and possibility to actively participate, including available time.

Measures and actions should never be imposed, but rather discussed. Moreover, teams and individuals should be provided with the resources and the freedom of action needed to fulfill their responsibilities, which should be clearly characterized and assigned. All members of the team can make a contribution and all must feel part of the programme. Joint efforts, involving all stakeholders, are needed to achieve full protection of workers' health.

9.4.3. Special Situations

Maintenance, repair and other non-routine activities usually receive less attention than required. Experience shows that such jobs may lead to overexposure since workers often make repairs without the required personal protection, for example, no hearing protection even if other noisy work processes are still operational.

Maintenance personnel usually works without any hearing protection because they feel that they have “to hear” the machinery; moreover, they often have to place themselves in awkward positions thus “dispensing” the additional burden of personal protection. It also happens that such operations are conducted outside normal working hours and unsupervised.

Maintenance and cleaning workers must also be protected, as needed, and should receive appropriate health and safety training. Particularly when maintenance and cleaning jobs are sub-contracted (which happens quite frequently) safety rules tend to be overlooked. This is more critical when dealing with hazards responsible for acute health effects, which is seldom the case of noise exposure.

9.4.4. Time Frame

A realistic appreciation of the time factor should be made at the planning stage. It is impossible to solve all problems at the same time, particularly if and when their solution requires medium to long-term interventions.

Therefore, priorities for action should be established considering aspects which include the following: number of workers exposed; nature and magnitude of exposure, hence the degree of hazard; feasibility of the action; availability of the required equipment and supplies, and, degree of interference with production.

Appropriate work practices and the use of personal protective equipment, such as hearing protection, can be implemented in a relatively short time. The full implementation, however, may take longer, as it depends on factors which often are out of the control of the occupational health professionals, such as having full cooperation from workers and supervisors, as well as from managers. Therefore, any preventive actions should be accompanied by adequate hazard communication, training and education of all stakeholders.

On the other hand, the design and implementation of engineering control measures - such as lining barrels or wheels with vibration-absorbing materials, acoustical enclosures, or acoustical treatment of surfaces, take time and usually require temporary shut-down of certain operations. Therefore, detailed timetables are indispensable.

Proposals presented to management should be feasible. Timetables should be prepared in collaboration with production managers/engineers and workers, and based on a realistic appreciation of the time needed to complete the installation of the controls.

9.5. PROGRAMME EVALUATION

Programmes should be periodically and critically evaluated, with a view to assessing their relevance and ensuring continuous improvement.

9.5.1. Monitoring Control Systems

Once a control system has been put into operation, it is necessary to ensure that the desired level of protection has been achieved and is maintained thereafter. In order to obtain the best possible performance, both engineering controls and personal protective equipment must be routinely inspected, maintained and, whenever necessary, replaced.

9.5.2. Indicators

An initial survey (ideally involving noise measurements and audiometric tests) should be carried out before a programme is implemented or reformulated. This provides good basic data for subsequent assessments of the effectiveness of the programme.

Indicators, which should be sensitive to changes in the work environment or in health parameters, usually relate an environmental condition to a health effect (e.g., noisy environment/hearing loss), or relate a certain environmental agent to an exposure factor (e.g., noisy machines/noise level at operator's ear).

Some indicators are used for decision-making purposes, others to monitor the efficiency of a preventive programme. For example, the "percentage of workers with a certain degree of hearing loss" indicates the need for immediate action. However, this should not be allowed to happen and a more acceptable decision-making indicator in this case would be "noise levels above a certain acceptable value".

Initial and follow-up audiometric examinations of workers provide valuable data for indicators.

In order to have scientific and user relevance, indicators should have characteristics which include the following: based on known linkages between, for example, noisy work environment and auditory effects; unbiased, reliable and valid; based on data of a known and acceptable quality; easily understood and acceptable by all stakeholders; based on data which are readily available or easily collected, at an acceptable cost, or, data which are needed anyway. Furthermore, indicators should be timely for policy and decision-making, and, appropriate to monitor the resulting actions.

For example, if the issue is noise control, it would not be "timely" to base a "decision-making indicator" on audiogram results, if audiometers were not available; the required equipment would have to be ordered and delivered, people trained in their use, hence a long time would elapse until the data could be obtained and the decision made. If, for example, it is impossible to understand normal conversation in the workplace in question, this would already serve as an indicator that noise control action is needed.

9.5.3. Environmental Surveillance for Control Purposes

Routine monitoring (continuous or intermittent) is a means to detect any alteration in the exposure conditions. This may result, for example, from changes in the process or materials utilized, from wearing off and deterioration of tools and machinery (such as unbalanced bearings), from deficiencies and breakdown in existing control systems, or from any accidental occurrence. Sound survey meters, although mostly not compliant to standards for integrating or normal sound level meters, have a wide application in "control" surveys.

It should be said that very accurate and precise quantitative evaluations are not necessary to check controls on a routine basis. Less sophisticated methods can be used to indicate alterations. Even some "practical surveillance" may be used; for example, observation of factors such as workers suddenly finding difficulties in understanding instructions, or reduced understanding via telephone.

In view of their familiarity with the operations, workers are usually in a position to provide valuable information about unusual occurrences and alterations that should be investigated in order to ensure the continued efficiency of the control systems.

Visualization techniques, for example, the "Picture Mix Exposure - PIMEX" (Rosen, 1993) can be very helpful in demonstrating the usefulness and relative efficiency of different control measures. This method combines a video image showing the worker performing his/her tasks, as well as a graduated bar displaying, for example, noise levels which are continuously measured at the worker's ear with a real time monitoring instrument. In the case of noise exposure, this method is particularly efficient in designing and evaluating work practices, since it enables one to "visualize" how noise levels vary while a task is performed in different manners.

9.5.4. Health Surveillance for Control Purposes

Health surveillance of workers includes pre-employment, periodic and special health examinations, including clinical observations, investigations of specific complaints, screening tests or investigations, and early detection of health impairment. In the case of noise exposure, audiometric tests are an important component of health surveillance.

Occupational hearing loss occurs very gradually. An early change in hearing ability indicates overexposure and, if immediate preventive action is taken to prevent further exposure, a more important hearing loss can be prevented. Therefore, early detection of noise-induced hearing loss, which is feasible through audiometry (see Chapter 8), should be part of any preventive programme. Through early detection of health impairment due to occupational health hazards, it is often possible to identify the hyper-susceptible workers and also to prevent further damage (secondary prevention).

Health surveillance should never be considered as a replacement for primary hazard prevention; however, it is an essential complement, as it contributes in many ways to preventive strategies. In the first place, results from health surveillance may serve as useful indicators of the need to control, and thereafter, of the efficiency of control systems, by detecting problems or failures in the control system. Comparisons of audiometric tests (of the same worker(s), at a time interval) that show some hearing loss can help trigger prompt preventive interventions and motivate workers to actively collaborate in order to prevent further damage. However, from an occupational hygiene point of view, this is much less desirable than actions triggered by the perception that there is overexposure but *before* any irreversible damage occurs.

Personnel responsible for health surveillance of workers should be kept informed about any hazard evaluation conducted in the workplace, and should have information on exposures observed at specific processes or operations, and vice versa.

Continuous communication, team work and exchange of data between health personnel and occupational hygienists are essential for the success of any hazard prevention and control programme. The establishment of correlations between working conditions and the health status of workers contributes to total exposure assessment and is indispensable for the evaluation of control strategies.

Workers should always be informed of the reasons for any health examinations and agree with the procedure. Participation of workers in surveillance and control actions may be spelled out in national legislation or supranational directives, for example, the European Directive 86/188/EEC on noise at work.

9.5.5. Record-keeping and Reports

It is important to keep good records and clear reports on measurements and tests, measuring instruments and control systems, as well as on the programme itself.

As to *noise measurements and audiometric tests*, the results should be well organized, identifiable and easily retrievable. Data to serve as indicators should be consistently gathered and analyzed. However, national legislations differ concerning to whom results from individual audiometric tests should be delivered. Usually such results are to be treated as confidential medical data and only group data used in connection with indicators of success (or failure) of programmes.

As to *measuring instruments and hearing protection*, all details concerning purchase (including contact person at the manufacturer's), as well as adequate logs on maintenance should be carefully kept. Measuring instruments also require records on routine calibration and hearing protection, on replacement deadlines.

Moreover, complete and accurate records of working conditions, materials used, and performance of control measures, should also be kept.

Objective and clear reports on the programme should be periodically prepared and critically analyzed by the team.

9.5.6. Continuous Improvement

In order to achieve continuous improvement, it is necessary to perform routine evaluations of how the programme is proceeding, including analysis of the selected indicators. It is important to establish an adequate system for the recognition and due appreciation of both failures and successes. Failures should be considered as learning experiences towards programme improvement, rather than as reason for criticism; pinpointing possible sources of mistakes, in order to correct and avoid them, is more important than "finding the guilty". On the other hand, successes should be fully recognized, given ample credit and celebrated by the team; this contributes to job satisfaction and improved performance.

9.6. REQUIRED RESOURCES

9.6.1. Human Resources

Even when the need for noise control has been established and the decision to implement the required preventive measures has been taken, there may be practical difficulties. One usual "stumbling block" is the shortage of adequately trained personnel, with specialized "know-how".

The required scientific, technical and managerial competence should be available among the members of the responsible team. For very specific technical issues, external professionals (for example acoustic engineers) may be engaged; however, their work should follow the specified control strategy and should be integrated into the comprehensive approach designed by the team.

In order to ensure that a programme is efficiently run, programme managers should have, in addition to knowledge and experience, also managerial competence.

9.6.2. Allocation of Financial Resources

The financial resources required for a hazard prevention and control programme have to be identified and secured before starting its implementation.

Financial resources must be optimized and carefully allocated within a framework of priorities, always keeping an appropriate balance among the different components, namely human resources and information, instrumentation and control systems. In certain situations, appreciable funds may be necessary for initial staff development.

In order to ensure sustainability of a programme, operational costs must be appropriately foreseen. These include, for example, expenses for: maintenance, repairs and purchase of spare parts for measuring instruments; maintenance, repairs and eventual replacement of personal protective equipment (e.g., hearing protectors); maintenance of staff competence, including continuing education and participation in scientific meetings; eventual hiring of external consultants, and, update of information systems (e.g., books, journals, CD-ROMs, access to data bases and the Internet - depending on the size and scope of the programme).

Some degree of financial flexibility should always be allowed, in order to respond to new needs which may eventually arise from periodic reassessments.

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Rosen, G. (1993). PIMEX - Combined Use of Air Sampling Instruments and Video Filming: Experience and Results During Six Years of Use. *Appl. Occup. Environ. Hyg.* **8** (4).

INTERNATIONAL STANDARDS

Titles of the following standards referred to in this chapter one will find together with information on availability in chapter 12:

ISO 11690-1, -2.

10

ENGINEERING NOISE CONTROL

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10.1. INTRODUCTION

As with any occupational hazard, control technology should aim at reducing noise to acceptable levels by action on the work environment. Such action involves the implementation of any measure that will reduce noise being generated, and/or will reduce the noise transmission through the air or through the structure of the workplace. Such measures include modifications of the machinery, the workplace operations, and the layout of the workroom. In fact, the best approach for noise hazard control in the work environment, is to eliminate or reduce the hazard at its source of generation, either by direct action on the source or by its confinement.

Practical considerations must not be overlooked; it is often unfeasible to implement a global control program all at once. The most urgent problems have to be solved first; priorities have to be set up. In certain cases, the solution may be found in a combination of measures which by themselves would not be enough; for example, to achieve part of the required reduction through environmental measures and to complement them with personal measures (e.g. wearing hearing protection for only 2-3 hours), bearing in mind that it is extremely difficult to make sure that hearing protection is properly fitted and properly worn.

This chapter presents the principles of engineering control of noise, specific control measures and some examples. Reading of chapter 1 is indispensable for the understanding of this chapter. Note that many of the specific noise control measures described are intended as a rough guide only. Further information on the subject can be found in ISO 11690 and in the specialised literature. Also suppliers of equipment and noise control hardware can often provide helpful noise control advice.

10.2. NOISE CONTROL STRATEGIES *(See ISO 11690)*

Prior to the selection and design of control measures, noise sources must be identified and the noise produced must be carefully evaluated. Procedures for taking noise measurements in the course of a noise survey are discussed in chapter 7.

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To adequately define the noise problem and set a good basis for the control strategy, the following factors should be considered:

- type of noise
- noise levels and temporal pattern
- frequency distribution
- noise sources (location, power, directivity)
- noise propagation pathways, through air or through structure
- room acoustics (reverberation).

In addition, other factors have to be considered; for example, number of exposed workers, type of work, etc. If one or two workers are exposed, expensive engineering measures may not be the most adequate solution and other control options should be considered; for example, a combination of personal protection and limitation of exposure.

The need for control or otherwise in a particular situation is determined by evaluating noise levels at noisy locations in a facility where personnel spend time. If the amount of time spent in noisy locations by individual workers is only a fraction of their working day, then local regulations may allow slightly higher noise levels to exist. Where possible, noise levels should be evaluated at locations occupied by workers' ears.

Normally the noise control program will be started using as a basis A-weighted immission or noise exposure levels for which the standard ISO 11690-1 recommends target values and the principles of noise control planning. A more precise way is to use immission and emission values in frequency bands as follows.

The desired (least annoying) octave band frequency spectrum for which to aim at the location of the exposed worker is shown in Figure 10.1 for an overall level of 90 dB(A). If the desired level after control is 85 dB(A), then the entire curve should be displaced downwards by 5 dB. The curve is used by determining the spectrum levels (see chapter 1) in octave bands and plotting the results on the graph to determine the required decibel reductions for each octave

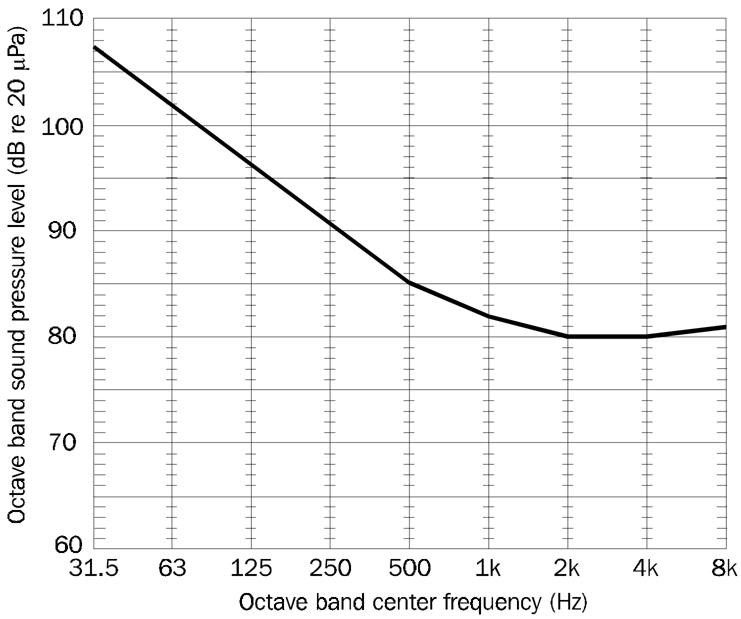


Figure 10.1. Desired noise spectrum for an overall level of 90 dB(A).

band. Clearly it will often be difficult to achieve the desired noise spectrum, but at least it provides a goal for which to aim.

It should be noted that because of the way individual octave band levels are added logarithmically, an excess level in one octave band will not be compensated by a similar decrease in another band. The overall A-weighted sound level due to the combined contributions in each octave band is obtained by using the decibel addition procedure described in chapter 1.

Any noise problem may be described in terms of a **source**, a **transmission path** and a **receiver** (in this context, a worker) and noise control may take the form of altering any one or all of these elements. The noise source is where the vibratory mechanical energy originates, as a result of a physical phenomenon, such as mechanical shock, impacts, friction or turbulent airflow. With regard to the noise produced by a particular machine or process, experience strongly suggests that when control takes the form of understanding the noise-producing mechanism and changing it to produce a quieter process, as opposed to the use of a barrier for control of the transmission path, the unit cost per decibel reduction is of the order of one tenth of the latter cost. Clearly, the best controls are those implemented in the original design. It has also been found that when noise control is considered in the initial design of a new machine, advantages manifest themselves resulting in a better machine overall. These unexpected advantages then provide the economic incentive for implementation, and noise control becomes an incidental benefit. Unfortunately, in most industries, occupational hygienists are seldom in the position of being able to make fundamental design changes to noisy equipment. They must often make do with what they are supplied, and learn to use effective "add-on" noise control technology, which generally involves either modification of the transmission path or the receiver, and sometimes the source.

If noise cannot be controlled to an acceptable level at the source, attempts should then be made to control it at some point during its propagation path; that is, the path along which the sound energy from the source travels. In fact, there may be a multiplicity of paths, both in air and in solid structures. The total path, which contains all possible avenues along which noise may reach the ear, has to be considered.

As a last resort, or as a complement to the environmental measures, the noise control problem may be approached at the level of the receiver, in the context of this document, the exposed worker(s).

In existing facilities, controls may be required in response to specific complaints from within the workplace, and excessive noise levels may be quantified by suitable measurements as described previously. In proposed new installations, possible complaints must be anticipated, and expected excessive noise levels must be estimated by some procedure. As it is not possible to entirely eliminate unwanted noise, minimum acceptable levels of noise must be formulated and these levels constitute the criteria for acceptability (see chapter 4) which are generally established with reference to appropriate regulations in the workplace.

In both existing and proposed new installations an important part of the process is to identify noise sources and to rank order them in terms of contributions to excessive noise. When the requirements for noise control have been quantified, and sources identified and ranked, it is possible to consider various options for control and finally to determine the cost effectiveness of the various options. As was mentioned earlier, the cost of enclosing a noise source is generally much greater than modifying the source or process producing the noise. Thus an argument, based upon cost effectiveness, is provided for extending the process of sourceidentification to specific sources on a particular item of equipment and rank ordering these contributions to the limits of practicality.

10.2.1. Existing installations and facilities *(See ISO 11690)*

In existing facilities, quantification of the noise problem involves identification of the source or sources, determination of the transmission paths from the sources to the receivers, rank ordering of the various contributors to the problem and finally determination of acceptable solutions.

To begin, noise levels must be determined at the locations from which the complaints arise. Once levels have been determined, the next step is to apply acceptable noise level criteria to each location and thus to determine the required noise reductions, generally as a function of octave or one-third octave frequency bands (see chapter 1).

Once the noise levels have been measured and the required reductions determined, the next step is to identify and rank order the noise sources responsible for the excessive noise. The sources may be subtle or alternatively many, in which case rank ordering may be as important as identification. Where many sources exist, rank ordering may pose a difficult problem.

When there are many sources it is important to determine the sound power and directivity of each to determine their relative contributions to the noise problem. The radiated sound power and directivity of sources can be determined by reference to the equipment manufacturer's data (ISO 4871) or by measurement, using methods outlined in chapter 1. The sound power should be characterised in octave or one third octave frequency bands (see chapter 1) and dominant single frequencies should be identified. Any background noise interfering with the sound power measurements must be taken into account and removed (see chapter 1).

NOTE: This is the ideal procedure. In reality, many people choose machinery or equipment using only noise emission values according to ISO 4871 and they make comparisons according to ISO 11689.

Often noise sources are either vibrating surfaces or unsteady fluid flow (air, gas or steam). The latter are referred to as aerodynamic sources and they are often associated with exhausts. In most cases, it is worthwhile to determine the source of the energy which is causing the structure or the aerodynamic source to radiate sound, as control may best start there.

Having identified the noise sources and determined their radiated sound power levels, the next task is to determine the relative contribution of each noise source to the noise level at each location where the measured noise levels are excessive. For a facility involving just a few noise sources, as is the case for most occupational noise problems at a specific location, this is usually a relatively straightforward task.

Once the noise sources have been ranked in order of importance in terms of their contribution to the overall noise problem, it is often also useful to rank them in terms of which are easiest to do something about and which affect most people, and take this into account when deciding which sources to treat first of all. This is discussed in more detail in Chapter 7.

10.2.2. Installations and facilities in the design stage

In new installations, quantification of the noise problem at the design stage may range from simple to difficult but never impossible. At the design stage the problems are the same as for existing installations; they are identification of the source or sources, determination of the transmission paths of the noise from the sources to the receivers, rank ordering of the various contributors to the problem and finally determination of acceptable solutions. Mostimportantly,at the design stage the options for noise control are generally many and may include rejection of the proposed design.

The first step for new installations is to determine the noise criteria for sensitive locations which may typically include locations of operators of noisy machinery. If the estimated noise levels at any sensitive location exceed the established criteria, then the equipment contributing most to the excess levels should be targeted for noise control, which could take the form of:

- specifying lower equipment noise levels to the equipment manufacturer (care must be taken whenever importing equipment, particularly second hand which can be very noisy and hence no longer acceptable in the country of origin);
- including noise control fixtures (mufflers, barriers, vibration isolation systems, enclosures, or factory walls with a higher sound transmission loss) in the factory design; or
- rearrangement and careful planning of buildings and equipment within them. In this context, note should be taken of the discussion on directivity in chapter 1. The essence of the discussion is that sources placed near hard reflective surfaces will result in higher sound levels at the approximate rate of 3 dB for each large surface, as illustrated in Figure 10.2. Note that the shape of the building space generally is not important, as a reverberant field can build-up in spaces of any shape. Care should be taken to organise production lines so that noisy equipment is separated from workers as much as possible.

Sufficient noise control should be specified to leave no doubt that the noise criteria will be met at <u>every</u> sensitive location. Saving money at this stage is not cost effective in the long term.

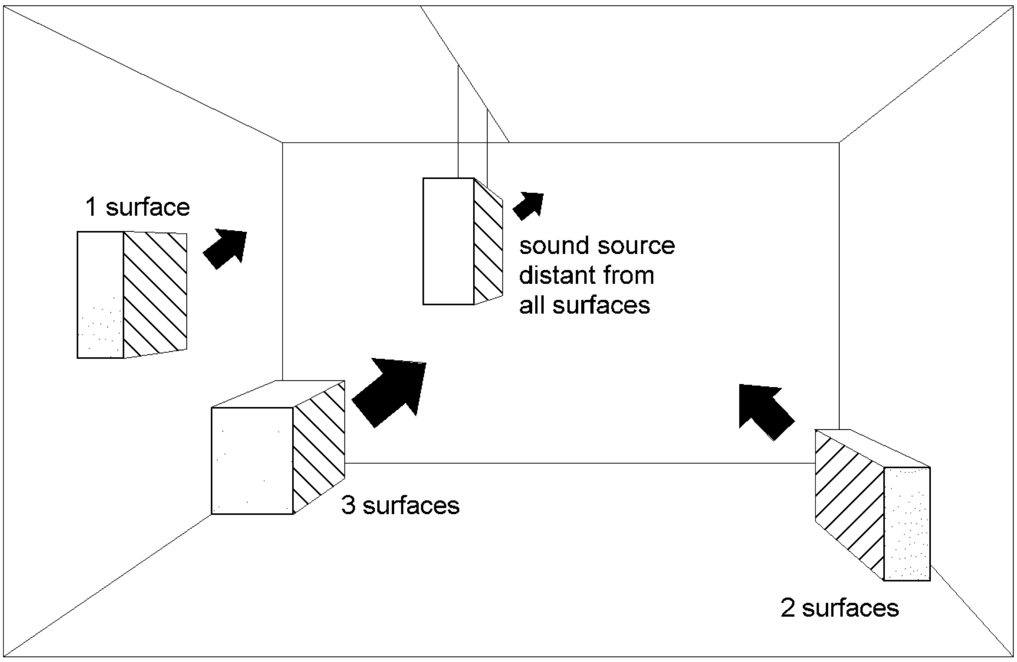


Figure 10.2. Sound sources should not be placed near corners (ASF, 1977)

10.3. CONTROL OF NOISE AT THE SOURCE *(See ISO TR 11688)*

To fully understand noise control, fundamental knowledge of acoustics is required. Although well covered in the specialised literature (OSHA, 1980; Beranek, 1988; Beranek and Ver, 1992;

Harris, 1991; Bies and Hansen, 1996), some fundamental concepts have been presented in chapter 1, and some additional concepts relevant to noise control are hereby reviewed.

To control noise at the source, it is first necessary to determine the cause of the noise and secondly to decide on what can be done to reduce it. Modification of the energy source to reduce the noise generated often provides the best means of noise control. For example, where impacts are involved, as in punch presses, any reduction of the peak impact force (even at the expense of a longer time period over which the force acts) will dramatically reduce the noise generated.

Generally, when a choice of mechanical processes is possible to accomplish a given task, the best choice, from the point of view of minimum noise, will be the process which minimises the time rate of change of force or jerk (time rate of change of acceleration). Alternatively, when the process is aerodynamic a similar principle applies; that is, the process which minimises pressure gradients will produce minimum noise. In general, whether a process is mechanical or fluid mechanical, minimum rate of change of force is associated with minimum noise.

Among the physical phenomena which can give origin to noise, the following can be mentioned:(see also chapter 5)

- mechanical shock between solids,
- unbalanced rotating equipment
- friction between metal parts,
- vibration of large plates,
- irregular fluid flow, etc.

Control of noise at the source may be done either indirectly,i.e.generally, or directly,i.e. related to the design process addressing one of the causes cited above. The latter is the aim of ISO TR 11688.

NOTE: In noise control by design the terms direct and indirect sometimes are used for the path of sound from the generation to propagation in the air. So airborne sound in a fan is radiated directly but solidborne sound in a gear is transmitted to the wall of the casing and radiated as airborne sound indirectly.

GENERAL SOURCE NOISE CONTROL CAN INVOLVE:

- **Maintenance:**
  - replacement or adjustment of worn or loose parts;
  - balancing of unbalanced equipment;
  - lubrication of moving parts;
  - use of properly shaped and sharpened cutting tools.

- **Substitution of materials** (e.g., plastic for metal), a good example being the replacement of steel sprockets in chain drives with sprockets made from flexible polyamide plastics.

- **Substitution of equipment:**
  - electric for pneumatic (e.g. hand tools);
  - stepped dies rather than single-operation dies;
  - rotating shears rather than square shears;
  - hydraulic rather than mechanical presses;
  - presses rather than hammers;
  - belt conveyors rather than roller conveyors.

- **Specification of quiet equipment.**

- **Substitution of parts of equipment:**
  - modification of gear teeth, by replacing spur gears with helical gears - generally resulting in 10 dB of noise reduction);
  - replace straight edged cutters with spiral cutters (e.g. wood working machines - 10 dB(A) reduction);
  - replace gear drives with belt drives;
  - replace metal gears with plastic gears (beware of additional maintenance problems);
  - replace steel or solid wheels with pneumatic tyres.

- **Change of work methods**
  - in building demolition, replace use of ball machine with selective demolition;
  - replace pneumatic tools by changing manufacturing methods, such as moulding holes in concrete rather than cutting after production of concrete component;
  - use remote control of noisy equipment such as pneumatic tools;
  - separate noisy workers in time, but keep noisy operations in the same area, separated from non-noisy processes;
  - select slowest machine speed appropriate for a job - also select large, slow machines rather than smaller faster ones;
  - minimise width of tools in contact with workpiece (2 dB(A) reduction for each halving of tool width);
  - woodchip transport air for woodworking equipment should move in the same direction as the tool;
  - minimise protruding parts of cutting tools.

- **Substitution of processes.**
  - mechanical ejectors for pneumatic ejectors;
  - hot for cold working;
  - pressing for rolling or forging;
  - welding or squeeze rivetting for impact rivetting;
  - welding for rivetting;
  - use cutting fluid in machining processes;
  - change from impact action (e.g. hammering a metal bar) to progressive pressure action (e.g. bending metal bar with pliers as shown in Figure 10.3, or increase of time during which a force is applied, as shown in Figure 10.4);
  - replace circular saw blades with damped blades (see Figure 10.9);
  - replace mechanical limit stops with micro-switches.

- **substitution of mechanical power generation and transmission equipment**
  - electric motors for internal combustion engines or gas turbines;
  - belts or hydraulic power transmissions for gear boxes;

- **replacement of worn moving parts** (e.g., replace new rolling element bearings for worn ones);

- **minimising the number of noisy machines running at any one time**.

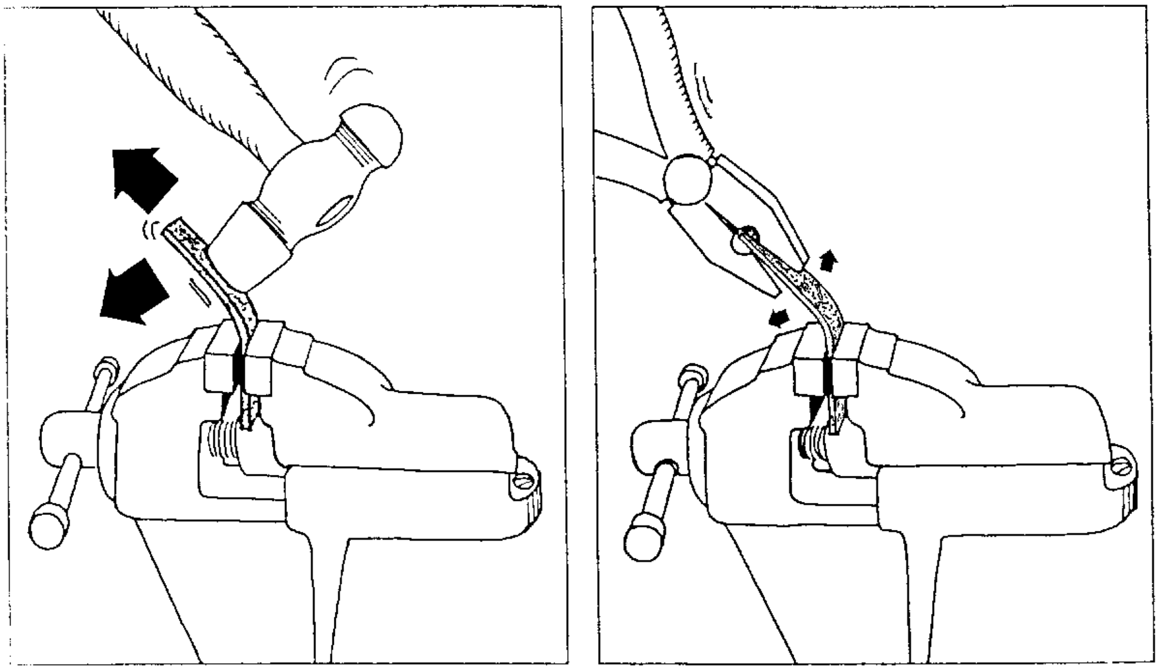


Figure 10.3. Example of bending instead of hammering (ASF, 1977)

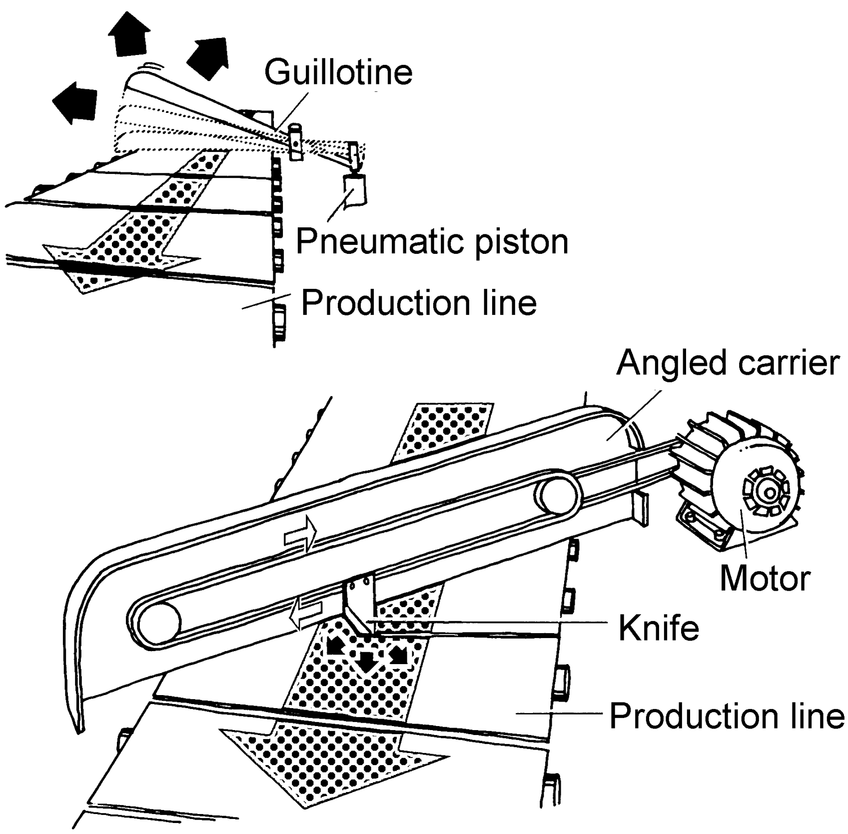


Figure 10.4. Example of increasing the time during which a force is applied (ASF, 1977).

