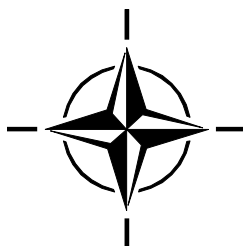AC/323(HFM-147)TP/337

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RTO TECHNICAL REPORT   **TR-HFM-147**

Hearing Protection –
Needs, Technologies and Performance

(Protection de l'ouïe –
Besoins, technologies et résultats)

This report has been prepared as a result of collaborations on
advanced hearing protection by Task Group HFM-147.

Published November 2010

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The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT   Applied Vehicle Technology Panel
- HFM   Human Factors and Medicine Panel
- IST   Information Systems Technology Panel
- NMSG   NATO Modelling and Simulation Group
- SAS   System Analysis and Studies Panel
- SCI   Systems Concepts and Integration Panel
- SET   Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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List of Acronyms

A/B or AB	Afterburner Power
AHAAH	Auditory Hazard Assessment Algorithm for the Human
AHUs	Auditory Hazard Units
ANR	Active Noise Reduction
APC	Armoured Personnel Carrier
ATF	Acoustic Test Fixture
BC	Bone Conduction
BFD	Battle Field Day
BFM	Battle Field Mission
CHABA	Committee on Hearing, Acoustics, and Bio-Acoustics
CHPPM	Centre for Health Promotion and Preventative Medicine
COTS	Commercial-Off-The-Shelf
dB	Decibel
DRC	Damage Risk Criteria
EAC	External Auditory Canal
ECS	Environmental Control System
EMI	Electro Magnetic Interference
EU	European Union
HFM	Human Factors and Medicine
HPD	Hearing Protection Device
ISL	Institute St. Louis
ISO	International Organisation for Standardisation
JCA	Joint Combat Aircraft
JSF	Joint Strike Fighter
MIRE	Microphone In Real Ear
MOD	Ministry Of Defence
NATO	North Atlantic Treaty Organisation
NIHL	Noise Induced Hearing Loss
NIOSH	National Institute for Occupational Safety and Health
NIPTS	Noise Induced Permanent Threshold Shift
PPE	Personal Protective Equipment
REAT	Real Ear Attenuation at Threshold
RFI	Radio Frequency Interference
RSG	Research Study Group
RTO	Research and Technology Organisation
SPL	Sound Pressure Level
TTS	Temporary Threshold Shift
TWA	Time Weighted Average
w-CEP	Wireless Communication Earplug

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Hearing Protection –
Needs, Technologies and Performance
(RTO-TR-HFM-147)

Executive Summary

Noise-induced hearing loss is a common and significant problem among member nations. Over the decades, the levels of noise in military environments have steadily increased and new vehicle and weapon types are often noisier than the ones they replace. There is also a heightened awareness of the hearing damage risk associated with exposure to high levels of noise and, as a consequence, the maximum noise exposure limits set by (inter)national standards and legislation has become more stringent. Hence, it is becoming increasingly difficult to adequately protect military personnel for the duty durations required to meet operational needs.

In recent years an improved scientific understanding of sound transmission paths including air, bone and tissue conducted noise have lead to new and improved hearing protection, communication and situation awareness technologies. The HFM-147 Task Group was formed in April 2005 to investigate advanced personal hearing protection technology and to address applications where adequate protection is currently unavailable. The aim of this report is to provide information that will support users of hearing protection and those in the business of hearing-protector acquisition or requirements in identifying the most suitable hearing protection for a specific application or role.

A detailed review has been conducted of the noise exposure criteria and damage risk criteria used across the different nations, and the types and levels of vehicle and weapon noise that may be experienced in a range of different operational environments. This information may be used in combination to predict the level of hearing damage risk specific operators may be exposed to and, consequently, the level of hearing protection required for compliance with exposure criteria. A comprehensive review of commercially available and near-term hearing protection technologies has been conducted and an overview has been provided of suitable laboratory and field evaluation test techniques that may be used to assess attenuation performance. However, when choosing a new hearing protection device to bring operator noise dose in line with noise exposure criteria there are many factors, other than the absolute level of attenuation a device affords