SOURCE CONTROL BY DESIGN INVOLVES ***(See ISO/TR 11688)***

- **reduction of mechanical shock between parts** by:
  - **modifying parts** to prevent rattle and ringing;
  - using an **adjustable height collector** (see Figure 10.5a) for parts falling into a bin, so that impact speed and thus radiated noise is reduced;
  - using an **adjustable height conveyor and rubber flaps** to minimise the fall height of the parts (see Figure 10.5b);
  - **lining** of tumbling barrels, parts collecting bins, metal chutes, hoppers, etc. with elastic material, e.g. cork, hard rubber, plastic, conveyor belt material, with the choice of material being as soft as possible but sufficiently hard to withstand the particular operating environment without wearing out prematurely. In extreme cases, an effective alternative is to line the chute or bin with a thin layer of viscoelastic material such as silicone rubber or silastic, sandwiched between the bin and a second layer of steel or other abrasion resistant material, with the latter layer being of similar thickness to the wall of the bin or chute (see Figure 10.6);
  - **covering** metal tables, metal wheels, etc. with a **material**, such as rubber;
  - using conveyor belts instead of chutes to avoid noisy falls.

- **Reduction of noise resulting from out-of-balance** by:
  - **balancing** moving parts;
  - use of **vibration absorbers and dampers** tuned to equipment resonances (see Bies and Hansen, 1996, Ch. 10).

- **Reduction of noise resulting from friction between metal parts** by:
  - **lubrication or use of soft elastic interspacing** (the classical example of a noisy door to which oil is applied to the hinges demonstrates the efficiency of this measure).

- **Reduction of noise resulting from the vibration of large structures (plates, beams, etc.)** by:
  - **ensuring that machine rotational speeds do not coincide with resonance frequencies of the supporting structure**, and if they do, changing the stiffness or mass of the supporting structure to change its resonance frequencies (increasing stiffness increases resonance frequencies and increasing the mass reduces resonance frequencies);
  - **reducing the acoustic radiation efficiency of the vibrating surface** by
    - replacement of a solid panel or machine guard with a woven mesh or perforated panel (see Figures 10.7a and b);
    - use of narrower belt drives, etc. (see Figure 10.8);
  - **damping a panel if it is excited mechanically** (see Figure 10.9), but note that if the panel is excited by an acoustic field, damping will have little or no effect upon its sound radiation;
    - the amount of damping already characterising a structure can be approximately determined by tapping it with a steel tool or rod. If the structure "rings" for a period after it is struck, then the damping is low. If only a dull thud is heard, then the damping is high. If the damping is low, then the surface may be treated either with a single layer damping treatment or a constrained layer treatment as described below. The noise reduction achieved is usually in the range 2 to 10 dB.

- **single layer damping treatments** are viscoelastic materials which include filled bitumens, silicone sealant and elastomeric polymers, all of which are available in the form of adhesive sheets or thick liquids for spraying or trowelling on to the surface to be treated. Care is necessary to ensure that the material selected can withstand the dirt, water or chemical environment to which it will be subjected. For effective results, the damping material thickness must be between one and three times the thickness of the surface being damped. Clearly this type of damping is most effective for thin structures.

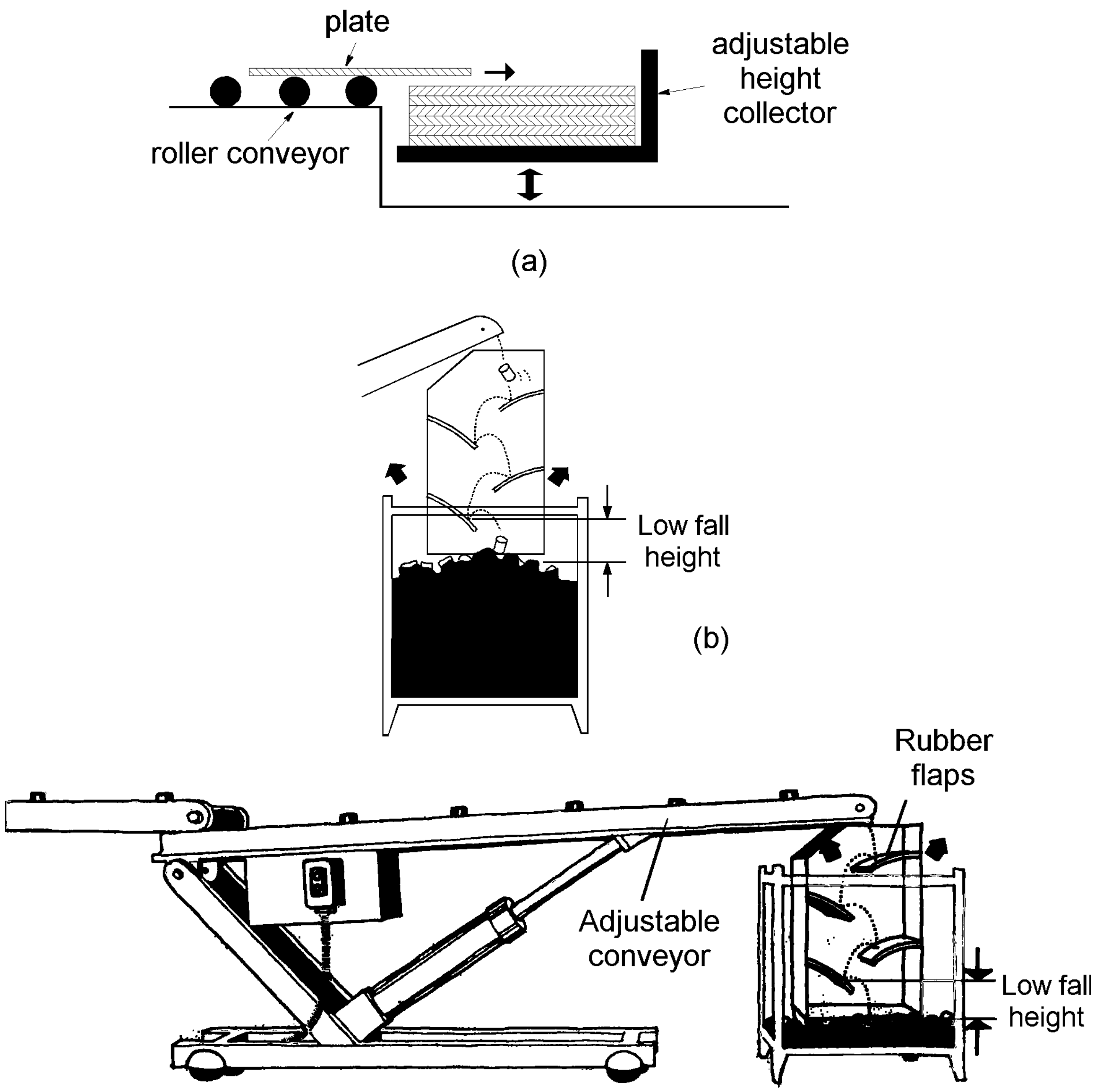


Figure 10.5. Examples of decrease of dropping height (ASF, 1977, with additions)
(a) Adjustable height collector.
(b) Adjustable height conveyor with rubber flaps.

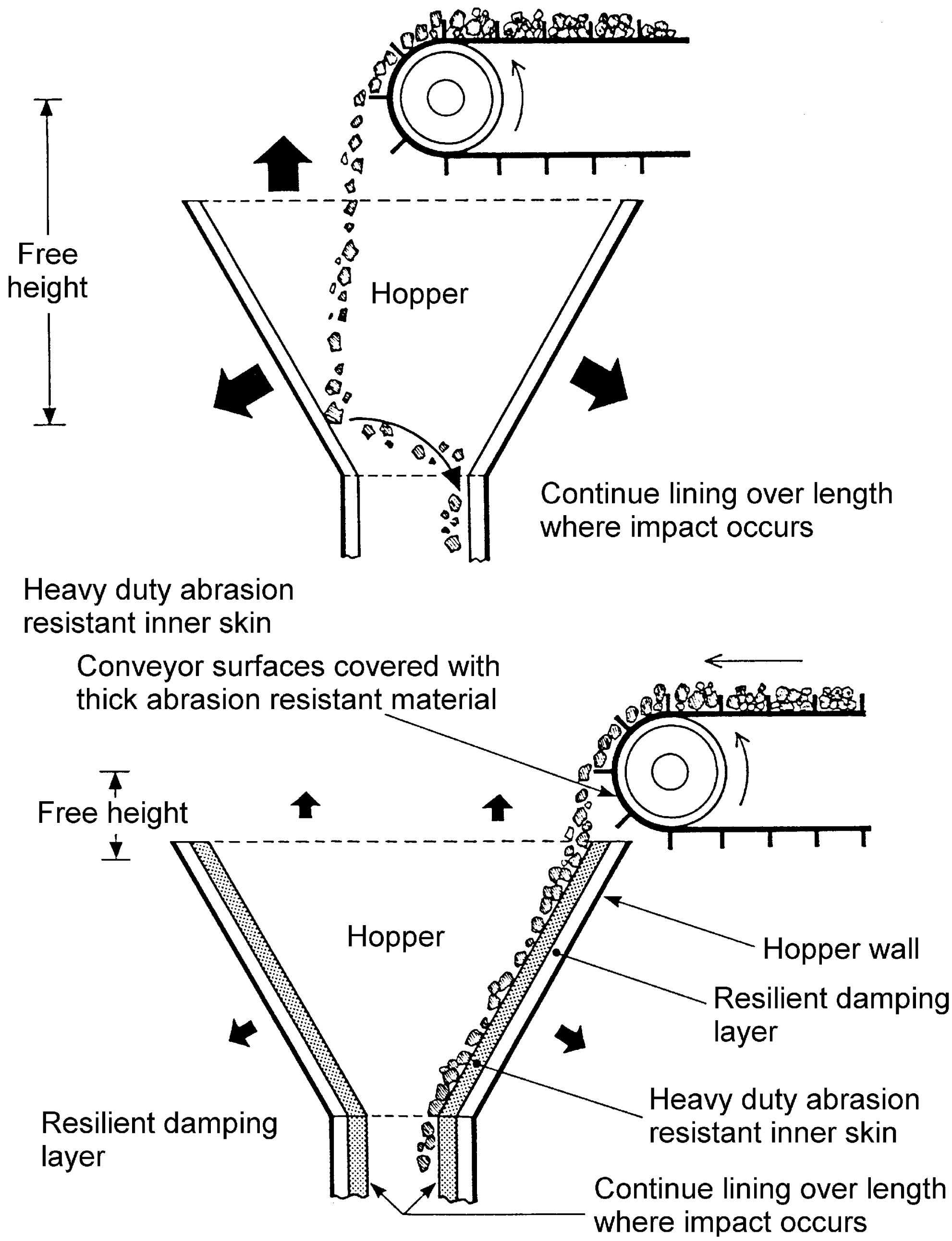


Figure 10.6. Lining a hopper with an impact absorbing and damping construction. Note that to achieve a constraint layer treatment, the "heavy duty abrasion resistant inner skin" in the lower figure could be replaced with a steel plate.

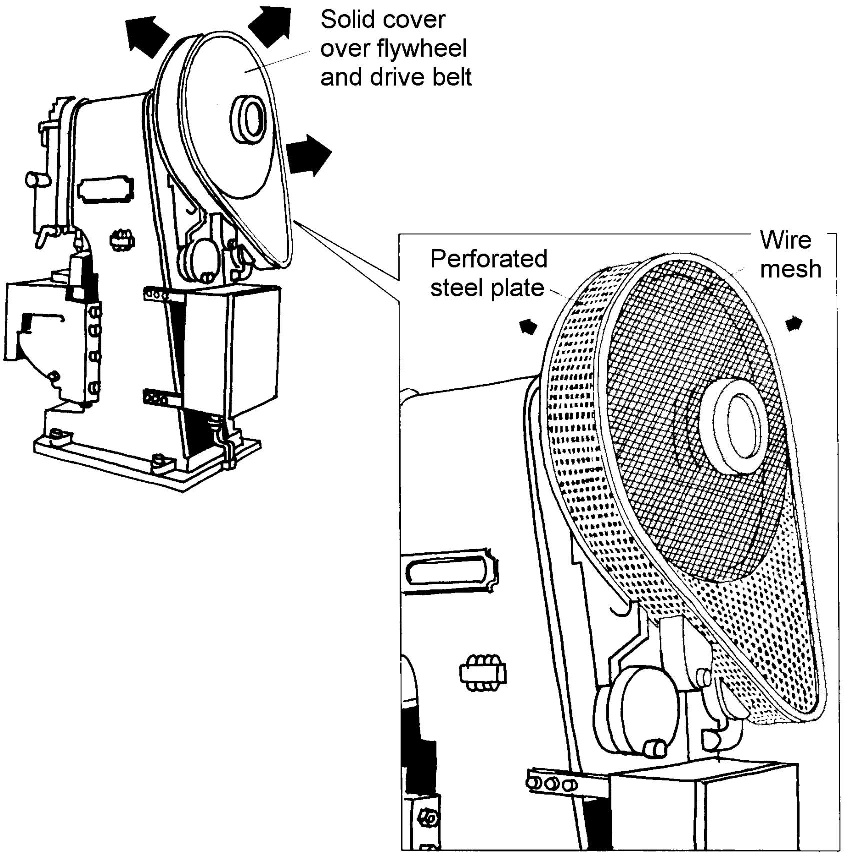


Figure 10.7(a). Use of a mesh protective cover for a flywheel, instead of a solid metal cover (ASF, 1977).

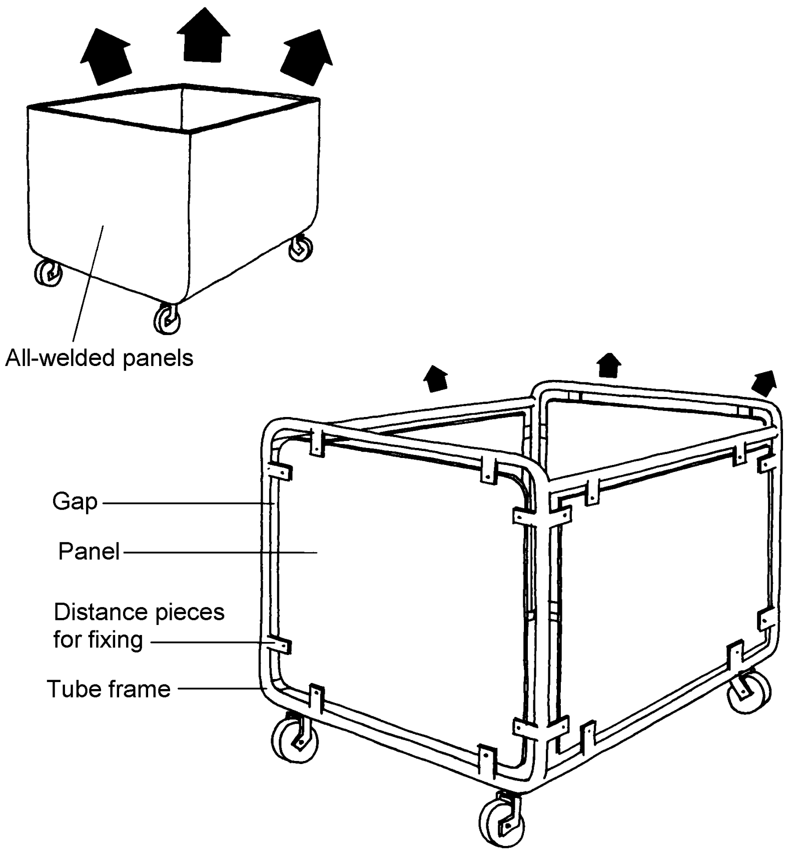


Figure 10.7(b). Use of open sided trolleys to transport material (ASF, 1977).

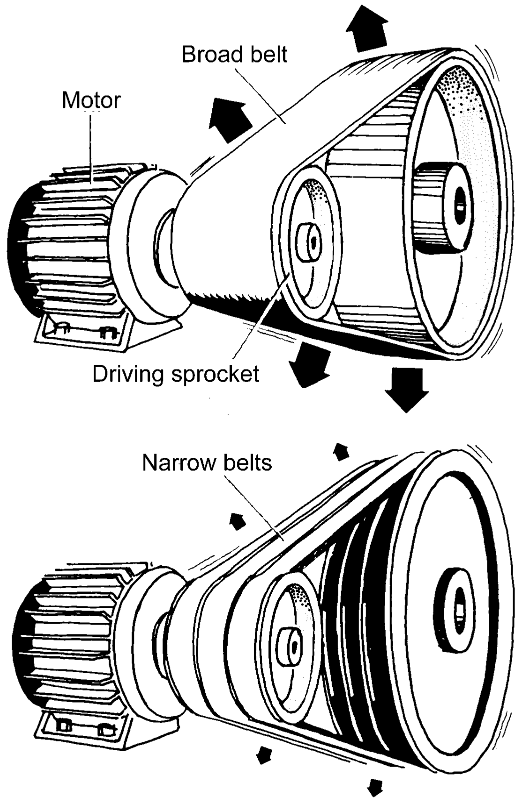


Figure 10.8. Use of narrower belts instead of a large belt drive (ASF, 1977).

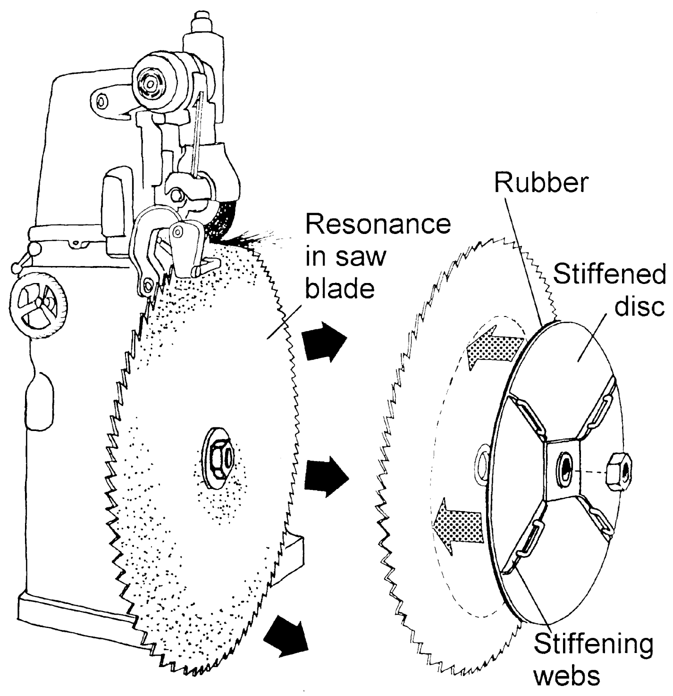


Figure 10.9. Damping of a circular saw (ASF, 1977).

- **constrained layer damping** treatments, such as illustrated in figure 10.6, consist of a layer of viscoelastic material sandwiched between the structure and a layer of steel or aluminium. As a rule of thumb, the viscoelastic layer is about 1/3 as thick as the surface to be damped and for vibrating structures less than 1.5 mm thick the constraining outer layer should be the same thickness. For vibrating structures of thickness between 1.5 and 3mm, the constraining layer should be 1.5mm thick and for vibrating structures with a thickness of greater than 3mm, the constraining layer should be 3mm thick. Sometimes these rules of thumb produce a structure which is effectively damped in a particular frequency range which may not be the frequency range in which the noise radiation is a problem. In this case it may be necessary to fine tune the layer thicknesses, either experimentally or theoretically (see Cremer et. al., 1988).

- **reducing area of radiating surfaces**;
  - use of perforated sheet metal machine covers;
  - use a number of narrow drive belts rather than one wide one;
- **blocking the transmission of vibration** along a noise radiating structure by the placement of a heavy mass on the structure close to the original source of the noise;
- **isolating the vibration source from the noise radiating structure** by physically separating them (see Figure 10.10) or by using one or more of isolating elements (see Figure 10.11) - see for example Figures 10.12 and 10.13 - and taking into account the following factors (Bies and Hansen, 1996**)**
  - the **resonance frequency**, f_0 (Hz), associated with the stiffness of the isolating spring (k Newtons/metre) and the mass which it is supporting (m kg) and given by $f_0 = [1/(2\pi)]\sqrt{k/m}$ Hz, should be well below (less than half) the lowest frequency which is to be isolated (see Figure 10.14). The resonance frequency may also be calculated by knowing how much the isolating spring compresses (d cm) under the weight of the machine (static deflection); That is, $f_0 = 4.98/\sqrt{d}$ Hz.
  - the **excitation frequency**, f (Hz), for a rotating machine mounted on an isolator is generally equal to the rotational speed, expressed as revolutions per second.
  - the **transmissibility**, T, of an isolator is given by

$$T = \sqrt{\frac{1 + (2\zeta X)^2}{(1 - X^2)^2 + (2\zeta X)^2}} \qquad (1)$$

  - where $X = f/f_0$ and ζ is the critical damping ratio which is approximately 0.005 for steel springs, 0.05 for rubber mounts, 0.12 to 0.15 for silicone or low-T elastomers, 0.1 to 0.2 for glass fibre pads and 0.3 for a composite pad. Note that increasing damping reduces the vibration amplitude of the isolated system as the exciting frequency passes through resonance (on machine start-up, for example), but decreases the isolation achieved for excitation frequencies above this frequency;
  - the **isolation efficiency**, η, of the isolator is related to the transmissibility, T, by $\eta = (1 - T) \times 100\%$. Generally a value of η between about 85 and 95% is used.
  - for systems using **more than one isolator** (generally 4 are used to support the 4 corners of the base of the equipment being isolated), then resonance frequencies associated with twisting and rocking motions must also be calculated to ensure that they are well below the excitation frequency range (see Bies and Hansen, 1996, Ch. 10);

- **elastomeric materials** such as rubber are often preferred over steel springs because their greater damping reduces the large vibration amplitudes which occur when an excitation frequency coincides with the isolation system resonance (see Figure 10.14). Also, rubber materials prevent the transmission of vibration in the audio frequency range which is often transmitted along the coils of a steel spring. A disadvantage of rubber is its lack of tolerance for oily or sunny environments and this should be taken into account in a regular maintenance program;
- if **steel springs** are used, then rubber inserts should be placed between the spring and its attachment to the supporting structure to prevent the transmission of vibration in the mid-audio frequency range;
- **isolating materials** such as foam rubber, mineral wool and cork are often used for heavy equipment, but become ineffective in a relatively short time due to the elastic nature of the deflection of the material gradually changing to a permanent deflection;
- the dimensions of the **equipment support base** must be much larger than the height of the centre of gravity of the equipment, to minimise the risk of the equipment swaying unstably when the base is supported by flexible vibration isolators (see Figures 10.15);
- **isolator selection procedure:**
  - determine lowest continuous forcing frequency of machine to be isolated;
  - establish desired isolation efficiency and then calculate required transmissibility;
  - use the above transmissibility equation to determine X, which together with lowest continuous forcing frequency may be used to calculate the required resonance frequency for the isolator (as $X=f/f_0$);
  - use the static deflection equation with the required f_0 to calculate the required static deflection of the isolator;
  - knowing the weight supported by each isolator, refer to manufacturer's load deflection data to select the most suitable isolator;
- **lateral restraints (or snubbers)** are available to prevent too much sideways movement during machine start-up or during earthquakes;

- **reduction of noise resulting from fluid flow** by:
  - providing machines with **adequate cooling fins** so that noisy fans are no longer needed;
  - using **centrifugal rather than propeller fans** when fan use is unavoidable;
  - **locating fans in smooth, undisturbed air flow** (see Figure 10.16);
  - using **curved fan blades** designed to minimise turbulence (see Figures. 5.2 and 5.3 in chapter 5)or use **irregular spacing** in fans with straight blades as in traction motors (see Figure 10.17);
  - using of large, **low speed fans** rather than smaller, faster ones;
  - **minimising velocity** of fluid flow and increase cross-section of fluid streams;
  - **reducing the pressure drop** across any one component in a fluid flow system;
  - **minimising fluid turbulence** where possible (eg avoid obstructions in the flow);
  - choosing **quiet pumps** in hydraulic systems;
  - choosing **quiet nozzles** for compressed air systems (see Figures. 10.18(a) to (c));
  - **isolating pipes** carrying the fluid from support structures, as in Figure 10.11;
  - using **flexible connectors** in pipe systems to control energy travelling in the fluid as well as the pipe wall (see Figure 10.19);
  - using **flexible fabric sections** in low pressure air ducts (near the noise source such as a fan).

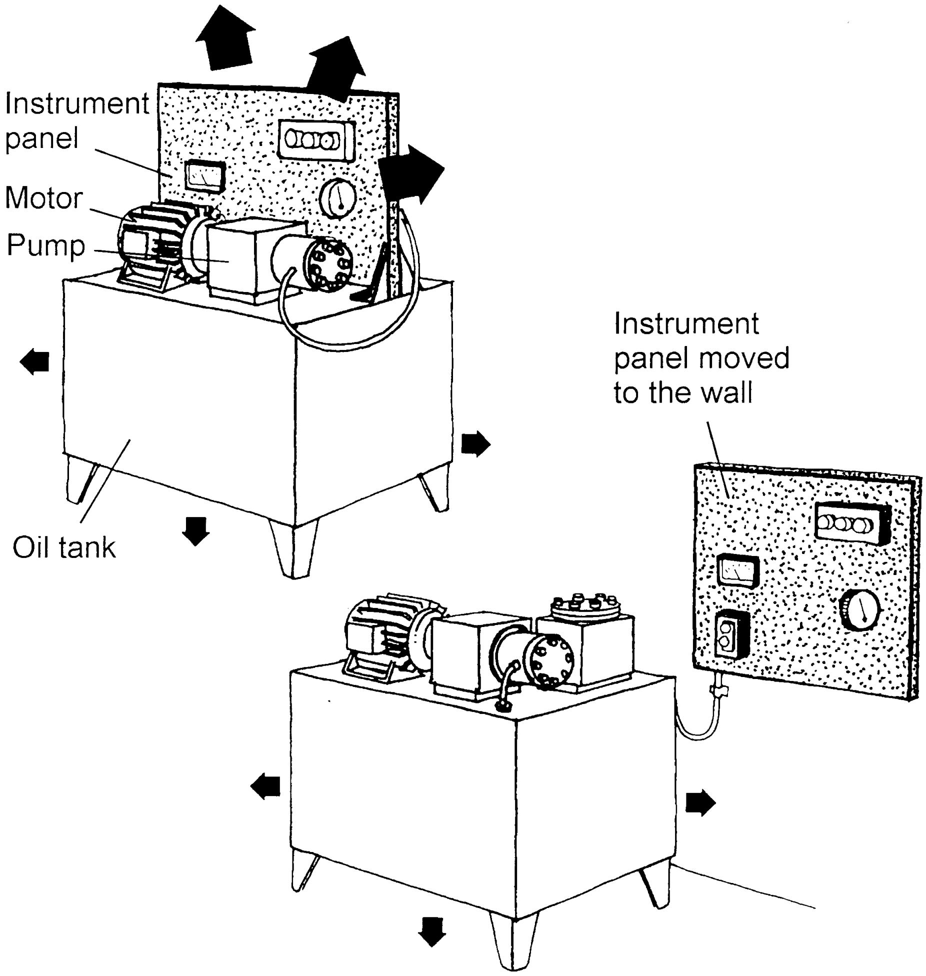


Figure 10.10. Vibration isolation by separation (ASF, 1977).

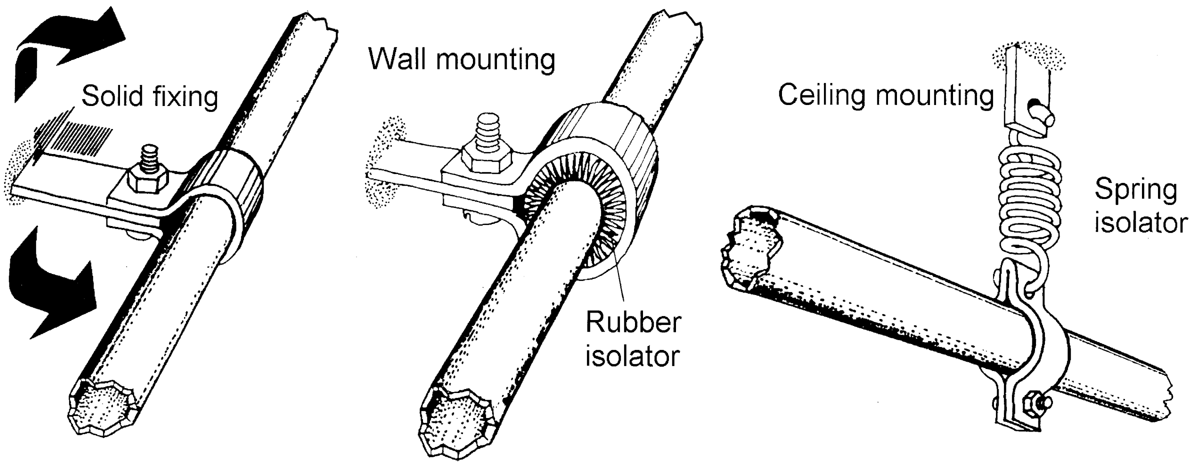


Figure 10.11. Reduction of vibration transmission from piping systems (ASF, 1977).

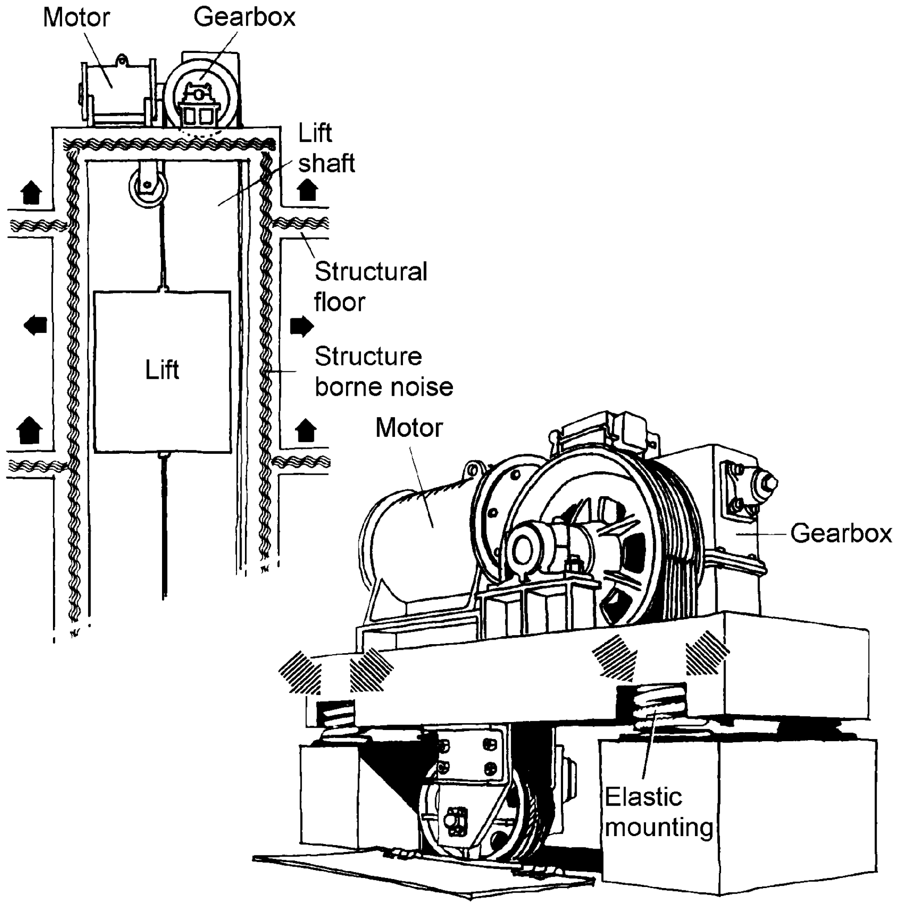


Figure 10.12. Vibration isolation of a lift to minimise lift noise transmitted throughout a building structure and then into occupied spaces (ASF, 1977).

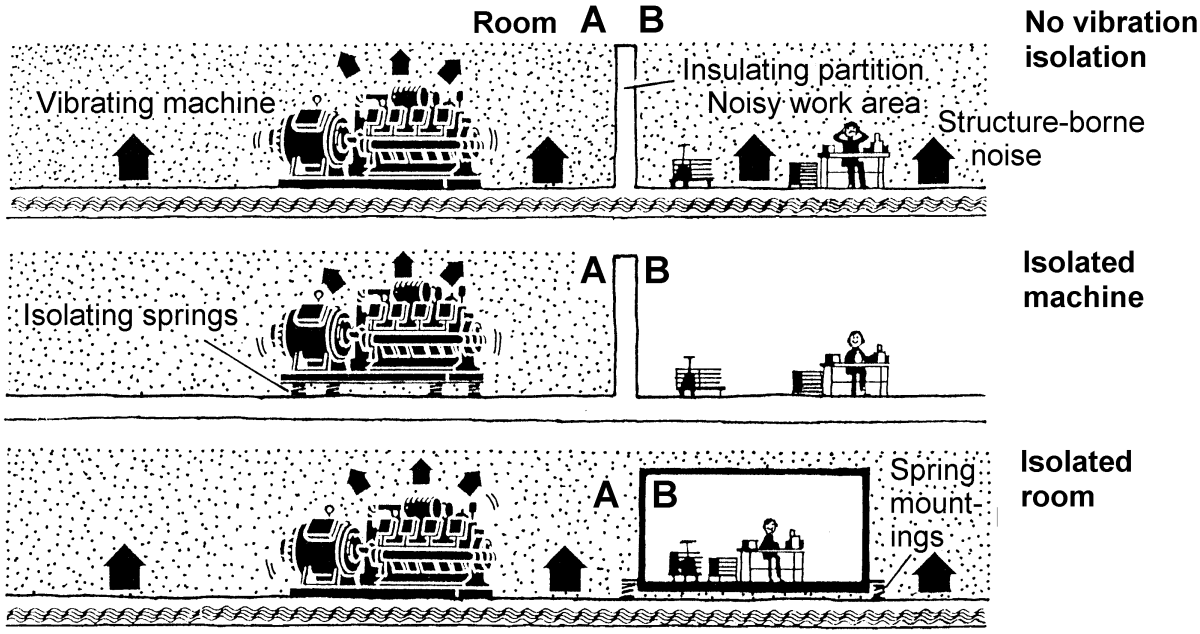


Figure 10.13. Vibration isolation to prevent noise transmitted through the machine supports to occupied spaces (ASF, 1977).

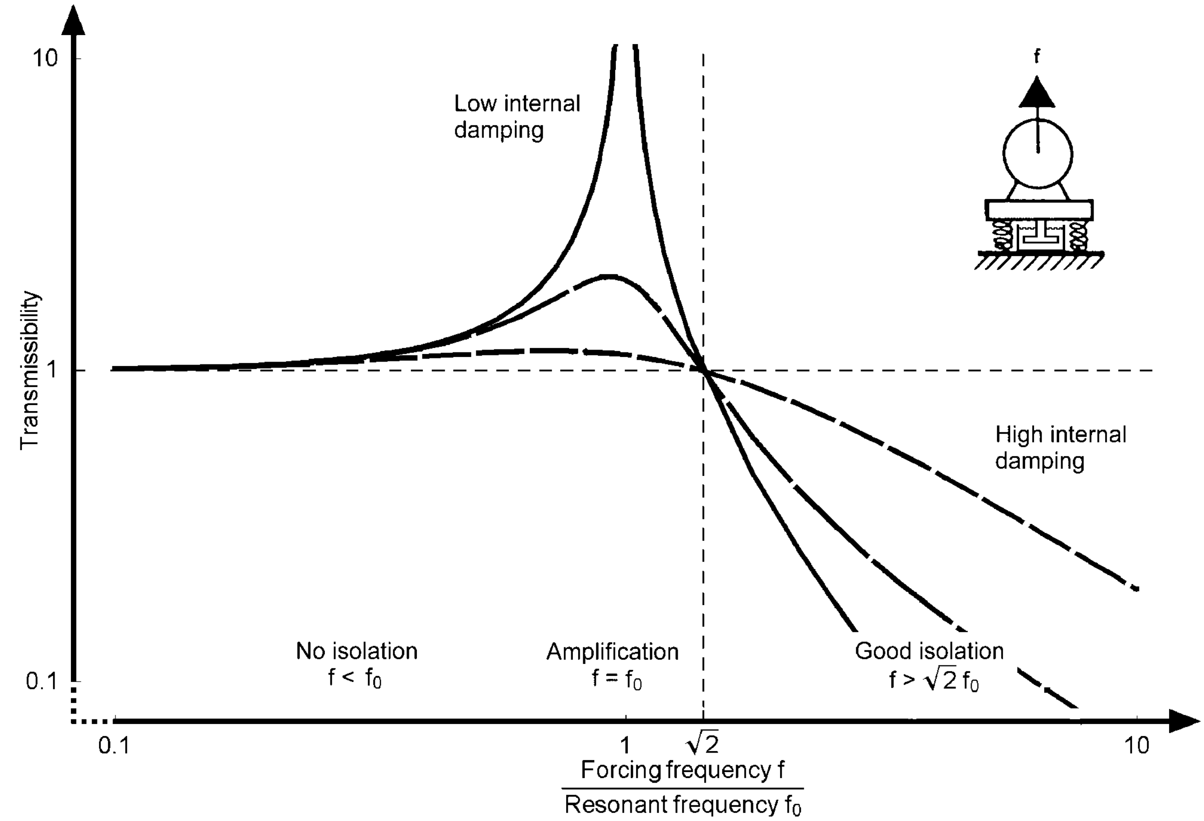


Figure 10.14. Illustration of vibration transmission through isolators as a function of frequency.

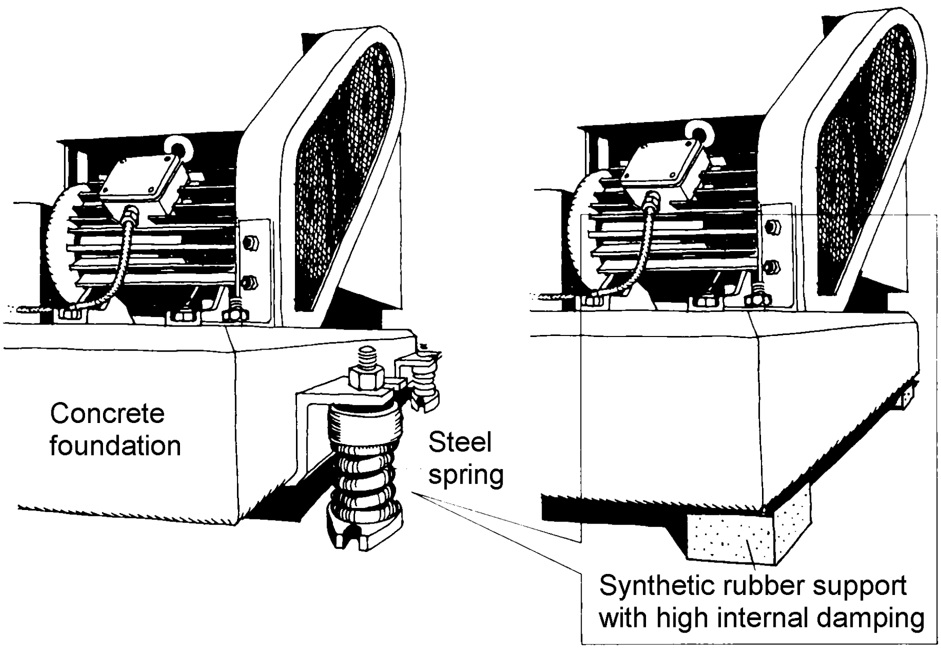


Figure 10.15. Steel vs rubber isolators (ASF, 1977).

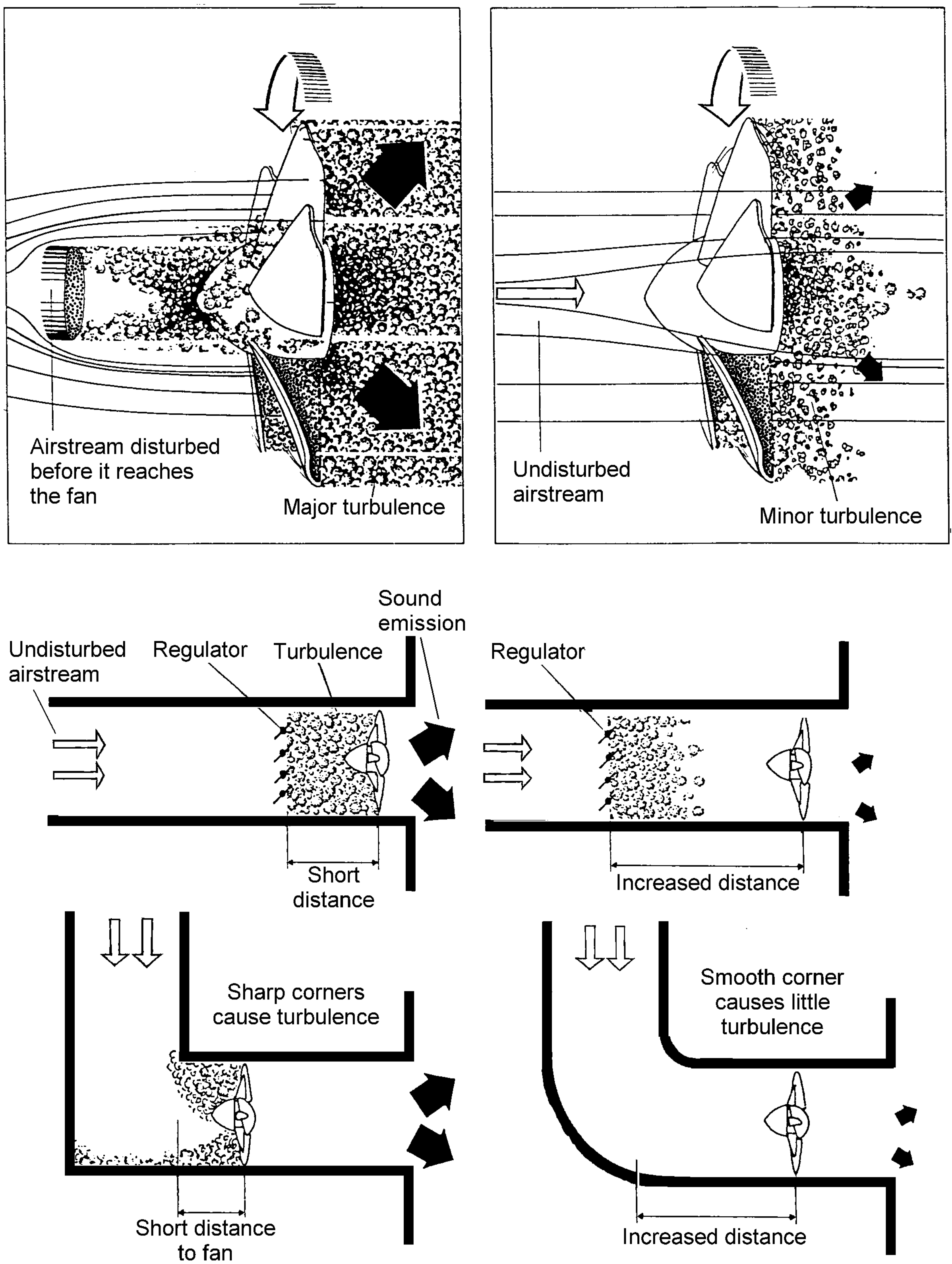


Figure 10.16. Location of fans in smooth air flows to reduce aerodynamic noise (ASF, 1977).

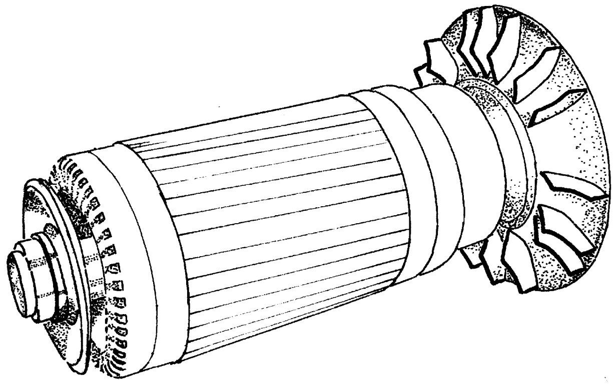


Figure 10.17. Centrifugal impeller with irregular spacing used in the self-ventilation of traction motors to reduce noise of straight blade fan (after Huebner, 1963).

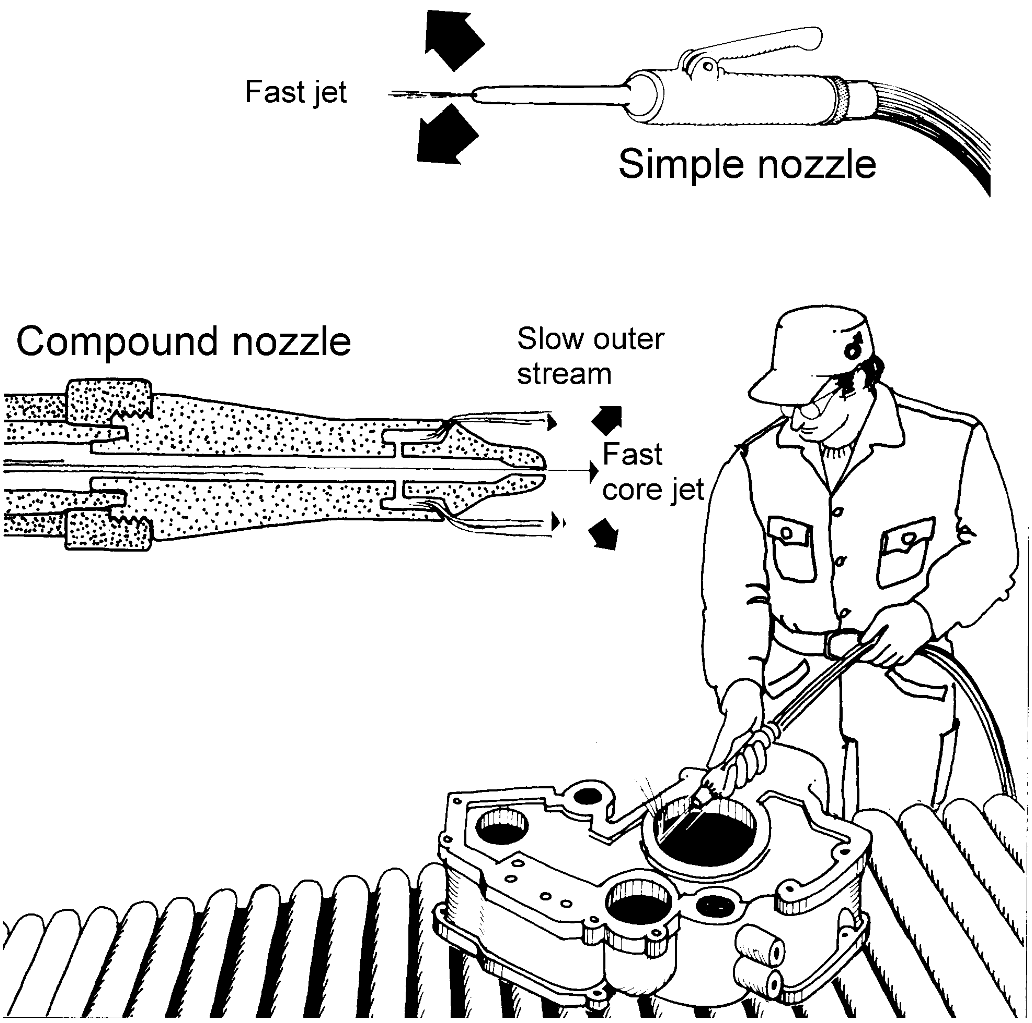


Figure 10.18(a). Use of a quiet air nozzle for air blasting of equipment (ASF, 1977).

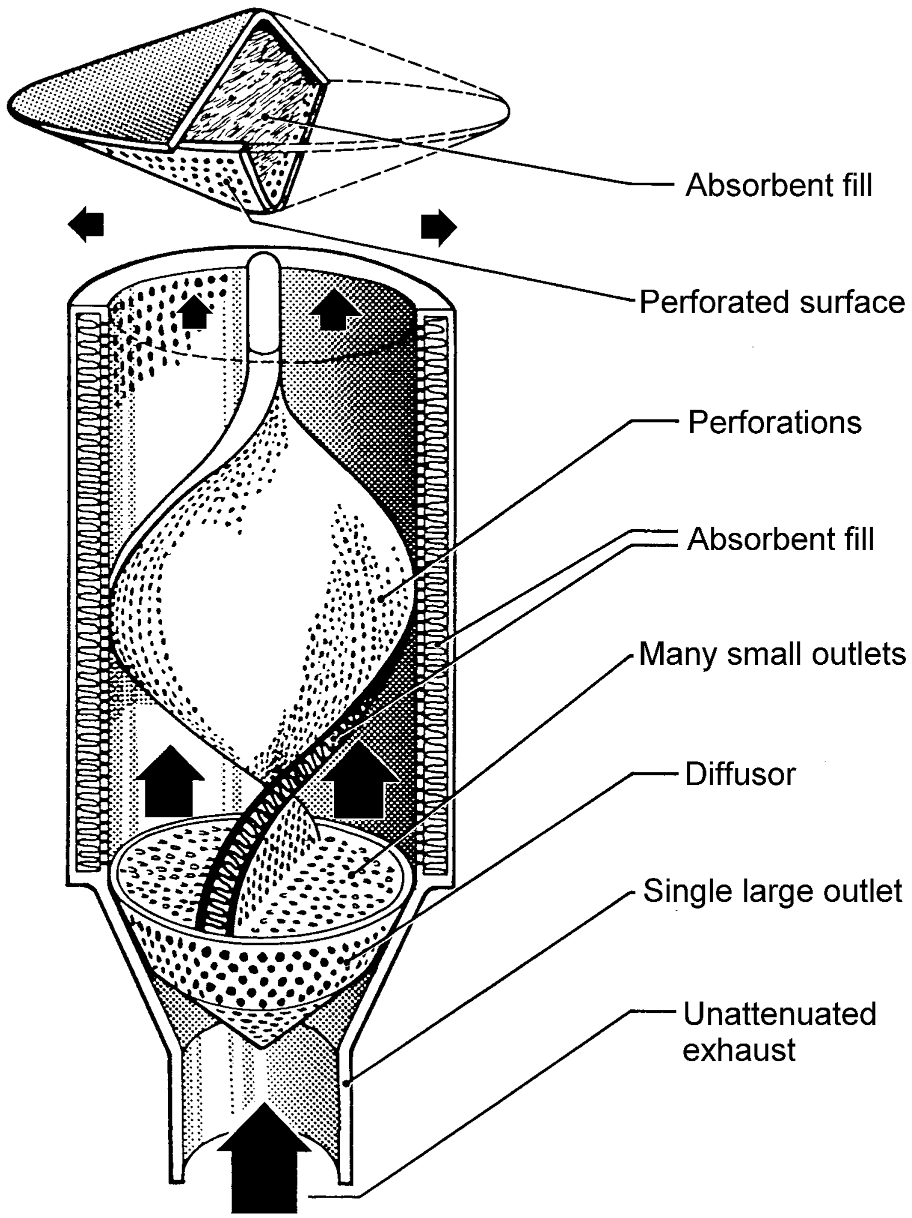


Figure 10.18(b). Use of a quiet nozzle for steam or air venting (ASF, 1977)

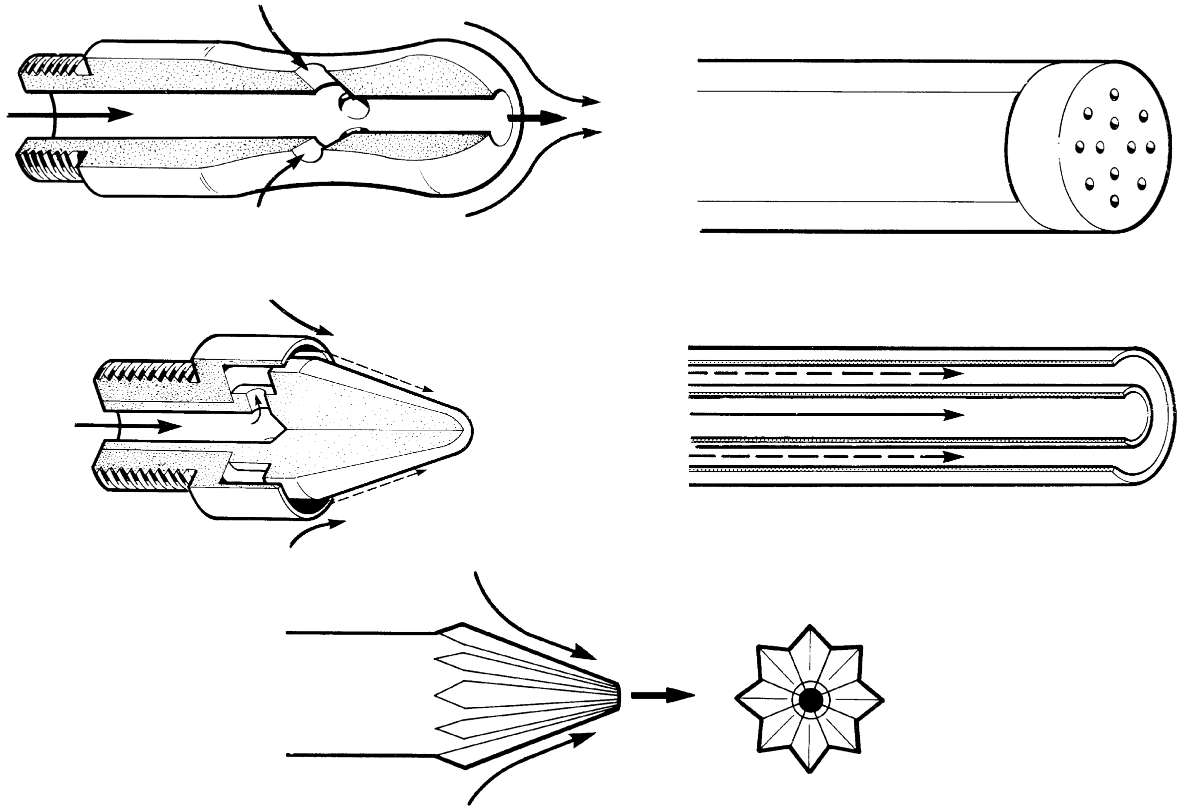


Figure 10.18(c). Commercially available low noise nozzles (after HSE 1985) for the same purpose as the nozzle of fig. 10.18(a), showing clockwise from left aspirated venturi nozzle, multi-jet nozzle, coannular jet nozzle, geometry effect nozzle and coanda effect nozzle; the most common and successful combination is the combined Coannual-Coanda effect nozzle, see also the compound nozzle in fig. 10.18(a).

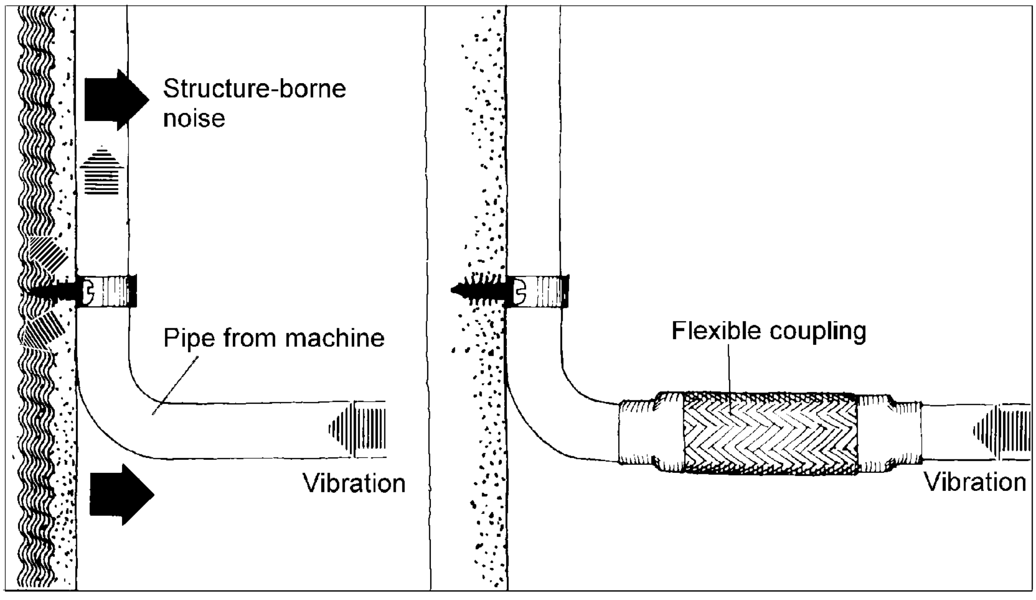


Figure 10.19. Reduction of vibration transmission along piping systems (ASF, 1977).

10.4. CONTROL OF NOISE PROPAGATION *(See ISO 11690-2)*

With regard to control of the noise during its propagation from the source to the receiver (generally the worker) some or all of the following actions need to be considered.

- Use of barriers (single walls), partial enclosures or full enclosure of the entire item of equipment.
- Use of local enclosures for noisy components on a machine.
- Use of reactive or dissipative mufflers; the former for low frequency noise or small exhausts, the latter for high frequencies or large diameter exhaust outlets.
- Use of lined ducts or lined plenum chambers for air handling systems
- Reverberation control - the addition of sound absorbing material to reverberant spaces to reduce reflected noise fields. Note that care should be taken when deciding upon this form of noise control, as direct sound arriving at the receiver will not be affected. Experience shows that it is extremely unusual to achieve noise reductions in excess of 3 or 4 dB(A) using this form of control which can be exorbitantly expensive when large spaces or factories are involved. In flat rooms the spatial sound distribution is of interest, see ISO 11690-1,-2.
- Active noise control, which involves suppression, reflection or absorption of the noise radiated by an existing sound source by use of one or more secondary or control sources.

To understand how best to design the propagation path controls mentioned above, the following concepts will be discussed: the determination of whether the problem arises from airborne or structure-borne transmission of the energy; noise absorption, reflection and reverberation; and transmission loss and isolation. This will be followed by a discussion of some of the controls which can be designed and implemented.

10.4.1. Airborne vs structure-borne noise

Very often in existing installations it is relatively straightforward to track down the original source(s) of the noise, but it can sometimes be difficult to determine how the noise propagates from its source to a receiver. A classic example of this type of problem is associated with noise on board ships. When excessive noise (usually associated with the ship's engines) is experienced in a cabin close to the engine room (or in some cases far from the engine room), or on the deck above the engine room, it is necessary to determine how the noise propagates from the engine. If the problem is due to airborne noise passing through the deck or bulkheads, then a solution may include one or more of the following: enclosing the engine, adding sound absorbing material to the engine room, increasing the sound transmission loss of the deck or bulkhead by using double wall constructions or replacing the engine exhaust muffler.

On the other hand, if the noise problem is caused by the engine exciting the hull into vibration through its mounts or through other rigid connections between the engine and the hull (for example, bolting the muffler to the engine and hull), then an entirely different approach would be required. In this latter case it would be the mechanically excited deck, hull and bulkhead vibrations which would be responsible for the unwanted noise. The solution would be to vibration isolate the engine (perhaps through a well constructed floating platform) or any items such as mufflers from the surrounding structure. In some cases, standard engine vibration isolation mounts designed especially for a marine environment can be used.

As both types of control are expensive, it is important to determine conclusively and in advance the sound transmission path. The simplest way to do this is to measure the noise levels in octave frequency bands at a number of locations in the engine room with the engine running, and also at locations in the ship where the noise is excessive. Then the engine should be shut down and a loudspeaker placed in the engine room and driven so that it produces noise levels in the engine room sufficiently high that they are readily detected at the locations where noise reduction is required.

Usually an octave band filter is used with the speaker so that only noise in the octave band of interest at any one time is generated. This aids both in generating sufficient level and in detection. The noise level data measured throughout the ship with just the loudspeaker operating should be increased by the difference between the engine room levels with the speaker as source and with the engine as source, to give corrected levels for comparison with levels measured with the engine running. The most suitable noise input to the speaker is a recording of the engine noise, but in some cases a white noise generator may be acceptable. If the corrected noise levels in the spaces of concern with the speaker excited are substantially less than those with the engine running, then it is clear that engine isolation is the first noise control which should be implemented. In this case, the best control that could be expected from engine isolation would be the difference in noise levels in the space of concern with the speaker excited and with the engine running.

If the corrected noise levels in the spaces of concern with the speaker excited are similar to those measured with the engine running, then acoustic noise transmission is the likely path, although structure-borne noise may also be important but at a slightly lower level. In this case, the treatment to minimise airborne noise should be undertaken and after treatment, the speaker test should be repeated to determine if the treatment has been effective and to determine if structure-borne noise has subsequently become the problem.

Another example of the importance of determining the noise transmission path is demonstrated in the solution of an intense tonal noise in the cockpit of a fighter airplane which was thought to be due to a pump, as the frequency of the tone corresponded to a multiple of the pump rotational speed. Much fruitless effort was expended to determine the sound transmission path until it was shown that the source was the broadband aerodynamic noise at the air conditioning outlet into the cockpit and the reason for the tonal quality was because the cockpit responded modally. The frequency of strong cockpit resonance coincided with the multiple of the rotational speed of the pump but was unrelated. In this case the obvious lack of any reasonable transmission path led to an alternative hypothesis and a solution.

10.4.2. Isolation of noise and transmission loss

The noise generated by a source can be prevented from reaching a worker by means of an obstacle to its propagation, conveniently located between the source and worker. This is the concept of sound isolation. Although one would ideally like the obstacle to isolate the noise completely, in practice, some of the noise always passes through it and the amount by which the noise is reduced by the obstacle, in dB, is dependent on the noise reducing properties of the material (its "transmission loss") and the acoustic properties of the room into which the noise is being transmitted. The transmission loss is defined as $TL = 10 \log_{10}\tau$, where the transmission coefficient, τ, is defined as the ratio of transmitted to incident energy (on the obstacle). If the receiving space is outdoors in a "free" field, the noise reduction is equal to the transmission loss (ignoring, for now the transmission of sound around the edges of the partition). If the receiving space is indoors, the noise reduction is given by

$$NR = TL - 10\log_{10}\left(\frac{A_{wall}}{S\bar{\alpha}}\right) \tag{2}$$

where

A_{wall} is the surface area of the partition and
$S\bar{\alpha}$ is the absorption of the receiving space

It can be seen from the preceding equation that the performance of the partition in reducing noise levels is improved as the amount of absorption in the receiving room is increased.

Example: The sound pressure level on one side of a 3m x 5m wall is measured 95 dB in the 500 Hz octave band. If the transmission loss of the wall is 35 dB in this band and in the receiving room $S\bar{\alpha}$ = 100 m^2, what will be the sound pressure level in the receiving room?

$$NR = 35 - 10\log_{10}\left(\frac{3\times5}{100}\right) = 35 + 8.2 = 43.2\ \text{dB}$$

Transmission loss through a partition depends on the type of material of which it is made and it varies as a function of frequency. For usual industrial noise, the transmission loss through a partition increases by about 6 dB for each doubling of its weight per unit of surface area. Therefore, the best sound isolating materials are those which are compact, dense, and heavy.

The transmission loss achieved by a single isotropic partition can be estimated from its weight per unit area, for each frequency, from the graph presented in Figure 10.20. The straight portion of the curves is referred to as the "mass law" range because in this range the transmission loss of the partition is proportional to its mass; that is, every doubling of the mass per unit area of the partition results in a 6 dB increase in transmission loss.

The equation describing the transmission loss in the mass law range is given by:

$$TL = 20\log_{10}(fm) - 47 \qquad \text{dB} \tag{3}$$

where f is the one third octave band centre frequency (Hz) and m is the mass per unit area of the partition (kg/m^2). The equation is only valid up to a maximum frequency of half the critical frequency, f_c, which is defined as the frequency at which the wavelength of sound waves in air is equal to the wavelength of the bending waves in the partition and is given by,

$$f_c = c^2(1 - \nu^2)^{1/2}/1.81\,c_L t \tag{4}$$

where c is the speed of sound in air (see chapter 1, equation (1)), t is the partition thickness (m) and c_L is the longitudinal wave speed in the panel given by $c_L = (E/\rho)^{1/2}$, where E, ρ and ν are Young's modulus of elasticity, density and Poisson's ratio respectively for the partition material. The lower frequency limit of validity of equation (3) is twice the lowest resonance frequency of the partition which is usually well below the audio frequency range for most constructions used for machine enclosures. Means for estimating the transmission loss of partitions at frequencies outside of the mass law range are discussed in the literature (Bies and Hansen, 1996, Ch. 8).

The term "isotropic" refers to a panel with uniform stiffness and mass properties and does not include ribbed or corrugated panels which are referred to as "orthotropic". The transmission loss of these latter panels is much less than the corresponding value for an isotropic panel and means for calculating the transmission loss of orthotropic panels are discussed in the specialised literature (Bies and Hansen, 1996, Ch. 8).

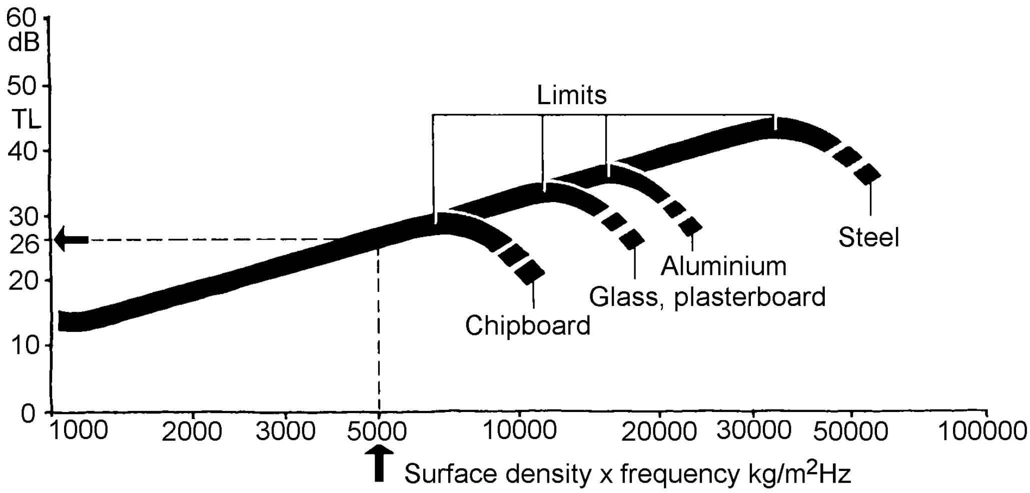


Figure 10.20. The transmission loss (TL) of a single wall is estimated from its weight per unit area (or surface weight) and frequency of the incident sound, (ASF, 1977).

Openings, even small holes or cracks greatly limit the noise reduction characteristics of a partition. The quantitative effect of openings and cracks in partitions is discussed in detail in Bies and Hansen (1996, Ch. 8). Including windows and doors in noise reducing walls also can have a large effect on the performance (Bies and Hansen, 1996, Ch. 8).

Noise reduction due to a partition can be substantially increased by constructing it as two panels separated by an air gap containing sound absorbing material. Details of these constructions and means for estimating their transmission loss are discussed in the literature (Bies and Hansen, 1996, Ch. 8).

Whenever planning for the isolation of a noise source, its characteristics (in terms of noise levels produced and frequency distribution) must be determined so that the appropriate material and construction can be selected. Tables giving transmission loss of usual construction materials and construction types as a function of frequency, may be found in the specialised literature and standards.

10.4.3. Enclosures *(See ISO 15667, ISO 11546-1, -2)*

The first task to consider in the design of an acoustic enclosure of a noise source is to determine the transmission paths from the source to the receiver and order them in relative importance. For example, on close inspection it may transpire that, although the source of noise is readily identified, the important acoustic radiation originates elsewhere, from structures mechanically connected to the source. In this case structure-borne sound is more important than the airborne component. In considering enclosures for noise control one must always guard against such a possibility; if structure-borne sound is the problem, an enclosure to contain airborne sound can be completely useless.

The wall of an enclosure may consist of several elements, each of which may be characterised by a different transmission loss. For example, the wall may be constructed of panels of different materials, it may include permanent openings for passing materials or cooling air in and out of the enclosure, and it may include windows for inspection and doors for access.

Each such element must be considered in turn in the design of an enclosure wall, and the transmission loss of the wall determined as an overall area weighted average of all of the elements.

For this calculation the following equation is used:

$$TL = -10\log_{10}\left(\frac{\sum_{i=1}^{q} S_i 10^{-TL_i/10}}{\sum_{i=1}^{q} S_i}\right) \tag{5}$$

where

S_i is the surface area (one side only), and

TL_i is the transmission loss of the *i*th element.

Example: Calculate the overall transmission loss at 125 Hz of a wall of total area 10 m^2 constructed from a material which has a transmission loss of 30 dB, if the wall contains a panel of area 3 m^2 of a material having a transmission loss of 10 dB .

The overall transmission loss is:

$$TL_{av} = 10 \log_{10}\left(\frac{7\times10^{-30/10} + 3\times10^{-10/10}}{10}\right) = 15.1 \text{ dB}$$

The noise reduction (*NR*) due to an enclosure may be calculated in terms of the transmission loss of the walls using the following equation.

$$NR = TL - C \tag{6}$$

where the quantity *C* is dependent on the enclosure internal conditions and may be estimated using Table 10.1.

Doors to give access to the enclosed equipment are usually needed and it must be possible to close them against rubber seals so that they are airtight. The transmission loss of both **doors and windows** should be as close as possible to that of the enclosure walls so that the presence of these items does not degrade the enclosure acoustic performance significantly. In the case of windows, this usually means double glazing and good rubber seals.

Many enclosures require some form of **ventilation** as illustrated in Figure 10.21(a) and (b). They may also require access for passing materials in and out. Such necessary permanent openings must be treated with some form of silencing to avoid compromising the effectiveness of the enclosure. In a good design, the acoustic performance of access silencing will match the performance of the walls of the enclosure. Techniques developed for the control of sound propagation in ducts may be employed for the design of silencers (see later section on mufflers).

Table 10.1. Values of constant *C* (dB) to account for enclosure internal acoustic conditions.

Enclosure internal acoustic conditions*	Octave band centre frequency (Hz)							
	63	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**	**8,000**
live	18	16	15	14	12	13	15	16
fairly live	16	13	11	9	7	6	6	6
average	13	11	9	7	5	4	3	3
dead	11	9	6	5	3	2	1	1

*Use the following criteria to determine the appropriate acoustical conditions inside the enclosure:

live: *all enclosure surfaces and machine surfaces hard and rigid*
fairly live: *all surfaces generally hard but some panel construction (sheet metal or wood)*
average: *enclosure internal surfaces covered with sound-absorptive material, and machine surfaces hard and rigid*
dead: *as for "average", but machine surfaces mainly of panels*

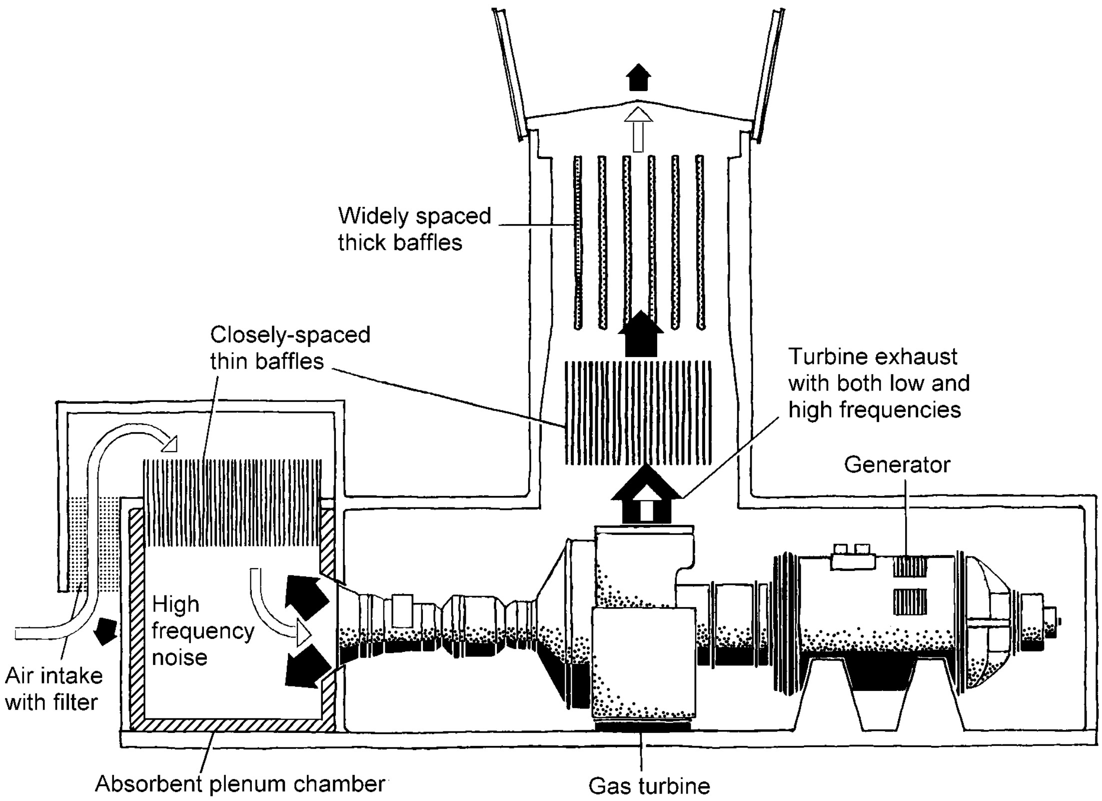


Figure 10.21(a). Example of a ventilated gas turbine enclosure (ASF, 1977).

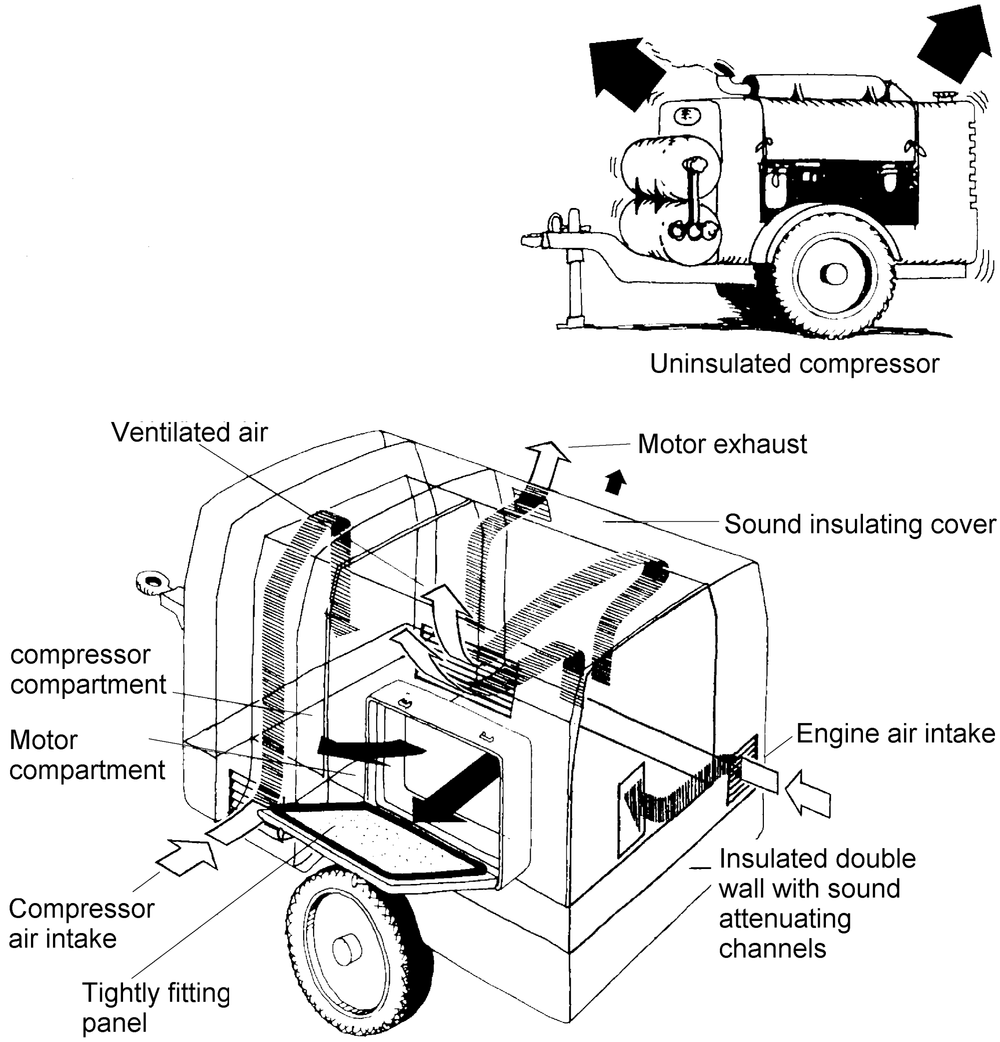


Figure 10.21(b). Example of a ventilated compressor enclosure (ASF, 1977).

If ventilation for heat removal is required but the heat load is not large, then natural ventilation with silenced air inlets (usually ducts lined in the inside with fiberglass or rockwool) at low levels close to the floor and silenced outlets at high levels, well above the floor, will be adequate. If forced ventilation is required to avoid excessive heating then the approximate amount of air flow needed can be determined using the following equation.

$$\rho C_p V = H/\Delta T \tag{7}$$

where

V is the volume ($m^3\ s^{-1}$) of airflow required,
H is the heat input (W) to the enclosure,
ΔT is the temperature differential (°C) between the external ambient and the maximum permissible internal temperature of the enclosure,
ρ is the gas (air) density ($kg\ m^{-3}$), and
C_p is the specific heat of the gas (air) in SI units (1,010 $m^2\ s^{-2}\ °C^{-1}$).

If a fan is provided for forced ventilation, the silencer will usually be placed external to the fan so that noise generated by the fan will be attenuated as well. When high volumes of air flow are required, the noise of the fan should be considered very carefully, as this noise source is quite often a cause of complaint. As fan noise generally increases with the fifth power of the blade tip speed, large slowly rotating fans are always to be preferred over small high-speed fans.

Any rigid connection between the machine and enclosure must be avoided. If at all possible, all pipes and service ducts passing through the enclosure wall should have flexible sections to act as vibration breaks; otherwise, the pipe or duct must pass through a clearance hole surrounded by a packing of mineral wool closed by cover plates and mastic sealant.

It is usually advisable to mount the machine on vibration isolators, particularly if low-frequency noise is the main problem. This ensures that little energy is transmitted to the floor. If this is not done there is the possibility that the floor surrounding the enclosure will re-radiate the energy into the surrounding space, or that the enclosure will be mechanically excited by the vibrating floor and act as a noise source. Sometimes it is not possible to mount the machine on vibration isolators. In this case, excitation of the enclosure can be avoided by mounting the enclosure itself on vibration isolators, while at the same time avoiding an air gap at the base of the enclosure by using heavy rubber flaps. Note that great care is necessary, when designing machinery vibration isolators, to ensure that the machine will be stable and that its operation will not be affected adversely. For example, if a machine must pass through a system resonance when running up to speed, then "snubbers" (which are usually horizontally mounted flexible elements) can be used to prevent excessive motion of the machine on its isolation mounts.

Two types of enclosure resonance are important and should be considered. The first is mechanical resonance of the enclosure panels, while the second is acoustic resonance of the air space between an enclosed machine and the enclosure walls. At the frequencies of these resonances the noise reduction due to the enclosure is markedly reduced from that calculated without regard to resonance effects.

The lowest order enclosure panel resonance is associated with a large loss in enclosure effectiveness at the resonance frequency. Thus the enclosure should be designed so that the resonance frequencies of its constituent panels are not in the frequency range in which appreciable sound attenuation is required. Only the lowest order, first few, panel resonances are of concern here. The panels may be designed such that their resonance frequencies are higher than or lower than the frequency range in which appreciable sound attenuation is required. Additionally, the panels should be well damped or "dead" which generally requires treatment with some form of visco-elastic damping material.

If the sound source radiates predominantly high-frequency noise, then an enclosure with low resonance frequency panels is recommended, implying a massive enclosure. On the other hand, if the sound radiation is predominantly low frequency in nature then an enclosure with a high resonance frequency is desirable, implying a stiff but not massive enclosure.

The resonance frequency of a panel may be increased by using stiffening ribs, but the increase that may be achieved is generally quite limited. For stiff enclosures with high resonance frequencies, materials with large values of Young's modulus to density ratio, E/ρ are chosen for wall construction, and for massive enclosures with small resonance frequencies, small values of E/ρ are chosen. In practice, stiff enclosures will generally be restricted to small enclosures.

If a machine is enclosed, reverberant build-up of the sound energy within the enclosure will occur unless adequate sound absorption is provided. The effect will be an increase of soundpressure at the inner walls of the enclosure over that which would result from the direct field of the source. A degradation of the noise reduction expected of the enclosure is implied.

In close-fitting enclosures, noise reduction may be degraded by yet another resonance effect. At frequencies where the average air spacing between a vibrating machine surface and enclosure wall is an integral multiple of half wavelengths of sound, strong coupling will occur between the vibrating machine surface and the enclosure wall, resulting in a marked decrease in the enclosure wall transmission loss.

The effect of inadequate absorption in enclosures is very noticeable. Table 10.2 shows the reduction in performance of an ideal enclosure with varying degrees of internal sound absorption. The sound power of the source is assumed constant and unaffected by the enclosure. "Percent" refers to the fraction of internal surface area which is treated.

Table 10.2. Enclosure interior noise increase as a function of percentage of internal surface covered with sound-absorptive material (referenced to 100% coverage).

Percent sound absorbent	10	20	30	50	70
interior noise increase (dB)	10	7	5	3	1.5

For best results, the internal surfaces of an enclosure are usually lined with glass or mineral fibre or open-cell polyurethane foam blanket. Typical values of absorption coefficients are given in Table 10.3.

Since the absorption coefficient of absorbent lining is generally highest at high frequencies, the high-frequency components of any noise will suffer the highest attenuation. Some improvement in low-frequency absorption can be achieved by using a thick layer of lining. However the liner should, in many cases, be protected from contamination with oil or water, to prevent its acoustical absorption properties from being impaired. This may be done by enclosing the liner in a polyethylene bag, about 20 μm thick. If mechanical protection is also required, then a perforated metal sheet of at least 25% open area may be added, provided that it does not contact the polyethylene bag lining. This latter condition can be achieved by placing an open wire mesh between the polyethylene and perforated metal. If this is not done, the performance of the sound absorbing material will be severely degraded.

The cost of acoustic enclosures of any type is proportional to size; therefore there is an economic incentive to keep enclosures as small as possible. Thus, because of cost or limitations of space, a close-fitting enclosure may be fitted directly to the machine which is to be quietened, or fixed independently of it but so that the enclosure internal surfaces are within, say, 0.5 m of major machine surfaces.

When an enclosure is close-fitting, the panel resonance frequencies will be somewhat increased due to the stiffening of the panel by the enclosed air volume. Thus an enclosure designed to be massive with a low resonance frequency may not perform as well as expected when it is close-fitting. Furthermore, system resonances will occur at higher frequencies; some of these modes of vibration will be good radiators of sound, producing low noise reductions, and some will be poor radiators, little affecting the noise reduction. The magnitude of the decrease in noise reduction caused by these resonances may be controlled to some extent by increasing the mechanical damping of the wall. Thus, if low-frequency sound (less than 200 Hz) is to be attenuated, the close-fitting enclosure should be stiff and well damped, but if high-frequency sound is to be attenuated the enclosure should be heavy and highly absorptive but not stiff.

Doubling of the volume of a small enclosure will normally lead to an increase in noise reduction of 3 dB at low frequencies, so that it is not desirable to closely surround a source, such as a vibrating machine, if a greater volume is possible.

Generally, if sufficient space is left within the enclosure for normal maintenance on all sides of the machine, the enclosure need not be regarded as close-fitting. If, however, such space cannot be made available, it is usually necessary to upgrade the transmission loss of an enclosure by up to 10 dB at low frequencies (less at high frequencies), to compensate for the expected degradation in performance of the enclosure due to resonances.

In many situations where easy and continuous access to parts of a machine is necessary, a complete enclosure may not be possible, and a partial enclosure must be considered (Alfredson & Seow, 1976). However, the noise reductions that can be expected at specific locations from partial enclosures are difficult to estimate and will depend upon the particular geometry. An example of a partial enclosure is shown in Figure 10.22. Estimates of the sound power reduction to be expected from various degrees of partial enclosure are presented in Figure 10.23.

Figure 10.23 shows fairly clearly that the enclosure walls should have a transmission loss of about 20 dB, and the most sound power reduction that can be achieved is about 10 dB. However, noise levels may in some cases be more greatly reduced, especially in areas immediately behind solid parts of the enclosure.

Some other practical considerations which should be taken into account are:

- who and what needs to be in the enclosure during operation of the noisy equipment (personnel should be excluded if possible);
- number and location of doors and windows (minimum possible);
- method of door closure (manual, automatic) and type of latch to ensure a tight seal around the door perimeter;
- automatic machine stop when doors are not closed properly;
- ease of cleaning inside the enclosure;
- ease of maintenance of enclosure and enclosed equipment;
- resistance of sound absorbing material to oil, dust, water or other chemicals; and
- attractiveness of finished enclosure

In many instances where there are a large number of noise sources and a few personnel in one or two localised areas, it may be preferable to enclose the people rather than the machines. In this case, many of the enclosure design principles outlined above still apply and the enclosure performance can be calculated using equation (6).

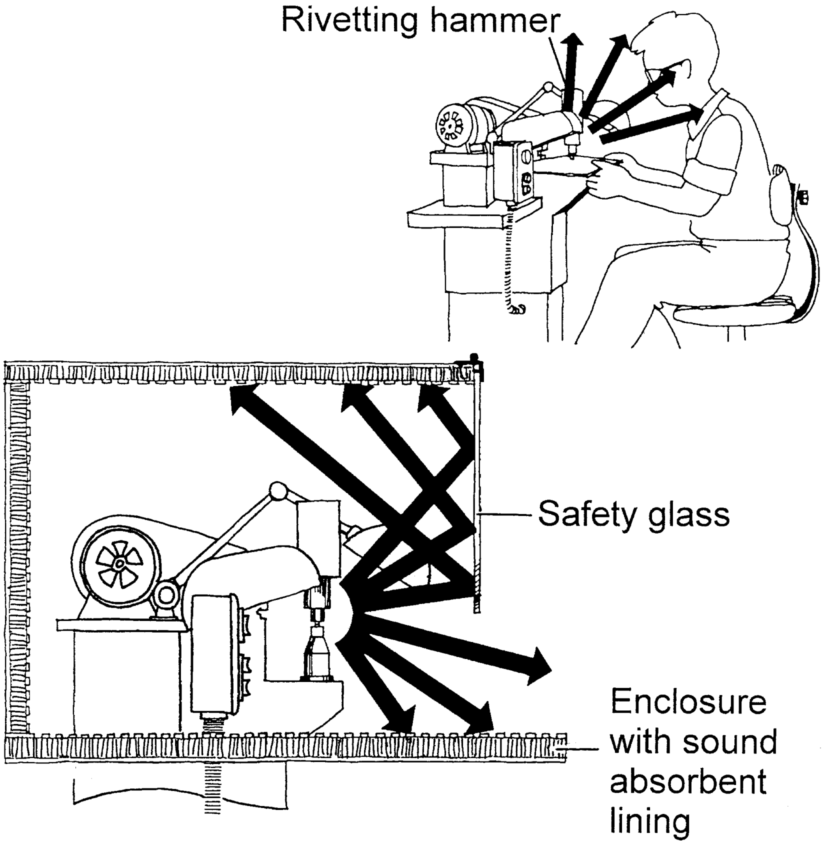


Figure 10.22. Example of a partial enclosure (ASF, 1977)

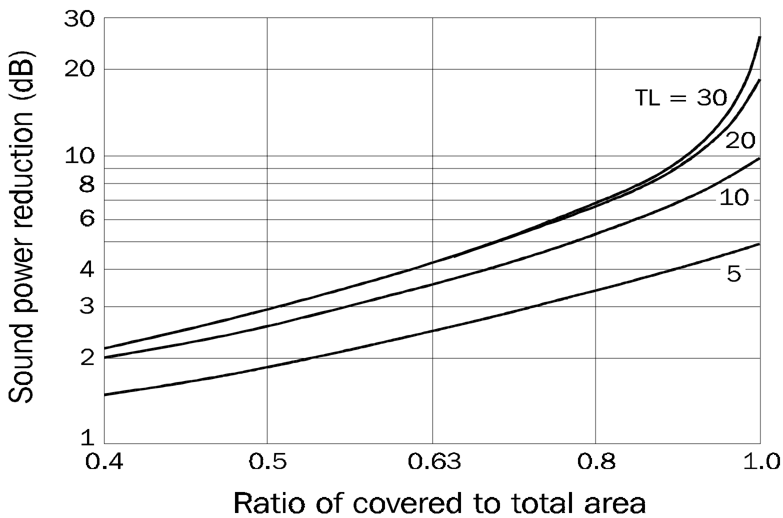


Figure 10.23. Estimate of sound power reduction due to a partial enclosure (see text for explanation).

10.4.4. Acoustic barriers *(See ISO 11821)*

Since detailed information on the calculation of the Insertion Loss of a single barrier (indoors and outdoors) is available in the literature (Bies and Hansen 1996, ISO 9613-2, ISO 10847, ISO 11821) this clause is concerned with the basic rules for the use of indoor barriers.

Barriers are placed between a noise source and a receiver as a means of reducing the direct sound observed by the receiver. In rooms, barriers suitably treated with sound-absorbing material may also slightly attenuate reverberant sound field levels by increasing the overall room absorption.

Barriers are a form of partial enclosure usually intended to reduce the direct sound field radiated in one direction only. For non-porous barriers having sufficient surface density, the sound reaching the receiver will be entirely due to diffraction around the barrier boundaries.

Now we will consider the effect of placing a barrier in a room where the reverberant sound field and reflections from other surfaces cannot be ignored.

In estimating the Insertion Loss of a barrier installed in a large room the following assumptions are implicit:

(1) The transmission loss of the barrier material is sufficiently large that transmission through the barrier can be ignored. A transmission loss of 20 dB is recommended.
(2) The sound power radiated by the source is not affected by insertion of the barrier.
(3) The receiver is in the shadow zone of the barrier; that is, there is no direct line of sight between source and receiver.
(4) Interference effects between waves diffracted around the side of the barrier, waves diffracted over the top of the barrier and reflected waves are negligible. This implies octave band analysis.

Barriers are ineffective in a highly reverberant environment. The performance of an indoor barrier is always improved by hanging absorptive baffles from the ceiling or by placing sound absorbing material directly on the ceiling (see Figure 10.24).

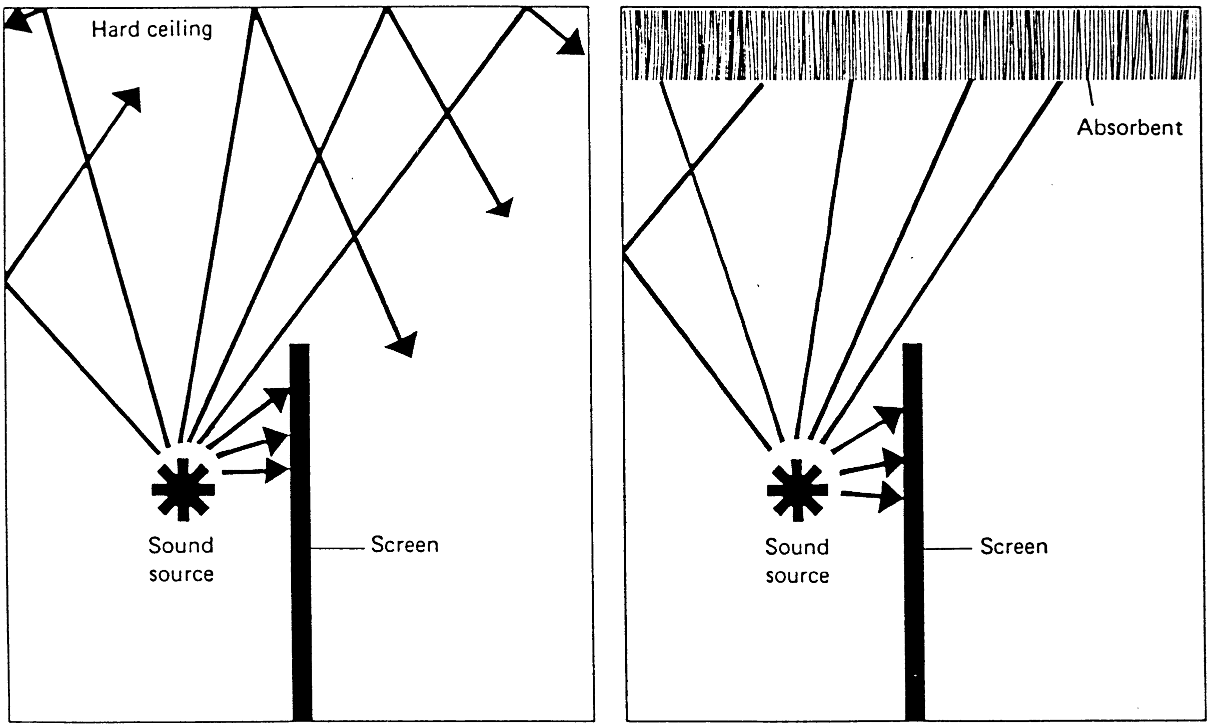


Figure 10.24. Use of a barrier indoors (ASF, 1977)

When multiple barriers exist, as in an open-plan office, experimental work (West & Parkin, 1978) has shown the following statements to be true in a general sense (test screens were 1.52 m high by 1.37 m wide):

(1) No difference in attenuation is obtained when a 300 mm gap is permitted between the base of the screen and the floor.

(2) When a number of screens interrupt the line of sight between source and receiver, an additional attenuation of up to 8 dB(A) over that for a single screen can be realised.

(3) Large numbers of screens remove wall reflections and thus increase the attenuation of sound with distance from the source.

(4) For a receiver immediately behind a screen, a local shadow effect results in large attenuation, even for a source a large distance away. This is in addition to the effect mentioned in (2) above.

(5) For a screen less than 1 m from a source, floor treatment has no effect on the screen's attenuation.

(6) A maximum improvement in attenuation of 4-7 dB as frequency is increased from 250 to 2 kHz can be achieved by ceiling treatment. However, under most conditions, this greater attenuation can only be achieved at the higher frequencies.

(7) Furnishing conditions are additive; that is, the attenuations measured under two different furnishing conditions are additive when the two furnishing conditions coexist.

10.4.5. Mufflers and lined ducts *(See ISO 14163, ISO 11820)*

Muffling devices are commonly used to reduce noise associated with internal combustion engine exhausts, high pressure gas or steam vents, compressors and fans. These examples lead to the conclusion that a muffling device allows the passage of fluid while at the same time restricting the free passage of sound. Muffling devices might also be used where direct access to the interior of a noise containing enclosure is required, but through which no steady flow of gas is necessarily to be maintained. For example, an acoustically treated entry way between a noisy and a quiet area in a building or factory might be considered as a muffling device.

Muffling devices may function in any one or any combination of three ways: they may suppress the generation of noise; they may attenuate noise already generated; and they may carry or redirect noise away from sensitive areas. Careful use of all three methods for achieving adequate noise reduction can be very important in the design of muffling devices, for example, for large volume exhausts.

Two terms, insertion loss, IL, and transmission loss, TL, are commonly used to describe the effectiveness of a muffling system. The insertion loss of a muffler is defined as the reduction (in decibels) in sound power transmitted through a duct compared to that transmitted with no muffler in place. Provided that the duct outlet remains at a fixed point in space, the insertion loss will be equal to the noise reduction which would be expected at a reference point external to the duct outlet as a result of installing the muffler. The transmission loss of a muffler, on the other hand, is defined as the difference (in decibels) between the sound power incident at the entry to the muffler to that transmitted by the muffler.

Muffling devices make use of one or the other or a combination of the two effects in their design. Either sound propagation may be prevented (or strongly reduced) by reflection (generally as the result of using orifices and expansion chambers), or sound may be dissipated, generally by the use of sound absorbing material. Muffling devices based upon reflection are called reactive devices and those based upon dissipation are called dissipative devices. A duct lined with sound absorbing material on its walls is one form of dissipative muffler.

A type of combined reactive/dissipative muffler is a plenum chamber which is a large volume chamber which connects two ducts. The interior of the chamber is lined with sound absorbing material, and thus part of the high frequency sound energy which enters the chamber is absorbed due to multiple reflections within the unit, while the low frequency energy is reflected or suppressed because of the sudden expansion and contraction in effective duct cross-sectional area as a result of the presence of the chamber. An example of a reactive muffler is shown in Figure 10.25, dissipative mufflers are shown in Figures 10.26(a)-(d), and a combined reactive / dissipative muffler is shown in Figure 10.27.

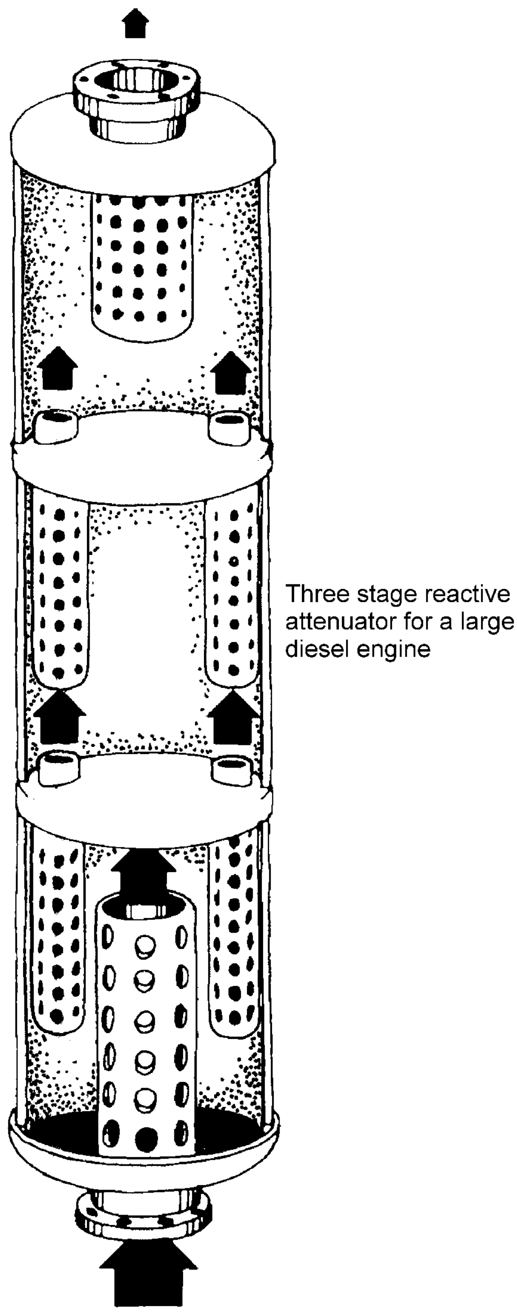


Figure 10.25. An internal combustion engine reactive muffler (ASF, 1977).

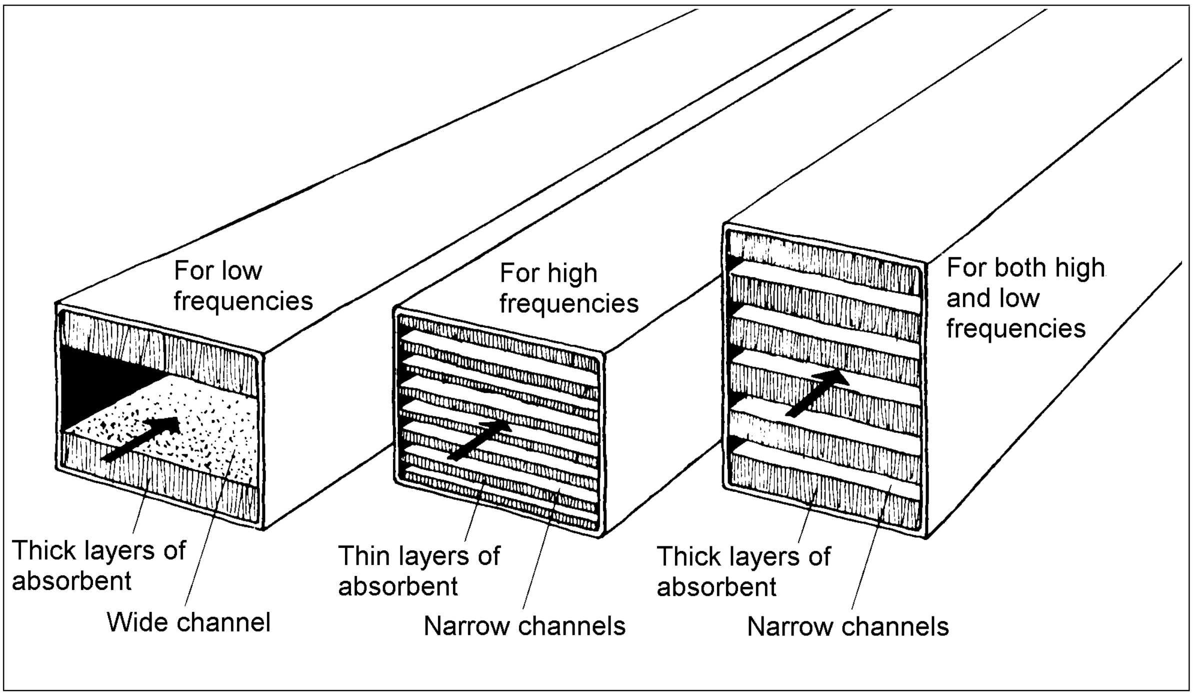


Figure 10.26(a). Examples of general dissipative mufflers (ASF, 1977).

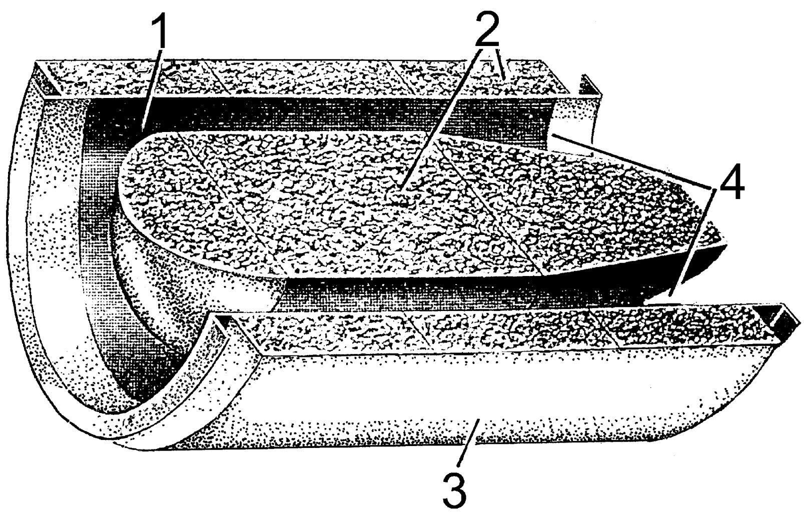


Figure 10.26(b). Circular silencer. (1) perforated, galvanized steel; (2) fiberglass or mineral wool acoustic fill; (3) steel casing; (4) low turbulence air passages.

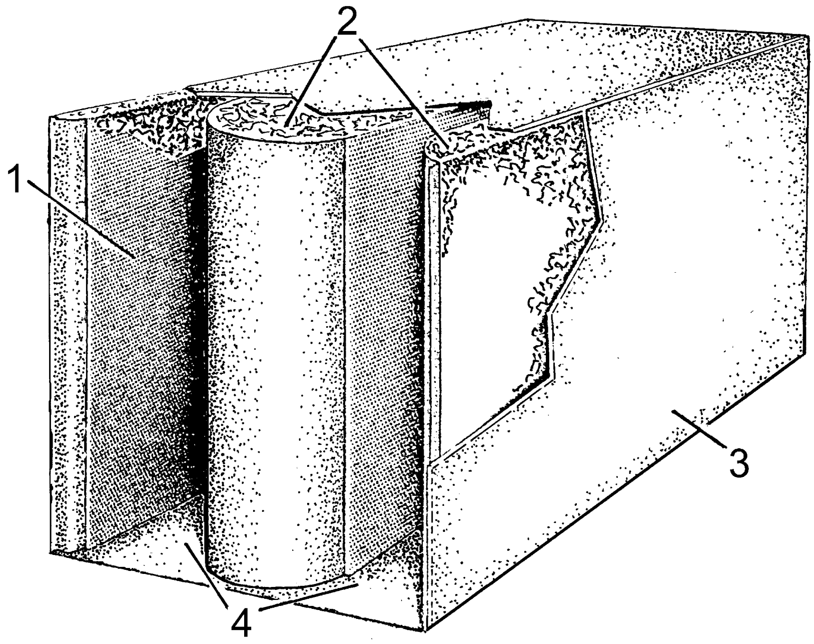


Figure 10.26(c). Parallel baffle rectangular silencer. (1) perforated, galvanized steel; (2) fiberglass or mineral wool fill; (3) sheet metal casing; (4) streamline inlet (Bell, 1982).

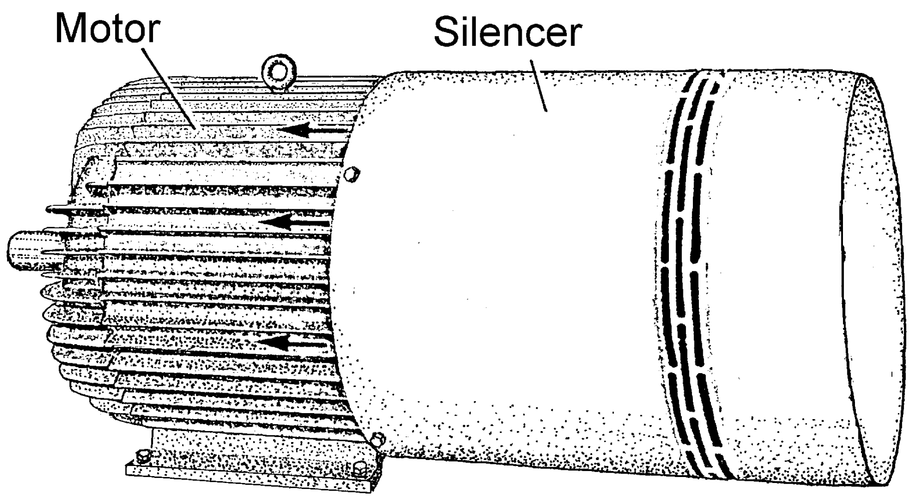


Figure 10.26(d). Electric motor with dissipative muffler (Bell, 1982).

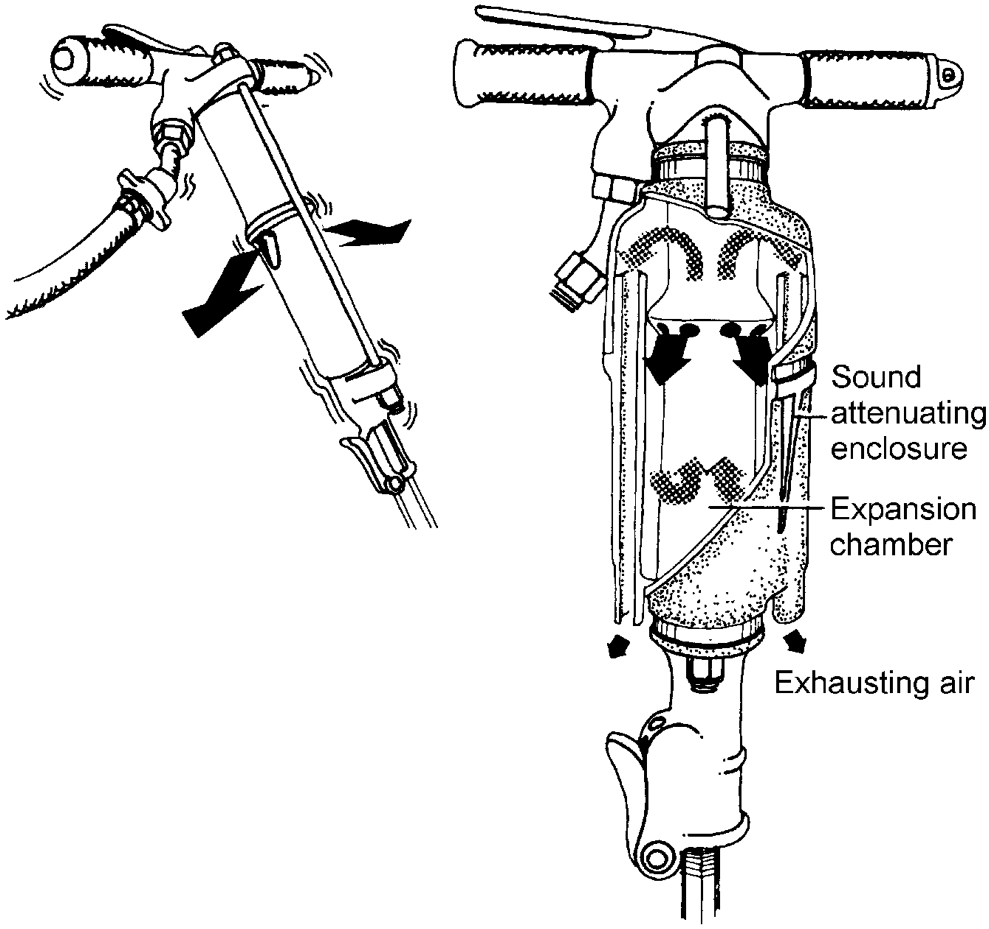


Figure 10.27. An example of a combined reactive/dissipative muffler

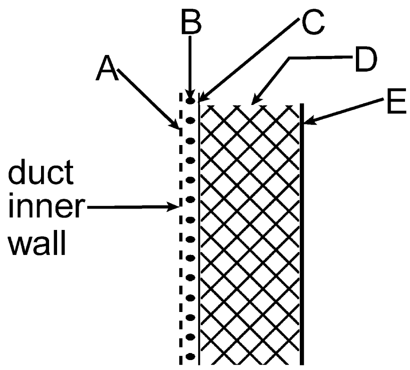
The performance of reactive devices is dependent upon the impedances of the source and termination (outlet). In general, a reactive device will strongly affect the generation of sound at the source. This has the effect that the transmission loss and insertion loss of reactive devices may be very different. As insertion loss is the quantity related to noise reduction, it should be used here to describe the performance of reactive muffling devices in preference to transmission loss which unfortunately is commonly used. Insertion Loss values for reactive mufflers vary depending on the design, but are generally in the range of 10 to 30 dB over several octaves.

The performance of dissipative devices, on the other hand, by the very nature of the mode of operation, tends to be independent of the effects of source and termination impedance. Provided that the transmission loss of a dissipative muffler is at least 5 dB it may be assumed that the insertion loss and the transmission loss are the same. This assertion is justified by the observation that any sound reflected back to the source through the muffler will be reduced by at least 10 dB and is thus small and generally negligible compared to the sound introduced. Consequently, the effect of the termination impedance upon the source must also be small and negligible. The Insertion Loss of dissipative silencer increases with the length and varies with the design of the silencer. It can range from 5 dB at low frequencies to 50 dB at high frequencies in typical installations. It is always best to consult manufacturer's data and to remember that larger Insertion Losses usually translate to large pressure drops imposed on any gas flowing through the muffler.

It is possible to design both reactive and dissipative mufflers to achieve desired noise reductions in specific applications and procedures for doing this are outlined by Bies and Hansen (1996, Ch. 9), where the design of sound reducing plenum chambers is also discussed. The procedures are relatively complex and are not discussed here.

The greater the sound attenuating performance of a muffler, the greater will be the pressure drop any gas flowing through it will experience. This pressure drop can be extremely important in some applications and must be considered in any design. In dissipative mufflers containing sound absorbing material, care must be taken to ensure that the material is not eroded by gas flowing through the muffler. In many cases, a thin plastic skin sprayed on to the face of the material is sufficient, but where relatively high speed flows exist, a higher level of protection may be necessary. This usually takes the form of a lightweight impervious layer (of about 10-20 grams per square metre) against the sound absorbing material and a perforated metal sheet between the impervious material and the duct airway, as illustrated in Figure 10.28.

Figure 10.28. Protective facings for duct liners. The elements of the liner are: A, 20 gauge (≈1mm) perforated facing, minimum 25% open area; B, wire mesh spacer, minimum mesh size 12mm, wire diameter minimum 1mm; C, light plastic sheet or fibreglass cloth or fine mesh metal screen; D, fibrous material of specified flow resistance, or unbonded but contained, as in a light plastic bag; E, rigid wall or air cavity backing. Maximum flow speeds up to 8 m s^{-1} do not require A or C. Speeds up to 10 m s^{-1} require that the fibrous material of C be coated or replaced with plastic. Speeds up to 25 m s^{-1} require B and C, while speeds up to 90 m s^{-1} require A, B, C and D. Higher speeds are not recommended. The gap between A and C is ensured by using an open steel mesh spacer, B, (e.g. 2mm wire on 20 mm centres).



10.4.6. Sound absorption and reflection

Sound absorption is the phenomenon by which sound is absorbed by transformation of acoustic energy into ultimately thermal energy (heat). Although some absorption always happens when a sound wave encounters an obstacle, it happens in an appreciable manner when the sound wave is incident on a sound absorbing material.

Sound absorbing materials are fibrous, lightweight and porous, possessing a cellular structure of intercommunicating spaces. It is within these interconnected open cells that acoustic energy is converted into thermal energy. Thus the sound-absorbing material is a dissipative structure which acts as a transducer to convert acoustic energy into thermal energy. The actual loss mechanisms in the energy transfer are viscous flow losses caused by wave propagation in the material and internal frictional losses caused by motion of the material's fibres. The absorption characteristics of a material are dependent upon its thickness, density, porosity, flow resistance, fibre orientation, and the like.

Common porous absorption materials are made from vegetable, mineral or ceramic fibres (the latter for high temperature applications) and elastomeric foams, and come in various forms.The materials may be prefabricated units, such as glass blankets, fibreboards, or lay-in tiles; the material may also be sprayed or trowelled on the surface; or it may be a foam or open-cell plastic. Each type of material has its inherent advantages and disadvantages, and quite often the particular application dictates which form of absorbent material to use. For example, the aesthetics of the environment often prove to be the factor that governs the choice of material. In addition to the acoustical efficiency of the material, one must also consider its cost, installation, maintenance, and resistance to wear and environmental factors.

If fibrous materials such as fibreglass and mineral wool are used it is important to ensure that other health problems arising from human contact with the fibres are avoided. This often means that the material should be enclosed in a thin plastic bag. If the plastic bag is sufficiently thin (20 µm thick polyethylene), the acoustic properties of the acoustic material will be unaffected. As the material is made heavier, the high frequency absorption ability of the material will be degraded, although there will be some improvement at low frequencies. Some manufacturers supply fibrous material which has been sprayed on the surface with a plastic or resin coating which may take the place of the plastic containment bag.

Often there is also a need for mechanical protection to ensure that the thin plastic containment bag remains undamaged. The usual form of protection is a thin sheet of perforated metal or wood. To ensure no effect on the acoustic properties of the material being protected, the perforated sheet should have a ratio of open area (holes) to solid area of greater than 25%. Open area ratios less than this will result in reduced sound absorption at high frequencies, although the absorption at low frequencies will be increased a little.

An important mistake often made in the installation of acoustic materials is to place the perforated sheet in contact with the plastic bag protection. This causes a very severe degradation in performance of the acoustic material and must always be avoided. The simplest way of avoiding the problem is to insert a spacer (usually thin wire mesh with holes at least 15mm in size) between the plastic bag and the perforated sheet (see Figure 10.28).

Acoustic absorbing materials can be rated by their sound absorption coefficients which are frequency dependent and defined as the fraction of incident energy which is absorbed when the incident sound field is diffuse. This is discussed in detail in the specialised literature (NIOSH, 1980; AIHA, 1975; Beranek, 1971; Beranek and Ver, 1992; Bies and Hansen, 1996) and data are usually provided by manufacturers of special acoustic materials. Because different materials have different absorption coefficients for different frequencies, a frequency analysis of the noise to be controlled should be made so that the most suitable materials can be selected.

Table 10.3 presents examples; however, it is always preferable to consult manufacturer's data when using absorptive materials to control reverberant sound fields. Note that the absorption coefficients listed in Table 10.3 are "Sabine" absorption coefficients as distinct from "statistical" absorption coefficients. The difference lies in the way in which the coefficients are measured. "Sabine" absorption coefficients are measured in a reverberation room, while "statistical" absorption coefficients are calculated from the normal incidence absorption coefficient measured in an impedance tube. Because of inaccuracies in the inherent assumptions involved in the measurement of "Sabine" absorption coefficients, values greater than the theoretical maximum of unity are often obtained. When using these values in practice, better sound prediction results are obtained if they are rounded down to one. On the other hand, "statistical" absorption coefficients are never greater than 0.94. For the purposes of predicting the effect of sound absorbing treatment on noise levels in an industrial space, it is probably better to use the "Sabine" absorption coefficient, and as it is always larger than the "statistical" absorption coefficient, it is the one usually quoted by manufacturers of sound absorbing materials. Further details on the measurement and use of absorption coefficients may be obtained from Bies and Hansen (1996, Ch. 7 and App. 3).

Table 10.3. Examples of Sabine absorption coefficients of general building materials
(Collected from the published literature and manufacturer's data)

	Octave-band centre frequency (Hz)					
	125	**250**	**500**	**1000**	**2000**	**4000**
Brick, unglazed	0.03	0.03	0.03	0.04	0.05	0.07
Brick, unglazed, painted	0.01	0.01	0.02	0.02	0.02	0.03
Carpet on foam rubber	0.08	0.23	0.57	0.69	0.71	0.73
Carpet on concrete	0.02	0.06	0.14	0.37	0.60	0.65
Concrete block, coarse	0.36	0.44	0.31	0.29	0.39	0.25
Concrete block, painted	0.10	0.05	0.06	0.07	0.09	0.08
Floors, concrete or terrazzo	0.01	0.01	0.015	0.02	0.02	0.02
Floors, resilient flooring on concrete	0.02	0.03	0.03	0.03	0.03	0.02
Floors, hardwood	0.15	0.11	0.10	0.07	0.06	0.07
Glass, heavy plate	0.18	0.06	0.04	0.03	0.02	0.02
Glass, standard window	0.35	0.25	0.18	0.12	0.07	0.04
Gypsum board 1/2 in.	0.29	0.10	0.05	0.04	0.07	0.09
Panels, fibreglass, 1.5 in.	0.86	0.91	0.80	0.89	0.62	0.47
Panels, perforated metal, 4 in. thick	0.70	0.99	0.99	0.99	0.94	0.83
Panels, perforated metal with fibre-glass insulation 4 in. thick	0.21	0.87	1.52	1.37	1.34	1.22
Panels, perforated metal with mineral fibre insulation, 4 in. thick	0.89	1.20	1.16	1.09	1.01	1.03
Panels, plywood, 3/8 in.	0.28	0.22	0.17	0.09	0.10	0.11
Plaster, gypsum or lime, rough finish on lath	0.02	0.03	0.04	0.05	0.04	0.03
Plaster, gypsum or lime, smooth finish on lath	0.02	0.02	0.03	0.04	0.04	0.03
Polyurethane foam, 1 in. thick	0.16	0.25	0.45	0.84	0.97	0.87
Tile, ceiling mineral fibre	0.18	0.45	0.81	0.97	0.93	0.82
Tile, marble or glazed	0.01	0.01	0.01	0.01	0.02	0.02
Wood, solid, 2 in. thick	0.01	0.05	0.05	0.04	0.04	0.04

One of the indices used to describe a sound-absorbing material is the noise-reduction coefficient (NRC). This is defined to be the arithmetic average of the material's sound absorption coefficients at 250, 500, 1000, and 2000 Hz:

$$NRC = \frac{\bar{\alpha}\,250 + \bar{\alpha}\,500 + \bar{\alpha}\,1000 + \bar{\alpha}\,2000}{4}$$

As such, the NRC is an index of the sound-absorbing efficiency of the material. Absorbing materials by their very nature are effective at reducing reflected sound fields but have little effect on noise transmitted through them, except at very high frequencies.

It should be kept in mind that walls covered with sound absorbing materials do not have the ability to reduce noise from a source. The maximum effect possible in covering walls with absorbing materials is to avoid reflected noise (which at best is equivalent to having no walls), and this measure therefore has little effect when the operator is close to the source or when reflected noise is not an important component of the total noise to which workers are exposed.

In practice, the importance of the reflected noise component can be estimated by measuring noise levels close to the source and then by making successive measurements at increasing distances. If the level does not appreciably drop, the reflected noise component is important; if the noise level drops appreciably with distance, then it is not efficient to recover walls with sound absorbing material. In the absence of any reflecting surfaces, the noise level should drop by 6 dB for each doubling of the distance from the noise source.

10.4.7. Reverberation

When sound reflects within boundaries, it "accumulates" as a result of the addition of the reflected sound to the original sound. Sound may continue even after the original source stops - this is called "reverberation".

Thus a reverberant field is one which is characterised by sound which has been reflected from at least one surface in a particular room or enclosure. When the enclosure boundaries are hard and reflective, the reverberant field can easily dominate the sound arriving directly (without reflection) from a particular sound source and this will become increasingly likely as the distance from the sound source is increased. The reduction of noise with distance from the source in a reverberant field is illustrated in Figure 10.29 (with distance, r in metres) for varying degrees of reverberation characterised in terms of a "room constant" which is a measure of the sound absorbing characteristics of a room and is expressed by the following equation:

$$R = \bar{\alpha} S / (1 - \bar{\alpha}) \tag{8}$$

where:

S = the total area of the boundaries of the room (m^2)

$\bar{\alpha}$ = the average absorption coefficient of the surfaces of the room at a given frequency. At high frequencies, absorption due to the air in the room must also be included in the calculation (see Bies & Hansen, Ch. 7, 1996).

In practice, all boundaries do not have the same acoustical absorption characteristics and the average absorption coefficient $\bar{\alpha}$ for i surfaces must be computed using

$$\bar{\alpha} = \sum_{i=1} S_i \alpha_i / S \tag{9}$$

where:

α_i = the absorption coefficient of surface i and

S_i = the area of surface i in the room (with corresponding coefficient α_i).

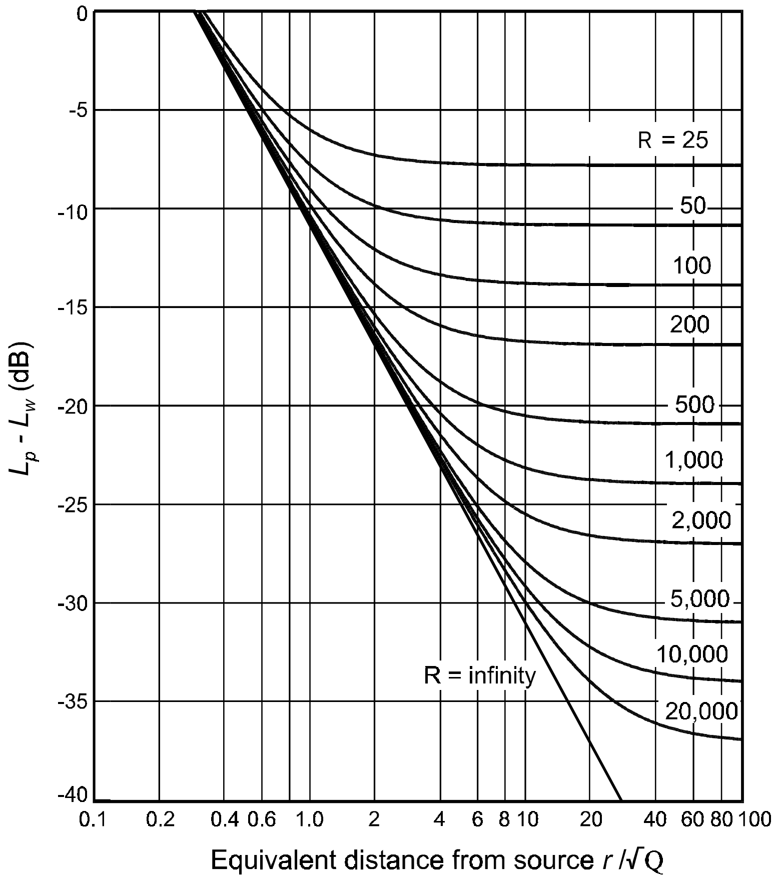


Figure 10.29. Sound attenuation in a reverberant field

The product $S\bar{\alpha}$ is called the absorption of the room and has the units m². The units are sometimes called sabines (m²).

In a reverberant field (which exists in most indoor situations), the mean square sound pressure at a given point is the sum of the mean square sound pressures of the direct sound waves and of all reflected sound waves. At a distance r from the source, the mean square sound pressure squared can be mathematically expressed by the following simplified equation (note that the equation is approximate only and more accurate analyses of factory noise can be made using finite element or boundary element analyses):

$$p^2 = W\rho c\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) \tag{10}$$

where:

Q = the directivity factor of the source towards the measuring point (see Ch. 1)
r = distance from the source (in meters)
R = room constant
ρ = density of air (1.21 kg/m³)
c = speed of sound in air (343 m/s at 20°C).

The preceding expression can be written approximately (to within 0.2 dB), in terms of levels, as follows:

$$L_p = L_w + 10\log_{10}\left(\frac{Q}{4\pi r^2} + \frac{4}{R} \right) \tag{11}$$

This relation is shown graphically in Figure 10.29. This graph allows the determination of attenuation in sound pressure level, with increasing distance from the source (in meters). There are different curves for different room constants, R.

In the case of a room for which the length width and height dimensions are not different by more than a factor of 10, the relative strength of the reverberant sound field may be compared with the direct field produced by a machine at a particular location by comparing the direct and reverberant field terms (the bracketed quantities of equation (11)); that is, $4/R$ and $Q/4\pi r^2$. When these two terms are equal, the direct and reverberant sound fields are equal (see Chapter 1, section 1.1.1 for definitions of direct and reverberant fields. The case of flat rooms or long rooms is a little different and is discussed in detail in Bies and Hansen (1996, Ch. 7).and is part of ISO 11690. Besides the reverberation time in this standard other parameters are defined and related to the spatial sound distribution curve which can be determined and verified with affordable means (ISO 14257). Some national legal provisions require acoustic quality of workrooms specified by parameters given by ISO 11690-1,-2 and -3.The prescribed values are related to the typical values of ISO 11690-2.

Example *(approximately cubic room)*:

Consider a room 10 meters long, 8 meters wide and 4 meters high, which has a ceiling covered with a material having an absorption coefficient of 0.7, while it is 0.2 and 0.05 for the floor and the walls respectively (at 500 Hz).

The products $S_i\alpha_i$ for ceiling, floor and walls are then respectively 56, 16 and 7 m^2. The equivalent absorption area A is the sum of these three quantities and is equal to 79 m^2. The total room surface area is 2(10×8 + 10×4 + 8×4) = 304 m^2. Using equation (9) then gives the average absorption coefficient $\bar{\alpha}$=0.26. Equation (8) then gives the room constant R = 107 m^2. If the sound power level of a source is 100 dB and the source is placed on a reflecting surface (Q = 2), use of equation (11) gives the sound pressure level, L_p, at 3 meters from the source in that room as 87.5 dB. In free field, R in equation (11) is equal to infinity, Q is equal to 1 and equation (11) gives L_p = 82.5 dB. In the purely reverberant field, r in equation (11) is sufficiently large that the first term in brackets of equation (11) can be ignored with the result that L_p = 86 dB.

The calculation of the room constant, R, in real occupational situations, is usually not very accurate, particularly in the industrial environment, as the absorption of the machines, pipes, etc., is almost impossible to take into account. However, it can be measured by measuring the reverberation time, T_{60}, of the indoor work area.

Reverberation time is the time (in seconds) required for the sound pressure level in an enclosed space to decay by 60 dB when the sound source is switched off. It is related to the Sabine absorption coefficient as follows:

$$T_{60} = \frac{55.25\,V}{Sc\bar{\alpha}} \tag{12}$$

where:

V is the room volume in m^3
S is the surface area of all surfaces and objects in the room.
If it is too difficult to estimate S, then the room constant is often approximated by substituting R for $S\bar{\alpha}$ in the above equation.
c=speed of sound in air as given for equation (10)

NOTE: The equation T60 = 0.163 V/A with A=$S\bar{\alpha}$ *as given in ISO 11690-2, Annex F, is accurate to within 2% for temperatures between 15 and 25 °C.*

If the reverberant sound field dominates the direct field, then the sound pressure level will decrease if absorption is added to the room or factory. The decrease in reverberant sound pressure level ΔL_p to be expected for a particular increase in sound absorption expressed in terms of the room constant R (see equation (11)) may be calculated by using equation (11) with the direct field term set equal to zero. The following equation is obtained where R_i is the initial room constant and R_f is the room constant after the addition of sound absorbing materials.

$$\Delta L_p = 10 \log_{10}\left[\frac{R_f}{R_i}\right] \tag{13}$$

It can be seen from the preceding equation that if the original room constant R_i is large then the amount of additional absorption to be added must be very large so that $R_f \gg R_i$ and ΔL_p is significant and worth the expense of the additional absorbent. Clearly it is more beneficial to treat hard surfaces such as concrete floors which have small Sabine absorption coefficients, because this will have greatest effect on the room constant.

Remember that when calculating the increase in room constant due to fixing absorbing material to an existing surface, the difference in absorption coefficient between the existing and new surface should be used together with equations (8) and (9). In many cases best results are obtained by increasing the room constant by hanging sound absorbing panels from the ceiling.

It is highly undesirable to use hard reflective materials as boundaries for a space where there are noise sources and occupants. In fact, even if there are no occupants, it may not be desirable to let such noise build up as this will increase the noise which escapes through the enclosing walls. So, even if noise is "closed in", there is interest in decreasing it. In fact, it should be kept in mind that even if isolation is used, reduction at the source should not be overlooked.

The same concept applies to the isolation of a noisy area inside a workplace, in which case workers must wear ear protection as part of a hearing conservation program. In this case, it is particularly important to treat the insides of the isolating walls with sound absorbing materials (see below) to avoid or reduce the reflected noise component which would add to the exposure of the workers inside the area.

10.4.8. Active noise control

Active control of noise is the process of reducing existing noise by the introduction of additional noise by means of one or more secondary (or control) noise sources. The introduced noise may achieve the required noise reduction by way of any one or combination of three different physical mechanisms.

One mechanism which is often used to describe the active control of noise in the popular press is that of sound field cancellation; that is, the introduced control sound is anti-phase to the original sound and cancellation results. This mechanism characterises cases where noise reduction is achieved in small local areas surrounding a control source; however, local areas of cancellation are always balanced by other areas of reinforcement where the sound level is increased. This type of control mechanism, which may be called "local cancellation", characterises the process involved in the control of noise around a passenger's head in an aircraft or motor vehicle using a loudspeaker embedded in the head rest of the seat or by use of a headset or earmuff containing a loudspeaker.

A second mechanism, which will be called suppression of sound generation, is possible and may be understood on the basis of the following considerations. If it were possible to make the entire control sound field (or almost all of it) 180° out of phase with the original (primary) field, then the sound radiated by the primary source would be effectively "cancelled" leaving one to wonder where all the energy had gone. The answer is that in this case, the control mechanism is not really cancellation; the sound field generated by the control sources has effectively "unloaded" the primary source, changing its radiation impedance so that it radiates much less sound (even though the motion of the physical source such as a vibrating surface may remain unchanged). In this case, the control sources act to suppress the sound power radiated by the primary source by making its radiation impedance reactive with only a negligible real part.

To achieve effective suppression of the primary source output by presenting a purely reactive impedance to it, the control sources must be large enough and located such that they are capable of presenting the required impedance to the primary source. In one dimensional wave guides, such as air conditioning ducts, these constraints are relatively easy to satisfy and the distance between the control and primary sources is not too important. However, in 3-D space, the control source in general will need to be close to the primary source to affect its radiation impedance significantly. It will also need to be of similar size with a similar volume velocity output.

A third mechanism of active noise control is that of absorption by the control sources. In this case, the primary sound field energy is used to assist in driving the control source (for example the speaker cone if the control source is a loudspeaker). However, the acoustical efficiency of loudspeakers and other artificial noise generators is so poor, that electrical energy is still needed to drive the source with sufficient amplitude and at the correct phase to enable it to absorb energy from the sound field. Except for plane wave sound propagation in ducts, this mechanism is likely to result only in areas of reduced noise close to the control source.

Feedforward and feedback control are the two main approaches which have been used in the past for active noise control. A feedforward controller requires a measure of the incoming disturbance sufficiently far ahead in time that it can be used to generate the required control signal for the control source. This type of control is ideal for periodic noise or for random noise propagating in ducts. An example of such a system is illustrated in Figure 10.30. Note that for the controller to remain stable, a measure of the cancellation path electroacoustic transfer function (from loudspeaker input to microphone output) is necessary. This is typically done on-line using low level random noise as illustrated in Figure 10.30.

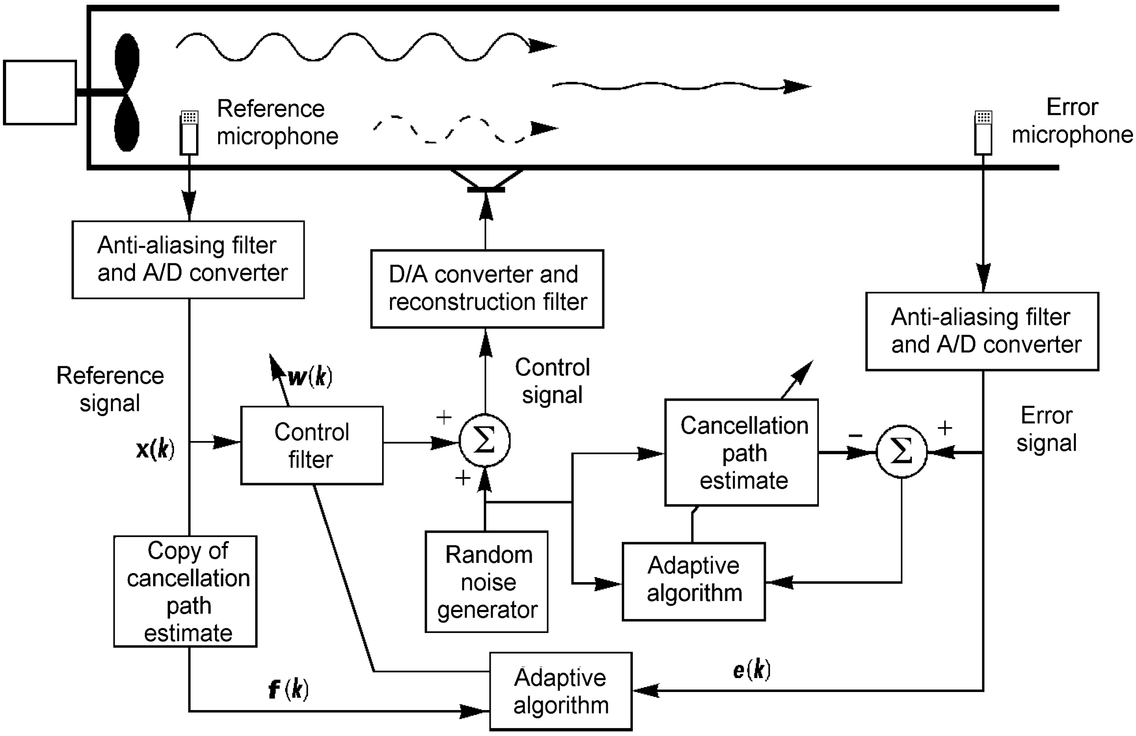


Figure 10.30(a). Configuration of a feedforward active noise control system to attenuate noise propagation along a duct (after Eriksson and Allie, 1989).

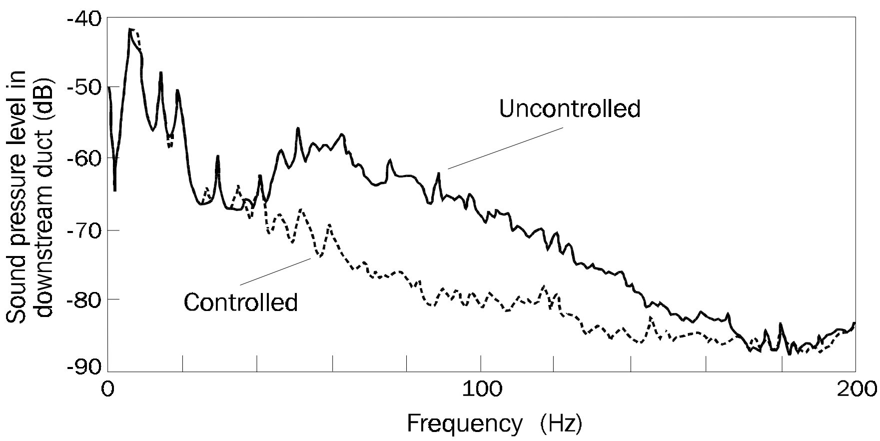


Figure 10.30(b). Attenuation of the feedforward systemof figure 10.30(a) achieved for broadband sound (after Eriksson and Allie, 1989).

Practical implementation of the system is much more complex than shown in the figure because allowance must be made for quantisation errors associated with the digital nature of the controller and the electro-acoustic delay between the controller signal input to the control sourceand the signal output from the error microphone. This is discussed in more detail in specialist books on the subject (Nelson and Elliott, 1992; Hansen and Snyder, 1996).

Feedforward controllers generally use a digital filter to act as an inverse model of the system to be controlled, with the measure of the incoming disturbance being passed through the digital filter and then to the control source. Practical systems are adaptive so that they can cope with changes over time of physical parameters such as temperature, speed of sound, and transducer contamination. Adaptation is achieved by using an error sensor, which detects the residual sound field after control, to provide a signal to a control algorithm which adjusts the weights of the digital filter.

When sound propagating in ducts is to be attenuated, the elements of the active system are usually sufficiently small to be mounted in the duct wall, thus minimising air flow pressure losses. Disadvantages of active attenuators are associated with their cost (although this is rapidly decreasing), the need for regular maintenance (speaker replacement every three to five years) the requirement for custom installation and testing by experts, the reduction in performance at mid to high frequencies and a requirement for a separation between the reference microphone and control loudspeaker of a minimum of 1m at 150 Hz to 10m at 20Hz.

A feedback controller requires no knowledge of the incoming disturbance and acts to change the system response by changing the system resonance frequencies and damping. To be effective, relatively high gains in the feedback loop are necessary which makes this type of controller prone to instability if any parameters describing the physical system change slightly. However, this type of controller is ideal in cases where it is not possible to sample the incoming disturbance or for random noise. To minimise acoustic delays and thus maximise system stability, the physical locations of the control source and error sensor should be as close together as possible.

Examples of the practical use of a feedback controller include active ear muffs (or active head sets - see Figure 10.31), active vehicle suspension systems and active control of structural vibration. Feedback controllers, however, are unsuitable for controlling travelling acoustic waves in ducts (where reflection from the end is negligible) or flexural waves in structures where no reflections are involved. However, in cases where reflections are involved, the damping introduced by the feedback controller minimises the transient or reverberant response of the acoustic or structural system and as such can be quite effective. An example of a feedback system to control noise propagating in a duct is illustrated in Figure 10.32.

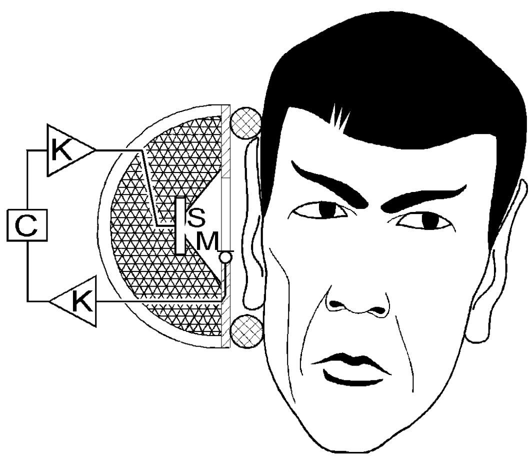


Figure 10.31. Feedback control system applied to a headset.

C = digital filter;
K = amplifier;
M = microphone;
S = loudspeaker.

It is important to discuss limitations on applications of active noise control. It is very cost effective and beneficial in some very specific applications, but it is definitely not the all encompassing answer to a wide range of noise problems which will become available just as soon as the cost of the electronic hardware falls low enough. Unfortunately active noise control is limited in application for physical reasons, and not because of limitations in electronic processing power.

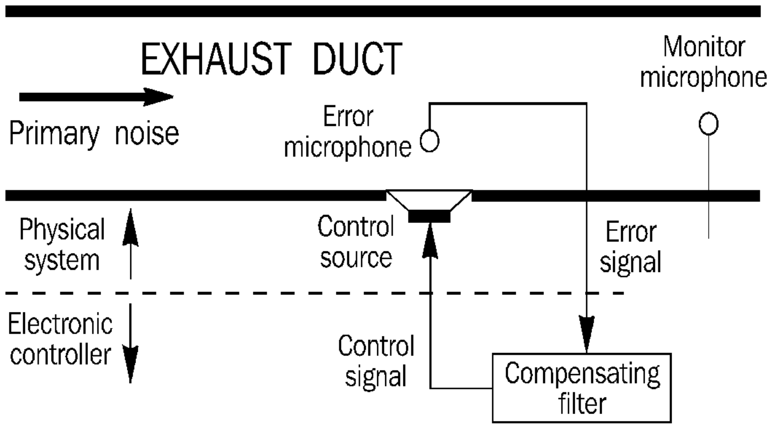


Figure 10.32. Feedback control system applied to sound propagating in a duct.

Active noise control is most suitable for low frequency tonal sound fields such as radiated by electrical transformers or exist in a propeller driven aircraft cabin. Even for tonal sound fields, a large number of control sources and error microphones are needed to make the systems effective. When the sound is confined to a duct and propagates as plane waves, broadband noise can be controlled actively as well using one or two control sources and error sensors, provided that an acoustic reference signal can be obtained sufficiently far upstream of the control source for the control system to generate the required control signal. In this case about 15 to 20 dB of noise reduction may be expected over 2-3 octave bands. However performance is usually reduced in the presence of large air flow speeds. In very small enclosures (smaller than a wavelength of sound at the highest frequency of interest), broadband and pure tone noise can both be controlled. In larger enclosures (and in free space or outdoors), the control of random noise is not practical. Thus active earmuffs are useful for frequencies below about 1500 Hz and a number of systems are commercially available. However it is not practical to use active noise control to reduce general broadband factory noise in the vicinity of workers.

A more detailed discussion of active noise control can be found in specialist books on the subject (Hansen and Snyder, 1996).

10.4.9. Separation of source and receiver

Another type of noise propagation control is the separation, which can be by distance or in time. As the direct field radiated by a source generally decreases by 6 dB for each doubling of the distance from it (after the initial 1 metre), separating the source and receiver by distance is beneficial.

Noisy operations can also be separated in time; that is, they are performed out of the usual shift.

10.5. RECEIVER CONTROL

Receiver control in an industrial situation is generally restricted to providing headsets and/or ear plugs for the exposed workers, see chapter 11. It must be emphasised that this is a last resort treatment and requires close supervision to ensure long term protection of workers' hearing. The main problems lie in ensuring that the devices fit adequately to provide the rated sound attenuation and that the devices are properly worn. Extensive education programs are needed in this regard. Hearing protection is also uncomfortable for a large proportion of the workforce; it can lead to headaches, fungus infections in the ear canal, a higher rate of absenteeism and reduced work efficiency. It is worth remembering that the most protection that a properly fitted headset/earplug combination will provide is 30 dB, due to conduction through the bone structure of the head. In most cases, the noise reduction obtained is much less than this.

Another option which is sometimes practical for receiver control is to enclose personnel in a sound reducing enclosure (see ISO 11957). This is often the preferred option in facilities where there are many noisy machines, many of which can be operated remotely. In this case, the enclosure design principles outlined in section 10.3.5 may be used and the enclosure performance may be calculated using equation (6) and the appropriate wall material and construction selected after the required noise reduction has been established. Guidelines which should be followed during design and construction are:

- doors, windows and wall panels should be well sealed at edges;
- interior surfaces of enclosure should be covered with sound absorptive material;
- all ventilation openings should provided with acoustic attenuators.

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INTERNATIONAL STANDARDS

Titles of the following standards related to or referred to in this chapter one will find together with information on availability in chapter 12:

ISO 4871; ISO 9613-2; ISO 10846; ISO 10847; ISO 11654; ISO 11689; ISO 11690-1, -2, -3; ISO 11820, ISO 11821; ISO 11957; ISO 14163; ISO 14257; ISO 15667; ISO/TR 11688.

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11

PERSONAL MEASURES AND HEARING CONSERVATION

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11.1. WORK PRACTICES AND ADMINISTRATIVE CONTROLS

Evaluation of the workplace for noise exposure includes preliminary noise measurements, separation of the workplace into different noise risk areas - and development of both short and long term noise management plans. After evaluation of the workplace, it might be appropriate to evaluate possibilities which the individual employee has to control his or her own (noise) work environment and to evaluate simple measures which may result in a further reduction of the noise level.

Whatever noise levels are agreed upon in the workplace, or have been legally demanded, there will always for the individual employee and for a specific group of employees in definite sections of the workplace be a question of *what risk is acceptable - or "the acceptability of the noise level in the work environment".*

Every human has their own limit of acceptance - according to their attitude to their own life and health, their family and their colleaques. This limit of acceptance varies a lot from human to human, but even if the limit is exceeded one will back away from the risk. The limit is rather vague and is related to workers' traditions, possibilities of finding other less unhealthy jobs and the degree of influence at the workplace. The individual limit of acceptance thus might be either above or beneath what is considered healthy or legally justifiable.

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To get closer to the individual limit of acceptance in a workplace, it should be noted that:

* everybody will obtain updated information of health effects of noise,
* there is a high level of information about organizational, managerial and technical efforts of noise reduction,
* proper maintained personal hearing protection is available to a certain extent - and it is worn whenever necessary.

Employees can make their own noise reduction measures by:

* Avoiding unnecessary noise at transport and handling - "don't throw the things".
* Stopping machines and equipment that is not in use at the moment
* Securing loose machine parts that rattle.
* Reducing occupation and staying in high noise areas to an absolutely minimum
* Using appropriate technical equipment, for example encapsulation and noise shields.
* Making their own routines for maintenance, adjusting and oiling machinery and equipment.
* Taking part in development and evaluation of new noise efforts.
* If anything else is impossible, and hearing protectors must be used: **Use them all the time!**
* By taking any incipient hearing damage seriously, involve health personnel and have all damages properly investigated.

11.2. EDUCATION AND TRAINING

A very high level of information, training and education is definitely important for the understanding of the meaning of the health effects of noise and for understanding possibilities of hearing loss prevention in reducing the noise levels. It is also important for ensuring the effectiveness of the agreed noise policies and noise plans in the companies. So it is important to emphasise that instruction and education is not only aiming at teaching the employees how to use hearing protection devices, but the target groups for education and training are much broader:

* Employees
* Health and safety representatives
* Foremen, supervisors, engineers and designers
* Management and the company's buyers
* Professionals and managers
* Future engineers and machine inventors.

11.2.1. Training Within the Workplace

11.2.1.1. Content of training

The employer must provide instruction, supervision and training to all employees who work in unacceptable hearing risk areas so that they can perform their work in a safe manner and without risk to their health and safety.

The employer must ensure that all employees with potential for exposure to (hazardous) noise in the workplace are trained in relation to the noise, its sources and propagation paths.

The main content of the training should at least concern:

1) The known noise levels of different places in the workplace

2) Identification of risks to health and safety associated with working in the noisy areas, (for instance with the use of tapes with different noise levels and how it is experienced with different grades of hearing loss)

3) The control measurements and administrative procedures implemented to minimize exposure to noise (including demonstrations of measuring equipment).

4) The necessity of good work practice and periodical maintenance of machinery and equipment,

5) The duties of suppliers, management, supervisors, employees, work hygienists,

6) The availability and use of information, including noise declarations and noise estimation schemes ,

7) the proper selection, evaluation and maintenance of hearing protection and the importance of wearing hearing protection all the time. (including practical exercises)

11.2.1.2. Time of training

The employer must ensure that training is provided:

a) before an employee first begins work within a risky noise area.

b) whenever new machinery or equipment is planned to be installed.

c) when there is a change in the noise control measures used or a change in the managerial noise policy or plans.

d) when there is new information available on health and safety matters concerning noise.

11.2.1.3. Target groups of training within the workplace

1) All employees working in noisy areas and their health and safety representatives,

2) persons responsible for workplace layout, plant, buying and maintenance of machinery and equipment, i.e. internal engineers, supervisors, and designers,

3) persons responsible for control measures, including the acqusition and maintenance of hearing protective equipment.

11.2.1.4. Training methods

Training on the job should be undertaken by a competent operator familiar with noise effects, noise measuring and engineering controls and familiar with the company' s plans for noise reduction.

More consideration should be made in developing and providing training programmes, such as:

* how to be sure that the contents of the training are clearly understood by the participants,
* that employees and others being trained should not be required to carry out any procedure which after the training could cause health and safety risks to themselves and to other employees,
* any special needs of the participants in the training such as specific skills, work experience, ethnicity and first language, literacy and age.
* there might be a differentiated training for individuals or for mixed groups within the workplace; in many cases it would be appropriate to mix up different groups of employees, engineers and administrative staff to get more experience, good suggestions

for further noise reduction and by that also training the different groups co-operatively. The training should be carried out in a way that permits two-way communications - also to get new ideas for further training.

11.2.2. Training and Education Outside the Workplace

Training courses concerning noise, including all kinds of new information, should be provided for occupational hygienists and for health and safety executives. It is of special importance that education in the technical universities also includes work and environmental aspects of noise so that future designers of machinery and equipment in an early stage recognise the importance of noise reduction.

RECOMMENDATIONS FROM THE WHO CONSULTATION ON NOISE ***(see Background)***
Education as to the dangers of overexposure to noise should aim not only at managers, workers and all professionals related to workplaces, but should start with school children and also include the general public.

Educational campaigns should follow adequate strategies and utilise materials appropriate to each target group. Mass media, for example, is an excellent tool to educate the general public.

11.3. PERSONAL HEARING PROTECTORS

11.3.1. Introduction

Despite the great progress in noise control technology, there are many noise situations where engineering noise reduction is neither economically nor technically feasible. Also in many practical situations, it may be many years before noisy machines and processes can be modified or replaced. Therefore, in these cases, or during the period in which noise control actions are being undertaken, personal hearing protection should be used as an interim solution. The use of personal hearing protectors is an ideal solution in many situations where a worker is exposed to high noise levels for short periods of time, particularly if communication is not necessary such as cutting a sheet of wood, in the circular saw room. In this case, the worker can go into the room in which the saw is enclosed, shut the door, put the hearing protector on, switch on the noisy circular saw, cut the sheet, switch off the saw, take off the protector and hang it on the inside side of the door, and then get out of the room. During the cutting period, which may last for minutes, there is no need to communicate with any other person, and the operator can withstand the disconfort of the protectors. Therefore the use of hearing protectors in this case, and similar cases, is the ideal solution.

11.3.2. Selecting Hearing Protection

A correctly selected hearing protector should provide enough noise reduction to remove the risk of hearing damage, and at the same time allow communication with the surroundings while ensuring the best available level of comfort. The acceptance of hearing protection is strongly linked to the likelihood of it being used. To get a 100 % use the noise reduction, the communication and the comfort should be considered.

High noise reduction requires heavy hearing protectors located very close to the head with a large pressure. But great weight and high pressure result in high discomfort which may be even so bad that nobody could stand to use the protector for a long period. High noise reduction protects against hazardous noise while at the same time allowing the user to hear desirable sounds (eg. conversation, warning sounds.

It should be emphasised that the hearing protector should be used in all the time that one is in a noise area. If one take off the protector even for a few percent of the time, maybe 5-10 minutes in a whole working-day, the protection could be reduced to half (see Figure 11.1).

If the protector is not used all the time, its nominal noise reduction will be unimportant. So it is very important that the protector should be accepted by the user. The selection of a hearing protector must be from a total point of view (including comfort) and not only on the basis of the noise reduction curve.

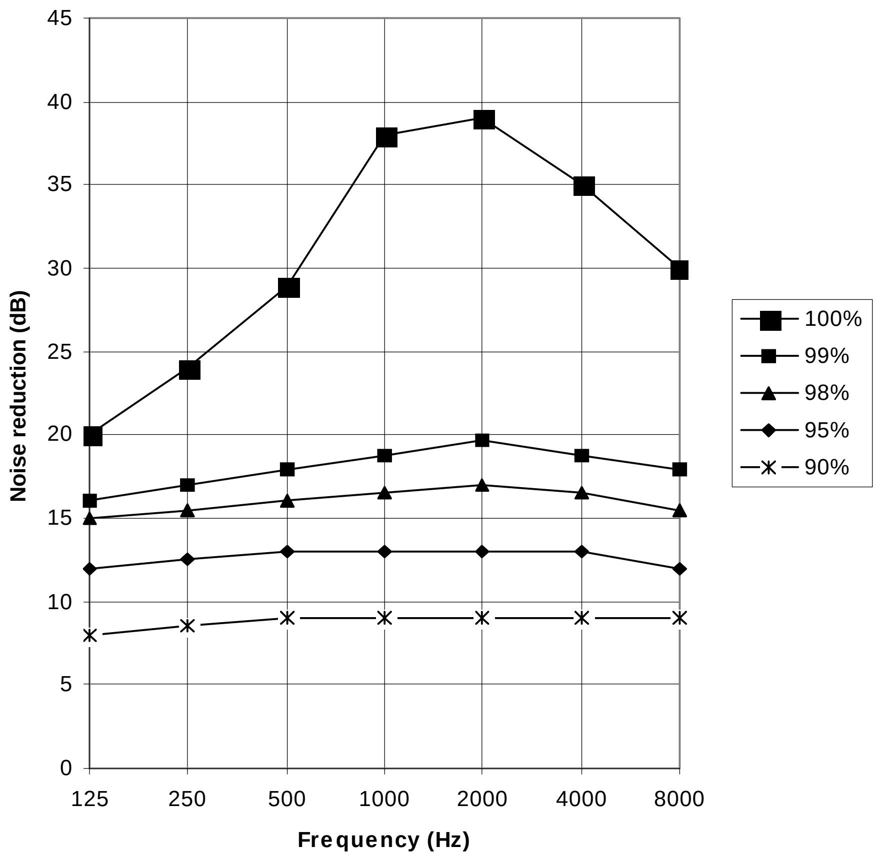

Figure 11.1. Effect of percentage of time typical hearing protection is worn on the effective noise reduction experienced by the wearer.

It has not yet been possible to find a method of measuring the comfort of the protectors. The comfort could vary significantly from person to person. The shape of the user's head and the ears and head dimensions vary greatly between individuals. Only the user can determine whether a specific protector gives enough comfort. So the user should always be provided with a number of different protectors to ensure that the protector is acceptable and thus it is used as intended.

11.3.3. Types of Protectors

Hearing protection devices may be broadly divided into three basic types: (1) earmuffs which cover the outer ear and act as an acoustic barrier sealing it against the head (2) earplugs which can be inserted into the outer ear canal, thereby blocking the propagation of airborne sound to the middle ear. (3) Canal caps (semi-aural) which are basically earplugs connected by flexible headband. Canal caps generally seal the ear canal at its opening and they are used extensively in the food industries. (4) Other special types are available such as helmets with circumaural, cups or muffs with communication. Other brands are also now available with electronic amplification or with active noise reducing digital circuits.

There are many varieties of hearing protection devices available on the market and several factors have to be considered in addition to the noise attenuation provided; such as selecting the most suitable type for each situation, comfort, cost, durability, chemical stability, safety, wearer acceptability and hygiene. No particular brand is obviously the best choice for all.

RECOMMENDATIONS FROM THE WHO CONSULTATION ON NOISE
(See Background)

As any personal protective equipment, hearing protection devices should be regarded as "last resource" measures, or for sporadic or temporary use. All efforts should be made to reduce noise levels in the work environment.

The provision of hearing protection of dubious or unknown effectiveness is unacceptable. In order to ensure effectiveness of hearing protection devices, it is imperative that their quality be assessed, for each type and manufacturer; national institutions should carry out or request such evaluations.

Furthermore, even protectors of proven quality need to be assessed for individual workers.

Protectors should have labels that are representative of their performance at the workplace.

Research on the development of open-back head-sets and ear plugs that use active noise control for broad-band noise reduction should be promoted. There is also scope for improvement of the classical passive types of ear protectors.

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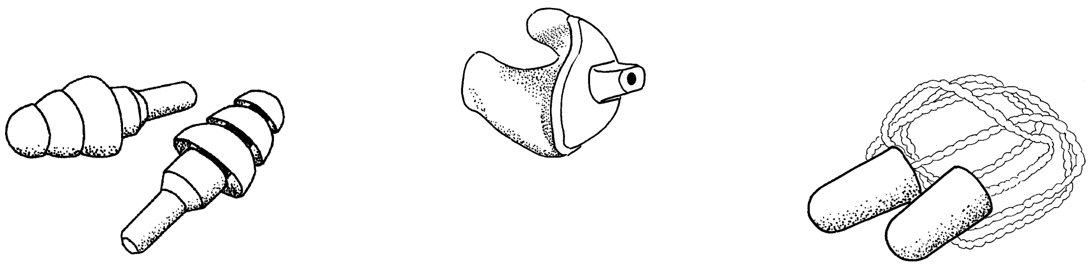
11.3.3.1. Earplugs

Earplugs can be classified by size, shape and construction materials such as; custom molded, premolded and expandable.

Premolded earplugs are generally made of soft plastic or silicone rubber and are available in different sizes (see Figure 11.2(a)). Generally they are available with an attached cord to prevent loss. The characteristics of these plugs depend on the fitting and maintenance. The wearer of these types can experience a feeling of pressure or discomfort due to their semi-solid construction.

Custom molded ear plugs are made of a soft rubber material which is molded into the individual's outer ear canal (see Figure 11.2(b)). In these case, a high degree of attenuation is obtained depending on each wearer.

Expandable earplugs are considered the most comfortable (see Figure 11.2(c)). Since they are porous and soft. They are made from slow recovery closed cell foam. They offer high attenuation since they expand against the outer ear canal and seal it with less pressure.



(a) **(b)** **(c)**

Figure 11.2. Earplugs.

11.3.3.2. Earmuffs

Ear muffs are made from rigid cups, are mostly oval shaped, and are designed to cover the external ear completely. They are held in place by a preformed or spring-loaded adjustable band and are sealed round the rim of each cup, with a soft foam-filled or liquid-filled circumaural cushion, to achieve a continuous seal contact.

The effectiveness of ear muffs depends mainly on the pressure exerted by the headband and the cushion to head sealing. The attenuation provided by ear muffs can be greatly reduced when the muff seal is displaced by the side arms of spectacles or long hair. Ear muffs fit most people, are easy to put on and remove in a hygienic way, and are therefore recommend for use in dirty areas and for workers who suffer from external ear canal problems.

11.3.3.3. Canal caps (semi-aurals or banded ear plugs)

They consist of flexible tips, made from silicone, vinyl or foam in mushroom, hollow bullet or conical shape, atached to a lightweight plastic headband. They are easily removed and replaced. They can be used under the chin and behind the head.

11.3.3.4. Special types of hearing protectors

There are a number of hearing protectors designed for special purposes. Ear muffs can be fitted with phones and wired-up or connected by radio in order to provide communication and/or entertainment. Also they can be fitted with acoustic frequency band-pass filters to provide speech communication between wearers, providing that the noise is out of the speech frequency band.

Ear muffs are also available which can reproduce music or messages from external units. These muffs have a peak limiting circuit (to about 80 dB(A)) to avoid hazard.

Active noise control ear muffs are now available which cancel the low frequency band noise inside the cups by out-of-phase generated sound. They provide good attenuation at low frequencies (up to 20 dB) and also serve as classical passive earmuffs with good attenuation at high frequencies. They are still expensive and have the possibility of electronic failure (see Figure 11.3).

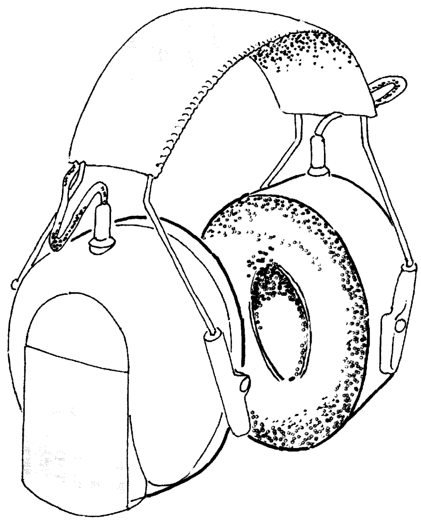


Figure 11.3. Active control muffs

11.3.4. Hearing Protector Attenuation

The maximum possible protection is dependent on the frequency of the noise and the noise attenuation is limited, especially at low frequencies. Noise can reach the inner ears of the person wearing the hearing protector by one or more of the following pathways (see Figure 11.4);

1- Leakage around the protector contact with the head (for muffs) or ear canal (for earplug)
2 - Vibration of the protector causing sound generation in the outer ear canal;
3 - Sound transmission through protector materials;
4 - Bone and tissue conduction through parts of the head not enclosed by the protector;

The four leakage pathways set practical limits to the noise attenuation provided by any ear protector. The maximum possible attenuation of the protector is unlikely to be achieved for various reasons e.g. protector-wearer coupling, but approximate values for wearers of both plugs and muffs are between 40 to 60 dB depending on the frequency bands (see Table 11.1). This maximum possible attenuation is unlikely to be achieved in practice.

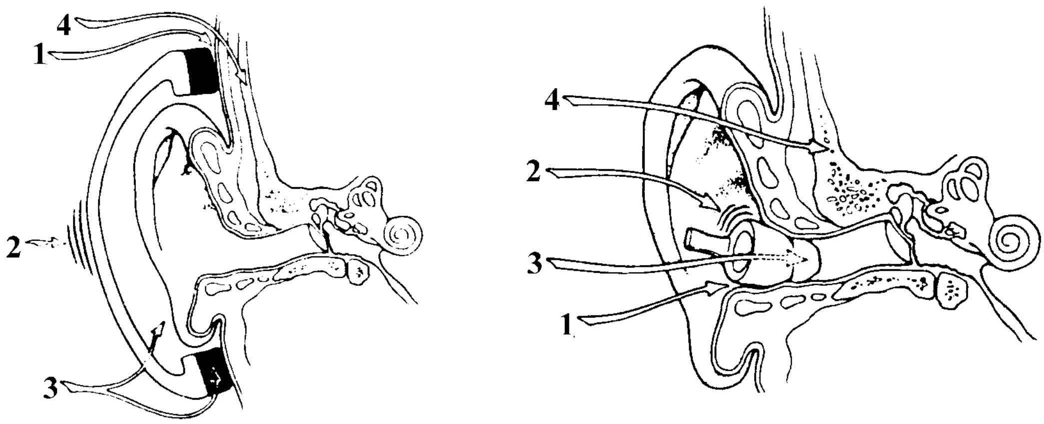


Figure 11.4. Sound pathways leakage (Berger et al. 1996)

The noise attenuation of a hearing protector is best represented by the "Insertion Loss (IL)" which is the difference between the sound pressure level at the outer ear canal with and without the hearing protector.

Working environments are generally reverberant fields characterised by broad or narrow band frequencies. Therefore any test method for measurement of hearing protector attenuation must reasonably represent this situation.

Table 11.1: Bone conduction limitation to hearing protector attenuation (Berger et al. 1996).

Frequency band Hz	125	250	500	1k	2k	3.15k	4k	6.3k	8k
Maximum Protection, dB	47	50	58	48	40	47	49	48	48

11.3.5. Hearing Protector Measurements (Franks et al. 1994)

Several national and international standards are available for the laboratory determination of hearing protector noise attenuation, mainly the ANSI standard used in the USA and ISO & EN standards (see list at end of this chapter)used in Europe.

The method specified by the Environmental Protection Agency "EPA" in the USA for determining the amount of noise attenuation that a hearing protector provides is based on subjective tests of protectors as worn by listeners rather than objective tests from an electromechanical device. The actual test method is called real-ear-attenuation-at-threshold (REAT), and the techniques for measuring REAT are specified in ANSI S3.19-1974. ANSI S3.19 - 1974 requires that auditory thresholds be obtained from a panel of 10 normal -hearing listeners sitting in a diffuse random-incidence sound field. The test signals are pulsed one-third-octave bands of noise which have centre frequencies of 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz. Thresholds are determined with the listeners' ears open and with their ears occluded by the hearing protector under test. The difference between the open-ear threshold and the occluded-ear threshold at each frequency is the REAT for that frequency. Each listener is tested three times with their ears open and three times with their ears occluded. The REATs for all 10 listeners are arithmetically summed and the mean attenuation is calculated for each test frequency. Since there are three REATs at each test frequency for 10 listeners, the average is calculated by dividing the grand total by 30 to get the grand mean. The standard deviation is also calculated for each test frequency using the number 29 (n-1 from the formula for the standard deviation of a sample, where n is the number of samples) as the denominator, as if 30 separate subjects had provided one REAT each per test frequency.

When a REAT is being determined for the purpose of labelling hearing protectors according to EPA labelling requirements, the protector is fitted into the ear or placed on the head by the experimenter in order to obtain maximum protector performance. Technically, the experimenter fit described in ANSI S3.19 - 1974 and adopted by the EPA does in fact permit the test subjects to fit the protector themselves (using a fitting noise to adjust the device for maximum attenuation) provided that the experimenter personally checks each installation for good fit and acoustic seal and reinserts or readjusts the protectors as necessary. In practice, however, the EPA has determined that "experimenter-fit" shall mean that the experimenter always personally fits the device under the test.

The current American National Standards Institute's method for determining REATs for hearing protectors is ANSI S12.6-1984. This standard, which replaced ANSI S3.19 - 1974, allows more freedom in setting up a diffuse sound field, defines sound-field noise-burst audiometry with greater precision, and is more explicit in its details about how audiograms are to be read and analysed (particularly in the areas of pairing open and occluded thresholds). S12.6 - 1984 requires an experimenter-supervised fit in which the listener fits the hearing protector while listening to a fitting noise and while gaining insight from the experimenter on optimum fitting techniques. The experimenter does not physically touch the protector or the listener after the final fitting. Calculations of mean REAT and standard deviations are identical to the earlier standard. Since ANSI 12.6 -1984 was adopted after the EPA hearing protector labelling laws were written, and since the EPA regulations made no provision for adopting newer standards, the older S3.19 method must be used when testing hearing protectors for EPA labelling purposes even though S12.6 is the most current methodology.

The European community also relies upon the REAT for determining hearing protector attenuation (ISO 4869-pt.1 - 1992). However, there are differences in methods. The number of subjects required is 16 rather than 10 and each subject is tested only once with ears open and once with ears occluded to produce one REAT at each test frequency. In addition, 4869-1 relies upon a subject-fit in which the listeners fit the hearing protectors using a fitting noise to adjust the protectors for best perceived attenuation, but without feedback from the experimenter. Because of the lack of coaching by the experimenter, when hearing protectors are tested for European markets, the reported REATs are usually lower than when they are tested for distribution in the United States.

In 1997 an ANSI new standard was approved -ANSI S12.6 -1997 (methods A and B). The method B, subject fit qualified subjects who are trained and experienced in audiometric test but naive with respect to use of hearing protectors. This subject fit the protector himself or herself using the manufacturer instruction with no assistance from the experimenter at all. This method provides data results that approximate the protection that can be attained by a group of informed users in the workplaces within a well managed and well supervised hearing conservation program (Berger et al. 19xx). The octave band results measured using the new standard can be converted to a single number called Norse. This number is the SNR for 84% (See ISO 4869-2) less 5 dB. The NRRsf may be subtracted from the A-weighted sound pressure level (or Leq) exposure to give directly the protected level for most users (84%).

11.3.6. Rating Systems (Franks et al. 1994)

The mean attenuation and standard deviations as reported by hearing protector suppliers were used to calculate all ratings of protector performance according to the various methods.

The *NRR* is a single-number rating method which attempts to describe a hearing protector based on how much the overall noise level is reduced by the hearing protector. The *NRR* is described in 40 CFR Part 211 EPA Product Noise Labeling Law, Subpart B Hearing Protective Devices (EPA 1979), and was adapted by the EPA from Method 2 in the first NIOSH Compendium (Kroes et al., 1975). The formula for calculating the *NRR* is

$$NRR = 107.9(\mathrm{dB(C)}) - 3 - 10\log_{10}\left[\sum_{f=125}^{8k} 10^{0.1(L_{af} - APV_{f98})}\right]$$

where L_{af} is the A-weighted octave band level at centre frequency f of a pink noise spectrum with 100 dB at each frequency band and an overall level of 107.9 dB(C); and APV_{f98} is the mean attenuation value minus 2 standard deviations at centre frequency f (two standard deviations accounts for 98% of the variance in a normal distribution).

The equation can be broken down into the steps shown in reference (Franks et al. 1994). The *NRR* assumes a background of pink noise with octave-band levels of 100 dB. The corrections for the C-weighting scale are then subtracted to compute unprotected C-weighted octave-band levels at the ear. These octave-band levels are logarithmically summed to obtain the overall sound level in dB(C) at the unprotected ear; this value is the first term of the equation and is always 107.9. The corrections for the A-weighting scale are then subtracted from the pink-noise octave-band levels to compute the A-weighted octave-band levels at the ear. The average attenuation minus twice the standard deviations are subtracted from the A-weighted octave-band levels to compute the protected A-weighted octave-band level at the ear. The adjustment of 2 standard deviations theoretically provides an *NRR* that 98% of the subjects will meet or exceed, provided that the wearers use the hearing protection device the way laboratory subjects did and that the subjects were a reasonable sample of the user population anatomically. The protected A-weighted octave-band levels at the ear is then logarithmically summed to calculate the overall protected A level. The *NRR* is computed by subtracting 3 dB from the difference between the unprotected C-weighted (107,9 dB(C)) and the protected A-weighted levels at the ear. The 3 dB factor is a correction for spectral uncertainty to account for whether the pink noise used in the computation really matches the noise in which the hearing protection devices is worn.

The *NRR* is intended to be used for calculating the exposure under the hearing protector by subtracting it from the C-weighted environmental noise exposure level. Thus, if a protector has an *NRR* of 17 dB and it is used in an environmental noise level of 95 dB(C), the noise level entering the ear could be expected to be 78 dB(A) or lower in 98% of the cases. An alternative use of the *NRR* is with dB(A) measurements, the *NRR* can be applied if 7 dB is subtracted from its value. Thus for the same protector above, if it is used at an environmental noise level of 90 dB(A), then the noise level entering the ear is 90 - (17-7) = 80 dB(A).

In Europe, new rating systems (ISO/DIS 4869 - 1992) have been adopted which may have as wide a use there as the *NRR* has in the United States. The systems are the Single-Number Rating (*SNR*), the High-Middle-Low (*HML*) rating, and the Assumed Protection Value (*APV*). These methods are based on REATs measured according to ISO 4869-pt.1 - 1992 (discussed above) for one-third octave bands in octave steps from 63 to 8000 Hz (when data for 63 Hz are not present, the summation occurs from 125 to 8000 Hz). All of these methods provide the user with the option of selecting a protection performance value which is an indication of the percentage of test subjects who achieved the specified level of noise reduction. The protection performance is computed by subtracting a multiple of the standard deviation from the mean attenuation values. The most commonly utilized protection performance value in Europe is 80%, which is computed by using a multiplier of 0.84 with the standard deviation values. However, in this document, a protection performance value of 98% (computed by multiplying 2.0 times the standard deviation) is utilized for all *SNR* , *HML*, and *APV* calculations in order to make them more directly comparable to the *NRR* values. It should be stressed, though, that these methods allow the user to select a protection performance level other than 98%, and that the ratings can be recalculated from the data provided.

The *SNR* is calculated much like the *NRR*, except that the values used may vary with the selected protection performance value and that there is no 3 dB spectral correction factor. The method for calculating the *SNR* is presented in (Franks et al. 1994). The *SNR* differs from the *NRR* further in that the base spectrum for calculations is made-up of octave-band noise levels which sum to 100 dB(C), rather than pink noise octave-band noise levels of 100 dB which sum to 107.9 dB(C). The *SNR* considers attenuation only at the octave centre frequencies and does not include the third-octave center frequencies of 3150 and 6300 Hz. The octave band levels are also adjusted by the A-weighting correction factors and summed to a value of 98.5 dB(A). The mean attenuation value for each octave-band, minus the standard deviation for that octave band, multiplied by a protection-performance value, is subtracted from the A-weighted corrected octave-band levels in order to calculate the *APV* for each band. The sum of the *APV* s is subtracted from 100 dB(C) to calculate the *SNR* . The *SNR* may be subtracted from the environmental noise level in dB(C) to predict the effective A-weighted sound pressure level under the hearing protector. Thus, if a hearing protector had an *SNR* of 16 dB and was used in a noise level of 95 dB(C), the effective A-weighted sound pressure level under the hearing protector would be assumed to be 79 dB(A).

The *HML* - method is a different rating system altogether, in that it provides three numbers to describe hearing protector attenuation. Which number will be used in a given instance depends upon the noise from which protection is sought. The *HML* - method has a number which describes the low-frequency attenuation (L value), the mid-frequency attenuation (M values), and the high-frequency attenuation (H value) of a protector. These numbers are calculated by taking into account typical industrial noise spectra. In the early 1970s, NIOSH collected noise spectra from a variety of industrial locations and developed the NIOSH 100 noises (Johnson and Nixon 1974). The noise-spectra array was reduced to 8 spectra for calculation of the *HML* based on the difference between the calculated dB(C) and dB(A) level for each noise.

As with the *NRR* and *SNR* values, the mean attenuation and the standard deviations for calculation of the *H*, *M* and *L* values are provided by the manufacturer. To use the values, the environmental noise level in dB(A) is subtracted from the environmental noise level in dB(C) to see which rating is appropriate. If the difference between the dB(C) and dB(A) levels is equal to or greater than 2 dB, the mean of the *M* and *L* values is used according to the equation:

$$M - \frac{(M - L)}{8}.(\mathrm{dB(C)} - \mathrm{dB(A)} - 2\mathrm{dB})$$

If the difference is between 2 dB and - 2 dB, the mean of the *M* and *H* values is used according to the equation.

$$M - \frac{(H - M)}{8}.(\mathrm{dB(C)} - \mathrm{dB(A)} - 2\mathrm{dB})$$

The *HML* method allows selection of a hearing protector so that it can be effective at the frequency range where it is needed most. For example, suppose an earplug had an H rating of 25 dB, and an M rating of 18 dB, and L rating of 13 dB. If the environmental noise level were 95 dB(C) and 92 dB(A), the dB(C)-dB(A) value would be calculated from the M and L values, 18 - (18-13)/8* (94-92-2) = 11.25. So the exposure level at the ear from the protector would be 95.0 - 11.25=80.75, which rounds to 81 dB(A). The method for calculating the *HML* is presented in (Franks et al. 1994).

The Assumed Protection Values (*APV*) are calculated for each test frequency by subtracting a coefficient multiplied by the standard deviation from the averaged attenuation. The coefficient varies depending upon the protection performance desired. For a protection performance of 84%, the coefficient is 1.0; for 80% , the coefficient is 0.84; and for 98% the coefficient is 2.0. The *APV* s are used in the calculation of the *SNR* and *HML* , and they may also be used frequency-by-frequency for a direct calculation of octave -band noise reduction. In a typical application, one would examine the noise spectrum to find the frequency regions with the most energy and then find a hearing protector with adequate *APV* s for those frequency bands so that the resultant overall dB(A) level at the ear would be safe. The method for calculating the *APV* is presented in (Franks et al. 1994).

The long-method calculation of hearing protector noise reduction is probably the most accurate method for rating. Considering that the protector user is wearing the device in the same manner as the listener during the laboratory test (which is not necessarily true), then the most detailed and accurate method is to use the noise floor level in frequency bands together with laboratory test data to calculate the user's exposure level. Table 11.2 gives a numerical example of how to carry-out this calculation.

Table 11.2. Calculated protection for 98% confidence

1- Center frequency octave band (Hz)	125	250	500	1 k	2 k	4 k	8 k	Total dB(A)
2- A-weighting SPL	83.9	93.4	101.8	106.0	102.2	97.0	88.9	109.0
3- Average attenuation	14	19	31	36	37	48*	40**	
4- Standard deviation x 2	10	12	12	14	14	14*	16**	
5- Estimated noise after protection = (step2 - step3 + step4)	79.9	86.4	82.8	84.0	79.2	63.0	64.9	90.3

* Arithmetic average of 3150 and 4000 Hz, ** Arithmetic average of 6300 and 8000 Hz

...

The estimated protection for 98% of the users exposed to the environment levels of step 2, assuming that they wear the protector in the same manner as the listener during the laboratory test, is : **109.0 - 90.3 = 18.7 dB(A)**

11.3.7. Variability of Attenuation Data between Laboratories

Berger et al. (1996), reported the results from a round robin test of eight laboratories' data. The comparison is shown in Figure 11.5 for the *NRR*'s values. These results show great variation between different laboratories in both the average attenuation and the standard deviation, leading to great differences in the *NRR*'s values. Three main factors are responsible for these differences; the fitting , subject selection and training. Even repeatability of results from the same laboratory for the same protector may also vary. That is why the use of two standard deviations when calculating the protection is recommended. Therefore any changes less than 3 to 5 dB(A) in *NRR* should not be considered of any practical importance.

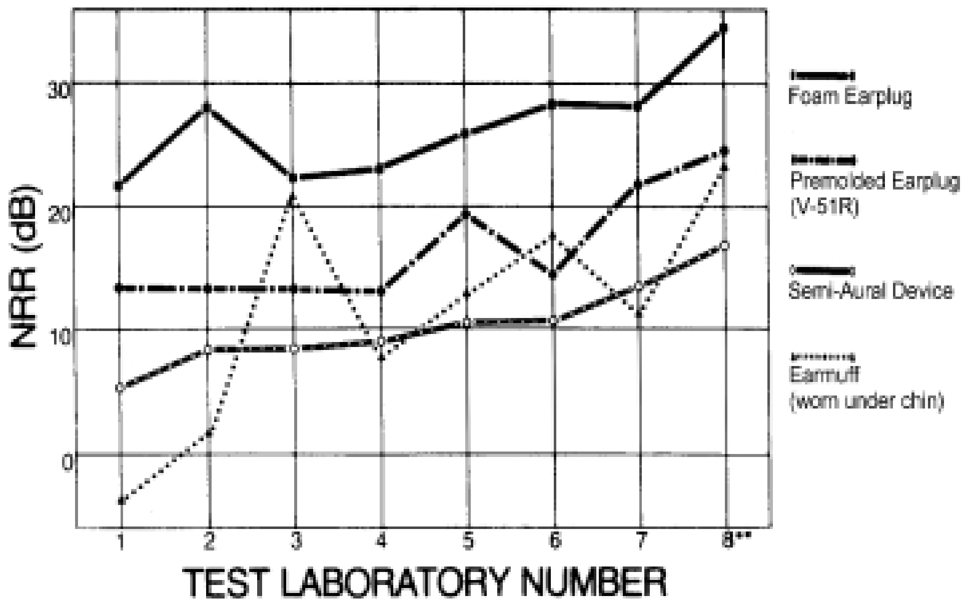


Figure 11.5. Comparison of 8 laboratory results for *NRR* (after Berger et al. 1996)

11.3.8. Head band force and Pressure of muffs

Comfort can be reduced if the head band force increases. However sufficient force is necessary for a close fit of the hearing protector which is in turn needed for the required sound attenuation. Therefore it is necessary to measure the headband force and also to use the measured force for quality control and life assessment. ANSI S3.19 - 1974 shows a mechanical device for head band force measurements. An alternative, and more accurate, mechanical /electric device is shown in Figures 11.6. There is between 2% and 5% variation in the measured force. The maximum mean force acceptable for reasonable comfort must not exceed 12 N. The applied pressure is more important than the headband force for acceptability comfort. Hearing protectors with broad cushions will give less pressure with the same force. Maximum acceptable pressure is about 4000N/m^2.

11.3.9. Simultaneous Use of Double Hearing Protection

Many situations exist where the use of a single protector is not sufficient. In these cases the use of "combined" protection (ear plug + Earmuff) should be considered, however extreme care is required and the performance of the "combination" should be known before use. Tests have shown that the performance of "combination"protection is not the sum of the protectors in use but something in the order of 5 to 15 dB more than the performance of the best of the combination (EN 458).

Berger et al. (1996, page 353) show that at and above 2 kHz most ear plug - plus - muff combinations provided attenuation that was approximately limited by the bone-conduction flanking (see Figure 10.20 in Berger et al. 1996). At frequencies below 2 kHz, it can be shown that the ear plug is the critical element. The extra attenuation gained, varied between 0 and 15 dB for the best of the individual devices. The increase in *NRR* is between 3 and 10 dB when compared with the higher of the two individual protectors.

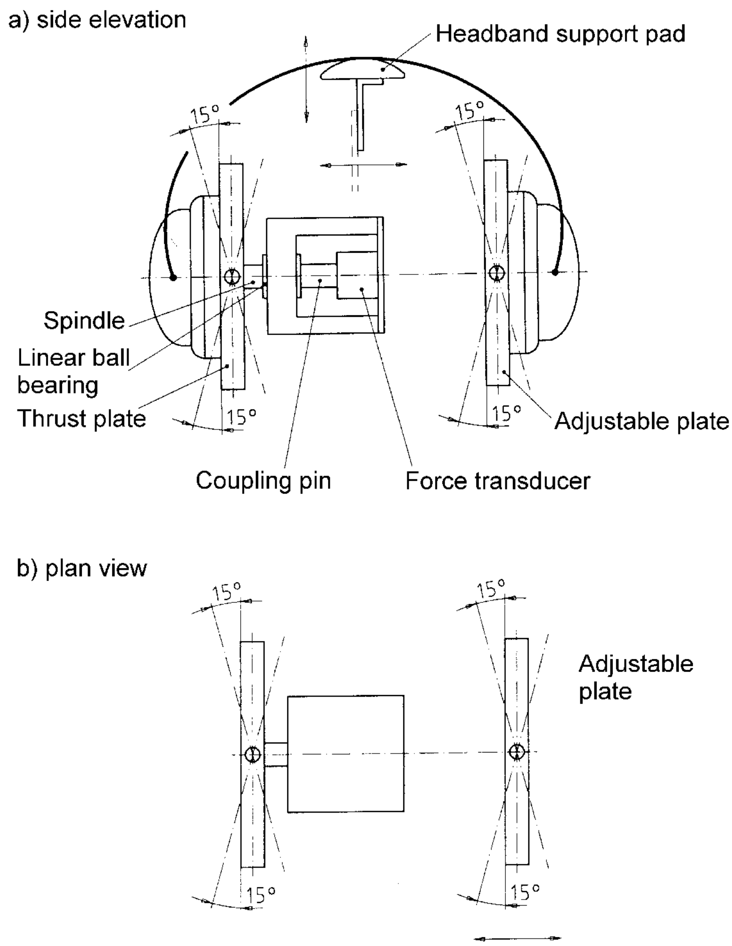


Figure 11.6. Band force measurement system (EN 352, part 1)

NOTE: The pinna simulators shown are fitted to the plates of the fixture so that the holes at the center of the simulators lie on the horizontal axis through the force transducer

11.3.10. Considerations in the Selection and Use of Hearing Protectors (Franks et al. 1994)

Although calculated noise-reduction capabilities are important factors to consider in the selection of hearing protection devices, several other points should also be considered. Studies by Casali (1992) and Riko and Alberti (1982) on the effectiveness of hearing protectors suggest that workers are most likely to demonstrate consistent wearing of devices which are comfortable and quick to insert regardless of the amount of attenuation they provide. Additional thought must be given to the worker's physical limitations including concurrent use of safety glasses or eyeglasses, the need for the worker to hear warning signals, and the need to communicate verbally. The environmental conditions of the workplace, such as temperature, confined working spaces, or the wearing of additional protective devices, also warrant consideration. The durability (shelf life or useful life) and sanitary-hygienic characteristics of each device, as well as the length of time it will be worn, are also factors that should not be overlooked. If custom-molded hearing protectors are to be used, it is important to ensure both the expertise of those who will prepare the impression and of those who will form the final earplug.

In order to ensure that a worker receives the most effective attenuation from the use of a hearing protector the worker should be trained in the use, care and maintenance of the protection. This training should be updated on a regular basis and should be provided by appropriately trained personnel.

Comfort is a personal matter. Ear protectors are generally uncomfortable. Some people find one brand more uncomfortable than the others. Therefore a chance should be given for a choice to be made between different types.

Ear protectors do not offer protection unless they are worn adequately and properly throughout the time of exposure. Small ear plugs or ear muffs with weak springs, may be more comfortable but offer low noise attenuation.

11.3.11. Real World Attenuation (Franks, et al., 1994)

Standard laboratory methods (ANSI S3.19 - 1974, ANSI S12.6 - 1984 and ISO 4869 pt. 1 - 1992) were developed to produce a measurement of attenuation for an "optimum fit" condition. Since the 1970's, researchers in various laboratories around the world (Franks et al. 1994) have been investigating the amount of attenuation workers typically receive. They found workers generally received much less attenuation than the optimum-fit laboratory methods predict. The magnitude of the difference was from 22% to 84% less attenuation for the real-world setting than for the laboratory setting. Researchers at NIOSH have worked with researchers from other laboratories as part of an ANSI working group to develop and test laboratory methods that give measurements of hearing protector attenuation which are more reflective of real-world performance and remain consistent from laboratory to laboratory. The new method, called the NIOSH/ANSI method (Franks et al. 1994) provides very consistent inter-laboratory results, much more consistent than those possible using the methods of ANSI S3.19 - 1974. The method also provides mean attenuations which are much lower than the optimum-fit attenuation and more in accord with real-world results, while maintaining a reasonable standard deviation. At the time of writing, the NIOSH/ANSI method was being prepared as an alternate procedure in a revision of ANSI-S12.6 - 1984.

It is also important that the hearing protector is worn 100% of the time. Figure 11.1 shows the effect of the percentage of time worn on the noise attenuation gained. For example, if a hearing protector has an effective attenuation of 20 dB(A), and it is worn in an ambient noise of 100 dB(A) for 8 hours daily exposure, then the worker will be exposed to 80 dB(A) (simple calculation). If the same hearing protector is not used for 50 minutes out of the 8 hour day, that means 90 % of the time the protector is worn, the worker will be exposed to 92 dB(A), i.e. despite the use of hearing protection there is still the risk of hearing loss. Additional calculations show also that if the worker uses any protector for only 4 hours, then the effective protection will be only 3 dB(A), and the worker will be exposed to a daily average of 97 dB(A) see also EN 458 (1993). Even in case of the 5 dB trading relation given in some regions by statutory rules there will be only 5 dB effective protection and therefore also the risk of hearing loss.

11.3.12. Problems with Hearing Protectors

Comfort, wearability and durability are more important than a few decibels more of attenuation. Provided that the attenuation is reasonable, human factors are more important. Some of the factors which should be considered when hearing protectors are implanted are; hygiene (especially for earplugs), discomfort, effects on communication, effect on directional localization of warning sounds and safety in general.

11.3.13. Costs of Hearing Protectors

The cost of hearing conservation by means of personal hearing protection should consider the following factors:

(1) Initial cost of muffs and/or plugs;
(2) Management and administrative costs of ordering, documentation, stores, issuing, fitting, training, etc.
(3) Replacements of the worn parts;
(4) Education in and encouragement towards the use of hearing protectors, correctly and consistently, using films, talks, posters, audiometry, etc.

These costs can be compared with other methods of engineering noise reduction, say for the period of a 5 or 10 year program.

11.4. REPORTING PROTECTIVE FAILURES

Every employee is responsible of reporting protective failures which include:

* damaged protectors
* changes in maintenance of machinery and equipment because of wear
* any change in noise perception due to moving of machines, altered working methods and work practices.

Responsibility for reporting should be given to the health and safety representatives, to foremen and supervisors and to the management aiming at direct action to be taken or to prioritise the protective failure within the company's noise plans. Reporting protective failures must not affect the worker’s social status in the workplace.

11.5. HEALTH SURVEILLANCE

Health surveillance programmes should be instituted and periodic audiometry upon commencement of work and according to national regulations should be carried out to ensure hearing conservation programmes are effective.

The employer must ensure that audiometric records are retained as confidential. Workers shall have access to their own medical records, either personally or through their own physicians. The results should be used to determine health status with respect to noise exposure and should not be used to discriminate against the worker. Suitable alternative work should be provided to persons with recognised hearing damage.

Records resulting from medical surveillance of workers should be kept for at least 30 years, in a form and by persons designated by the regulatory authority.

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EN 24969 Pt 1, "Sound Attenuation of Hearing Protectors - Part 1 - Subjective methos of measurement"

EN 24869 Pt 2, "Estimation of Effective A-Weighted Sound Level of Hearing Protectors when Worn".

EN 24869 Pt 3, "Measurement of Insertion Loss"

EN 24869 Pt 4, "Measurement of the Sound Attenuation of Amplitude Sensitive Muffs"-

EN 352 Pt 1, "Hearing Protectors - Safety Requirements & Testing" - Part 1 : Ear Muffs.

EN 352 Pt 2, "Hearing Protectors - Safety Requirements & Testing - Part 2 : Ear Plugs".

EN 352 Pt 3, "Hearing Protectors - Safety Requirements & Testing - Part 3 : Helmet Mounted Muffs".

EN 352 Pt 4, "Hearing Protectors - Safety Requirements & Testing - Part 4 : Level Dependent Ear Muffs".

EN 458, "Hearing Protectors - Recommendation for the selection, Use, Care and Maintenance - Guidance Document".

Franks J.R., Themann C.R. and Sherris C. (1994). *The NIOSH Compendium of Hearing Protection Devices*. U.S. Department of Health and Human Services, Public Health Service, Centres for Disease Control and Prevention,

Johnson, D.L. and Nixon, C.W. (1974). Simplified Methods for Estimating Hearing Protector Performance. Sound and Vibration, 8(6):20-27.

Kroes P., Fleming, R., and Lempert, B. (1975). List of Personal Hearing Protectors and Attenuation Data, NIOSH Technical Report, HEW Publication No. (NIOSH) 76-120.

INTERNATIONAL STANDARDS

Titles of the following standards referred to in this chapter one will find together with information on availability in chapter 12:

ISO 4869-1, -2;

Other relevant standards included in the list of general references, see above

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SOURCES OF INFORMATION

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12.1. INTRODUCTION

This chapter contains a listing of relevant International (ISO & IEC) standards,. Home pages on the internet which contain important noise control information are also listed. The chapter concludes with collections of noise control case studies**,** handbooks and periodicals.

ISO or IEC standards are available in all countries from the national member bodies. Where there is an equivalent national standard, the member body concerned will probably say so when asked to supply the ISO or IEC standard.
European or EN standards have been adopted generally as national standards of the member bodies of the European Union and the European Free Trade Association. A great deal of these EN standards are equivalent to ISO or IEC standards. But a group of EN standards concerning safety of machinery and containing clauses on noise or EN standards which are noise test codes for specific machines have an international counterpart only in exceptional cases. From outside Europe one will get these EN standards from the standards organisations CEN or CENELEC.
There are other regional standard organisations shown in the ISO internet homepage.

Numbers in { } give the corresponding chapter.

12.2. STANDARDS OF THE INTERNATIONAL ORGANIZATION FOR STANDARDIZATION *(partly updated January/February 2001)*

ISO 31-7:1992 Quantities and units -- Part 7: Acoustics ***{ 1 }***
(Will be revised as ISO 80000-8)

ISO/TR 140-13:1997 Acoustics -- Measurement of sound insulation in buildings and of building elements -- Part 13: Guidelines ***{ 10 }***
This part of ISO 140 may be used as an introduction to definitions and measurement procedures which are described in the preceding twelve parts.

ISO 226:1987 Acoustics -- Normal equal-loudness level contours ***{ 1 }***

ISO 266:1997 Acoustics -- Preferred frequencies ***{ 1 }***

ISO 230-5:2000 Test code for machine tools -- Part 5: Determination of the noise emission ***{ 5, 10 }***

ISO 389-1:1998 Acoustics – Reference zero for the calibration of audiometric equipment -- Part 1: Reference equivalent threshold sound pressure levels for pure tones and supra-aural earphones ***{ 8 }***

ISO 389-2:1994 Acoustics -- Reference zero for the calibration of audiometric equipent --Part 2: Reference equivalent threshold sound pressure levels for pure tones and insert earphones ***{ 8 }***

ISO 389-3:1994 Acoustics -- Reference zero for the calibration of audiometric equipment --Part 3: Reference equivalent threshold force levels for pure tones and bone vibrators ***{ 8 }***

ISO 389-4:1994 Acoustics -- Reference zero for the calibration of audiometric equipment --Part 4: Reference levels for narrow-band masking noise ***{ 8 }***

ISO/TR 389-5:1998 Acoustics -- Reference zero for the calibration of audiometric equipment -- Part 5: Reference equivalent threshold sound pressure levels for pure tones in the frequency range 8 kHz to 16 kHz ***{ 8 }***

ISO 389-7:1996 Acoustics -- Reference zero for the calibration of audiometric equipment --Part 7: Reference threshold of hearing under free-field and diffuse-field listening conditions ***{ 8 }***

ISO 532:1975 Acoustics -- Method for calculating loudness level ***{ 1 }***

ISO 1680: 1999 Acoustics -- Test code for the measurement of airborne noise emitted by rotating electrical machinery (Revision of ISO 1680-1:1986 and ISO 1680-2:1986) ***{ 5, 10 }***

ISO 1683:1983 Acoustics -- Preferred reference quantities for acoustic levels ***{ 1 }***

ISO 1999:1990 Acoustics -- Determination of occupational noise exposure and estimation of noise-induced hearing impairment ***{ 4 }***

ISO 2151:1972 Measurement of airborne noise emitted by compressor/primemover-units intended for outdoor use. ***{ 5, 10 }***

ISO 2533:1975 Standard Atmosphere ***{ 1 }***

ISO 2923:1996 Acoustics -- Measurement of noise on board vessels ***{ 5, 10 }***

ISO/TR 3352:1974 Acoustics -- Assessment of noise with respect to its effect on the intelligibility of speech ***{ 4 }***

ISO 3381:1976 Acoustics -- Measurement of noise inside railbound vehicles ***{ 5, 10 }***

ISO 3382:1997 Acoustics -- Measurement of the reverberation time of rooms with reference to other acoustical parameters ***{ 1 }***

ISO 3740:2000 Acoustics -- Determination of sound power levels of noise sources --Guidelines for the use of basic standards and for the preparation of noise test codes ***{ 5, 10 }***

ISO 3741:1999 Acoustics -- Determination of sound power levels of noise sources using sound pressure --Precision methods for reverberation rooms ***{ 5, 10 }***

ISO 3743-1:1994 Acoustics -- Determination of sound power levels of noise sources -- Engineering methods for small, movable sources in reverberant fields -- Part 1: Comparison method for hard-walled test rooms ***{ 5, 10 }***

ISO 3743-2:1994 Acoustics -- Determination of sound power levels of noise sources using sound pressure -- Engineering methods for small, movable sources in reverberant fields --Part 2: Methods for special reverberation test rooms ***{ 5, 10 }***

ISO 3744:1994 Acoustics -- Determination of sound power levels of noise sources using sound pressure -- Engineering method in an essentially free field over a reflecting plane ***{ 5, 10 }***

ISO/DIS 3745 Acoustics -- Determination of sound power levels of noise sources using sound pressure --Precision methods for anechoic and hemi-anechoic rooms ***{ 5, 10 }***

ISO 3746:1995 Acoustics -- Determination of sound power levels of noise sources using sound pressure -- Survey method using an enveloping measurement surface over a reflecting plane ***{ 5, 10 }***

ISO 3747:2000 Acoustics -- Determination of sound power levels of noise sources using sound pressure –Comparison method in situ ***{ 5, 10 }***

ISO 4412-1:1991 Hydraulic fluid power -- Test code for determination of airborne noise levels -- Part 1: Pumps ***{ 5, 10 }***

ISO 4412-2:1991 Hydraulic fluid power -- Test code for determination of airborne noise levels -- Part 2: Motors ***{ 5, 10 }***

ISO 4412-3:1991 Hydraulic fluid power -- Test code for determination of airborne noise levels -- Part 3: Pumps -- Method using a parallelepiped microphone array ***{ 5, 10 }***

ISO 4869-1:1990 Acoustics -- Hearing protectors -- Part 1: Subjective method for the measurement of sound attenuation ***{ 11 }***

ISO 4869-2:1994 Acoustics -- Hearing protectors -- Part 2: Estimation of effective A-weighted sound pressure levels when hearing protectors are worn ***{ 11 }***

ISO/TR 4869-3:1989 Acoustics -- Hearing protectors -- Part 3: Simplified method for the measurement of insertion loss of ear-muff type protectors for quality inspection purposes ***{ 11 }***

ISO/TR 4869-4:1998 Acoustics -- Hearing protectors -- Part 4: Measurement of effective sound pressure levels for level-dependent sound restoration ear-muffs ***{ 11 }***

ISO/TR 4870:1991 Acoustics -- The construction and calibration of speech intelligibility tests ***{ 4 }***

ISO 4871:1996 Acoustics -- Declaration and verification of noise emission values of machinery and equipment ***{ 5, 10 }***

ISO 4872:1978 Acoustics -- Measurement of airborne noise emitted by construction equipment intended for outdoor use -- Method for determining compliance with noise limits ***{ 5, 10 }***

ISO 5128:1980 Acoustics -- Measurement of noise inside motor vehicles ***{ 5, 10 }***

ISO /DIS 5129 Acoustics -- Measurement sound pressure levels in the interior of aircraft during flight ***{ 5, 10 }***

ISO 5131:1996 Acoustics -- Tractors and machinery for agriculture and forestry --Measurement of noise at the operator's position -- Survey method ***{ 5, 10 }***

ISO 5135:1997 Acoustics -- Determination of sound power levels of noise from air-terminal devices, air-terminal units, dampers and valves by measurement in a reverberation room ***{ 5, 10 }***

ISO /DIS 5136 Acoustics -- Determination of sound power radiated into a duct by fans and other air-moving devices --In-duct method ***{ 5, 10 }***

ISO 6189:1983 Acoustics -- Pure tone air conduction threshold audiometry for hearing conservation purposes ***{ 11 }***

ISO 6393:1998 Acoustics -- Measurement of exterior noise emitted by earth-moving machinery -- Stationary test condition ***{ 5, 10 }***

ISO 6394:1998 Acoustics -- Measurement at the operator's position of noise emitted by earth-moving machinery -- Stationary test conditions ***{ 5, 10 }***

ISO 6395:1988 Acoustics -- Measurement of exterior noise emitted by earth-moving machinery -- Dynamic test conditions ***{ 5, 10 }***

ISO 6396:1992 Acoustics -- Measurement at the operator's position of noise emitted by earth-moving machinery -- Dynamic test conditions ***{ 5, 10 }***

ISO 6798:1995 Reciprocating internal combustion engines -- Measurement of emitted airborne noise -- Engineering method and survey method. ***{ 5, 10 }***

ISO 6926:1999 Acoustics -- --Requirements for the performance and calibration of reference sound sources used for the determination of sound power levels ***{ 5, 10 }***

ISO/FDIS 7029 Acoustics -- Statistical distribution of hearing thresholds as a function of age ***{ 11 }***

ISO 7182:1984 Acoustics -- Measurement at the operator's position of airborne noise emitted by chain saws ***{ 5, 10 }***

ISO 7196:1995 Acoustics -- Frequency-weighting characteristic for infrasound measurements ***{ 4 }***

ISO 7216:1992 Acoustics -- Agricultural and forestry wheeled tractors and self-propelled machines -- Measurement of noise emitted when in motion ***{ 5, 10 }***

ISO 7235:1991 Acoustics -- Measurement procedures for ducted silencers -- Insertion loss, flow noise and total pressure loss ***{ 5, 10 }***

ISO 7574-1:1985 Acoustics -- Statistical methods for determining and verifying stated noise emission values of machinery and equipment -- Part 1: General considerations and definitions ***{ 5 }***

ISO 7779:1999 Acoustics -- Measurement of airborne noise emitted by information technology and telecommunications equipment ***{ 5, 10 }***

ISO 7917:1987 Acoustics -- Measurement at the operator's position of airborne noise emitted by brush saws ***{ 5, 10 }***

ISO 7960:1995 Airborne noise emitted by machine tools -- Operating conditions for woodworking machines ***{ 5,10 }***

ISO 8201:1987 Acoustics -- Audible emergency evacuation signal ***{ 4 }***

ISO 8253-1:1989 Acoustics -- Audiometric test methods -- Part 1: Basic pure tone air and bone conduction threshold audiometry ***{ 8 }***

ISO 8253-2:1992 Acoustics -- Audiometric test methods -- Part 2: Sound field audiometry with pure tone and narrow-band test signals ***{ 8 }***

ISO 8253-3:1996 Acoustics -- Audiometric test methods -- Part 3: Speech audiometry ***{ 8 }***

ISO/DIS 8500 Airborne noise emitted by machine tools -- Operating conditions for mechanical presses up to 2500 kN ***{ 5, 10 }***

ISO 8528-10:1998 Reciprocating internal combustion engine driven alternating current generating sets -- Part 10: Measurement of airborne noise by the enveloping surface method. ***{ 5, 10 }***

ISO/DIS 8579-1 Acceptance code for gear units -- Part 1:Test code for airborne sound ***{5, 10 }***

ISO 9207:1995 Manually portable chain-saws with internal combustion engine --Determination of sound power levels -- Engineering method (grade 2) ***{ 5, 10 }***

ISO 9295:1988 Acoustics -- Measurement of high-frequency noise emitted by computer and business equipment ***{ 5, 10 }***

ISO 9296:1988 Acoustics -- Declared noise emission values of computer and business equipment ***{ 5, 10 }***

ISO 9568:1993 Cinematography -- Background acoustic noise levels in theatres, review rooms and dubbing rooms ***{ 4 }***

ISO 9611:1996 Acoustics -- Characterization of sources of structure-borne sound with respect to sound radiation from connected structures -- Measurement of velocity at the contact points of machinery when resiliently mounted ***{ 5, 10 }***

ISO 9612:1997 Acoustics -- Guidelines for the measurement and assessment of exposure to noise in a working environment ***{ 4 }***

ISO 9613-2:1996 Acoustics -- Attenuation of sound during propagation outdoors -- Part 2: General method of calculation ***{ 10 }***

ISO 9614-1:1993 Acoustics -- Determination of sound power levels of noise sources using sound intensity -- Part 1: Measurement at discrete points ***{ 5, 10 }***

ISO 9614-2:1996 Acoustics -- Determination of sound power levels of noise sources using sound intensity -- Part 2: Measurement by scanning ***{ 5, 10 }***

ISO 9902:1993 Textile machinery acoustics -- Determination of sound pressure levels and sound power levels emitted by textile machines -- Engineering and survey methods ***{ 5, 10 }***
Parts 1 to 7 are now DISs

ISO 9921-1:1996 Ergonomic assessment of speech communication -- Part 1: Speech interference level and communication distances for persons with normal hearing capacity in direct communication (SIL method). ***{ 4 }***

ISO 10053:1991 Acoustics -- Measurement of office screen sound attenuation under specific laboratory conditions ***{ 5, 10 }***

ISO 10302:1996 Acoustics -- Method for the measurement of airborne noise emitted by small air-moving devices ***{ 5, 10 }***

ISO/DIS 10449 Hearing protectors -- Safety requirements and testing -- Ear-muffs. ***{ 11 }***

ISO/DIS 10452 Hearing protectors -- Recommendations for selection, use, care and maintenance -- Guidance document. ***{ 11 }***

ISO/DIS 10453 Hearing protectors -- Safety requirements and testing -- Ear-plugs. ***{ 11 }***

ISO 10494:1993 Gas turbines and gas turbine sets -- Measurement of emitted airborne noise-- Engineering/survey method ***{ 5, 10 }***

ISO 10534-1:1996 Acoustics -- Determination of sound absorption coefficient and impedance in impedance tubes -- Part 1: Method using standing wave ratio ***{ 5 }***

ISO 10534-2:1998 Acoustics - Determination of sound absorption coefficient and impedance in impedance tubes -- Part 2: Transfer-function method ***{ 5 }***

ISO 10843:1997 Acoustics -- Methods for the description and physical measurement of single impulses or series of impulses ***{ 4, 5 }***

ISO 10846-1:1997 Acoustics and vibration -- Laboratory measurement of vibro-acoustic transfer properties of resilient elements -- Part 1: Principles and guidelines ***{ 10 }***

ISO 10846-2:1997 Acoustics and vibration -- Laboratory measurement of vibro-acoustic transfer properties of resilient elements -- Part 2: Dynamic stiffness of elastic supports for translatory motion -- Direct method ***{ 10 }***

ISO/DIS 10846-3 Acoustics and vibration -- Laboratory measurement of vibro-acoustic transfer properties of resilient elements -- Part 3: Dynamic stiffness of elastic supports for translatory motion -- Indirect method ***{ 10 }***

ISO 10847:1997 Acoustics -- In-situ determination of insertion loss of outdoor noise barriers of all types ***{ 10 }***

ISO 10996:1999 Photography -- Still-picture projectors -- Determination of noise emissions. ***{ 10 }***

ISO 11094:1991 Acoustics -- Test code for the measurement of airborne noise emitted by power lawn mowers, lawn tractors, lawn and garden tractors, professional mowers, and lawn and garden tractors with mowing attachments ***{ 5, 10 }***

ISO 11200:1995 Acoustics -- Noise emitted by machinery and equipment -- Guidelines for the use of basic standards for the determination of emission sound pressure levels at a work station and at other specified positions ***{ 5, 10 }***

ISO 11201:1995 Acoustics -- Noise emitted by machinery and equipment -- Measurement of emission sound pressure levels at a work station and at other specified positions --Engineering method in an essentially free field over a reflecting plane ***{ 5, 10 }***

ISO 11202:1995 Acoustics -- Noise emitted by machinery and equipment -- Measurement of emission sound pressure levels at a work station and at other specified positions -- Survey method in situ ***{ 5, 10 }***

ISO 11203:1995 Acoustics -- Noise emitted by machinery and equipment -- Determination of emission sound pressure levels at a work station and at other specified positions from the sound power level ***{ 5, 10 }***

ISO 11204:1995 Acoustics -- Noise emitted by machinery and equipment -- Measurement of emission sound pressure levels at a work station and at other specified positions -- Method requiring environmental corrections ***{ 5, 10 }***

ISO/DIS 11205 Acoustics -- Noise emitted by machinery and equipment -- Dtermination of emission sound pressure levels using sound intensity ***{ 5, 10 }***

ISO 11546-1:1995 Acoustics -- Determination of sound insulation performances of enclosures -- Part 1: Measurements under laboratory conditions (for declaration purposes) ***{ 5, 10 }***

ISO 11546-2:1995 Acoustics -- Determination of sound insulation performances of enclosures -- Part 2: Measurements in situ (for acceptance and verification purposes) ***{ 5, 10 }***

ISO 11654:1997 Acoustics -- Sound absorbers for use in buildings -- Rating of sound absorption ***{ 10 }***

ISO/TR 11688-1:1995 Acoustics -- Recommended practice for the design of low-noise machinery and equipment -- Part 1: Planning ***{ 5, 10 }***

ISO/TR 11688-2:1998 Acoustics -- Recommended practice for the design of low-noise machinery and equipment -- Part 2: Introduction to the physics of low-noise design ***{ 5, 10 }***

ISO 11689:1996 Acoustics -- Procedure for the comparison of noise-emission data for machinery and equipment ***{ 5, 10 }***

ISO 11690-1:1996 Acoustics -- Recommended practice for the design of low-noise workplaces containing machinery -- Part 1: Noise control strategies ***{ 5, 7, 10 }***

ISO 11690-2:1996 Acoustics -- Recommended practice for the design of low-noise workplaces containing machinery -- Part 2: Noise control measures ***{ 5, 7, 10 }***

ISO/TR 11690-3:1997 Acoustics -- Recommended practice for the design of low-noise workplaces containing machinery -- Part 3: Sound propagation and noise prediction in workrooms ***{ 5, 7, 10 }***

ISO 11691:1995 Acoustics -- Measurement of insertion loss of ducted silencers without flow-- Laboratory survey method ***{ 5, 10 }***

ISO 11820:1996 Acoustics -- Measurements on silencers in situ ***{ 5, 10 }***

ISO 11821:1997 Acoustics -- Measurement of the in situ sound attenuation of a removable screen ***{ 5, 10 }***

ISO 11957:1996 Acoustics -- Determination of sound insulation performance of cabins -- Laboratory and in situ measurements ***{ 5, 10 }***

ISO 12001:1996 Acoustics -- Noise emitted by machinery and equipment -- Rules for the drafting and presentation of a noise test code ***{ 1 }***

ISO 13261-1:1998 Sound power rating of air-conditioning and air-source heat pump equipment -- Part 1: Non-ducted outdoor equipment. ***{ 5, 10 }***

ISO 13261-2 :1998 Sound power rating of air-conditioning and air-source heat pump equipment -- Part 2: Non-ducted indoor equipment. ***{ 5, 10 }***

ISO/FDIS 13332 Reciprocating internal combustion engines -- Test code for the measurement of structure-borne noise emitted from high-speed and medium-speed reciprocating internal combustion engines measured at the engine feet. ***{ 5, 10 }***

ISO 13475-1:1999 Acoustics -- Stationary audible warning devices used outdoors -- Part 1: Field measurements for determination of sound emission quantities ***{ 4 }***

ISO 14163:1998 Acoustics -- Guidelines for noise control by silencers ***{ 5, 10 }***

ISO /DIS 14257 Acoustics -- Measurement and modelling of spatial sound distribution curves in workrooms for evaluation of their acoustical performance ***{ 10 }***

ISO 15667 :2000 Acoustics -- Guidelines for noise control by enclosures and cabins ***{5, 10}***

12.3. INTERNATIONAL ELECTROTECHNICAL COMMISSION STANDARDS

IEC 60034-9(1997-07). Rotating electrical machines - Part 9: Noise limits. ***{ 5, 10 }***

IEC 60050-801(1994-08). International Electrotechnical Vocabulary - Chapter 801: Acoustics and electroacoustics. ***{ 1 }***

IEC 60303(1970-01). IEC provisional reference coupler for the calibration of earphones used in audiometry. ***{ 8 }***

IEC 60318(1970-01). An IEC artificial ear, of the wide band type, for the calibration of earphones used in audiometry. ***{ 8 }***

IEC 60534-8-1(1986-09). Industrial-process control valves. Part 8: Noise considerations. Section One: Laboratory measurement of noise generated by aerodynamic flow through control valves. ***{ 5, 10 }***

IEC 60534-8-2(1991-05). Industrial-process control valves - Part 8: Noise considerations - Section 2: Laboratory measurement of noise generated by hydrodynamic flow through control valves ***{ 5, 10 }***

IEC 60534-8-3(1995-08). Industrial-process control valves - Part 8: Noise considerations - Section 3: Control valve aerodynamic noise prediction method. ***{ 5, 10 }***

IEC 60534-8-4(1994-05). Industrial-process control valves - Part 8: Noise considerations - Section 4: Prediction of noise generated by hydrodynamic flow. ***{ 5, 10 }***

IEC 60551(1987-12). Determination of transformer and reactor sound levels. ***{ 5, 10 }***

IEC 60645-1(1992-10). Audiometers - Part 1: Pure-tone audiometers. ***{ 8 }***

IEC 60645-2(1993-11). Audiometers - Part 2: Equipment for speech audiometry. ***{ 8 }***

IEC 60645-3(1994-10). Audiometers - Part 3: Auditory test signals of short duration for audiometric and neuro-otological purposes. ***{ 8 }***

IEC 60645-4(1994-10). Audiometers - Part 4: Equipment for extended high-frequency audiometry. ***{ 8 }***

IEC 60651 - 1979. Sound Level Meters. ***{ 6 }***

IEC 60704-1(1997-03). Household and similar electrical appliances - Test code for the determination of airborne acoustical noise - Part 1: General requirements. ***{ 5, 10 }***

IEC 60804 - 1985. Integrating averaging sound level meters. ***{ 6 }***

IEC 60942(1997-11). Electroacoustics - Sound calibrators. ***{ 6 }***

IEC 61012 - 199x. Filters for the measurement of audible sound in the presence of ultrasound. ***{ 6 }***

IEC 61043(1993-11). Electroacoustics - Instruments for the measurement of sound intensity - Measurements with pairs of pressure sensing microphones. ***{ 6 }***

IEC 61063(1991-04). Acoustics - Measurement of airborne noise emitted by steam turbines and driven achinery. ***{ 5, 10 }***

IEC 61183(1994-06). Electroacoustics - Random-incidence and diffuse-field calibration of sound level meters. ***{ 6 }***

IEC 61252(1993-06). Electroacoustics - Specifications for personal sound exposure meters ***{ 4, 6, 7 }***

IEC 61260(1995-08). Electroacoustics - Octave-band and fractional-octave-band filters. ***{ 6 }***

IEC 61027(1991-04). Instruments for the measurement of aural acoustic impedance/admittance. ***{ 8 }***

IEC 61063(1991-04). Acoustics - Measurement of airborne noise emitted by steam turbines and driven machinery. ***{ 5, 10 }***

12.4. INTERNET SITES FOR MORE INFORMATION

(updated January 2001)

ACGIH American Conference of Governmental Industrial Hygienists, USA: **http://www.acgih.org**

CCOHS Canadian Centre for Occupational Health and Safety: **http://www.ccohs.ca**
Bilingual English/French

FIOH Finnish Institute for Occupational Health: **http://www.occuphealth.fi/e/**
Trilingual English/Finnish/Swedish

FIOSH Federal Institute for Occupational Safety and Health, Germany: **http://www.baua.de**
Partly bilingual English/German

HSE Health and Safety Executive, UK: **http://www.open.gov.uk/hse/hsehome.htm**

I-INCE International Institute of Noise Control Engineering: **http://users.aol.com/iince1/**

INRS Institut National de Recherche et de Securité, France: **http://www.inrs.fr/**
partly bilingual English/French

NIOSH, National Institute for Occupational Safety and Health, USA:
http://www.cdc.gov/niosh/

OSHA Occupational Safety and Health Administration , USA: **http://www.osha.gov**

WHO World Health Organization, Geneva: **http://www.who.int/peh/noise/**
partly bilingual English/French

Standards

IEC International Electrotechnical Commission: **http://www.iec.ch**

ISO International Organization for Standardization: **http://www.iso.ch**

WSSN World Standards Services Network: **http://www.wssn.net/WSSN/script-cache/links**
Links to national and regional standards institutions, e.g. ANSI; CEN; CENELEC.

12.5. COLLECTIONS OF CASE STUDIES
(updated January 2001)

CCOHS, Canadian Centre for Occupational Health and Safety (ed.) (Updated quarterly). *Noise Levels Database*. Available on *OSH CanData CD-ROM* , CCOHS Client Services, Hamilton,Ontario, Canada Examples on the website (see section 12.4.)

FIOH Finnish Institute for Occupational Health, Finland (ed.) (1999). Noise emission data of electrical hand held power tools. Available on website:
http://www.occuphealth.fi/e/dept/u/spteam/tools/en_cont.htm

HSE, Health and Safety Executive,UK (ed.) (1995). *Sound solutions: Techniques to reduce noise at work.* Guidance HSG138, HSE Information Services, Merseyside,UK (see section 12.4.).

HSE (ed.) (1995). *Noise control at foundry shakeouts.* Specific Guidance (unnumbered), HSE Information Services, Merseyside,UK.

HSE (ed.) (1998). *Control of noise at metal cutting saws.* Specific Guidance EIS27, HSE Information Services, Merseyside,UK.

HSE (ed.) (1998). *Control of noise at power presses.* Specific Guidance EIS29, HSE Information Services, Merseyside,UK.

HSE (ed.) (1993). *Control of noise in quarries.* Specific Guidance HSG109, HSE Information Services, Merseyside,UK.

HSE (ed.) (1990). *Noise control in the rubber industry.* Specific Guidance (unnumbered), HSE Information Services, Merseyside,UK.

Ingemansson, Stig: *Noise control - principles and practice*.
This book , first published in Swedish by Arbetarskyddsfonden, the Swedish Work Environment Fund was translated in different languages and disseminated as a guide for workers and employers by the U.S. Department of Labor. It has been checked and improved by the author and edited with William W.Lang in *Noise/News International* (*NNI*) beginning with Vol. 2. No. 2, 1994 June. The outstanding illustrations should assist engineers in explaining to others the fundamental principles of noise control. An overwiew was given in *NNI* Vol. **7**, No. X, 1999, June.

Kurze, U.J. et al (1992). *Noise reduction at the workplace (III).* (in German) Research applications Fa14, 2nd ed. FIOSH Federal Institute for Occupational Safety and Health, Berlin/Dortmund (see section 12.4.).

NIOSH, National Institute for Occupational Safety and Health, USA (ed.) (1975). *Industrial noise control manual*. Download as pdf-document from website (see section 12.4.), with collection of case studies.

Schmidt, K.-P.(1992). *Noise reduction at the workplace (IV).* (in German) Research applications Fa15, 2nd ed. FIOSH Federal Institute for Occupational Safety and Health, Berlin/Dortmund (see section 12.4.).

12.6. HANDBOOKS

(updated January 2001)

AIHA Noise Committee; Berger, E.H. et al.(ed.) (1986). *Industrial Noise Manual*. American Industrial Hygiene Association, 4th edition,AIHA Press,Fairfax, VA.

Barber, A. (1992). *Handbook of noise and vibration control*, 6th edition. Elsevier, Oxford.

Beranek, L.L. (1988) (ed.) *Noise and Vibration Control*, Revised edition. Institute of Noise Control Engineering, Washington, DC.

Beranek, L.L. & Ver, I.L. (eds.) (1992). *Noise and vibration control engineering*. McGraw Hill, New York.

Bies, D.A. and Hansen, C.H. (1996). *Engineering noise control*. 2nd edition, E & FN Spon, London.

Crocker (Ed.) (1998). *Handbook of acoustics*. Publication 99-010, ACGIH, Cincinnati,Ohio (see section 12.4.)

Harris, C.M. (1991) (ed.) *Handbook of Acoustical Measurements and Noise Control*. 3rd ed.., McGraw-Hill Book Co., New York. Reprint in 1997 by ASA, Acoustical Society of America.

ISO (Ed.) (1995). *Acoustics - Vol.1: General aspects of acoustics; methods of noise measurement in general; noise with respect to human beings*. ISO, Geneva (see section 12.4.)

ISO (Ed.) (1995). *Acoustics - Vol.2*: *Noise emitted by vehicles; noise emitted by specific machines and equipment; acoustics in building*. ISO, Geneva (see section 12.4.)

NIOSH (1978). *Industrial Noise Control Manual*. DHHS(NIOSH) Publication No. 79-117, Cincinnati, Ohio (as pdf-document online see section 12.4.).

NIOSH (1996). *Preventing occupational hearing loss - A practical guide*.DHHS(NIOSH) Publication No.96-110, Cincinnati, Ohio (as pdf-document online see section 12.4.).

Probst, W. (1995). *Noise abatement products - components and systems for absorption and insulation of sound*.(in German, partly trilingual German, English, French) Edited by FIOSH Federal Institute for Occupational Safety and Health, Berlin/Dortmund, TÜV-Verlag,Cologne.

Schaffer, M.E. (1993). *Practical Guide to Noise and Vibration Control for HVAC Systems (SI).* ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.(see website: **http://www.ashrae.org**)

Sound Research Laboratories (1991). *Noise control in industry*. E&FN Spon, London.

Suter, A.H. (Chapter Editor) (1998). *Noise*. In: ILO Encyclopaedia of Occupational Health and Safety,4th edition, wholly rearranged and revised in print, on CD-ROM and online, ILO International Labour Organization, Geneva.(see website in English, French & Spanish: **http://www.ilo.org/public/english/support/publ/**)

12.7. PERIODICALS

NOISE CONTROL ENGINEERING JOURNAL, bi-monthly, peer reviewed, published by INCE/USA Institute of Noise Control Engineering of the USA, Saddle River, NJ, (see website: **http://users.aol.com/ncejcost.html**)

NOISE AND HEALTH, quarterly, Editor-in-Chief Deepak Prasher, NRN Publications, London (see website: **http://www.ucl.ac.uk/noiseandhealth/**)

NOISE/NEWS INTERNATIONAL (NNI), quarterly, news magazine with internet supplement, published by I-INCE and INCE/USA, Saddle River, NJ, (see website: **http://users.aol.com/noisenewsi/nni.html**)

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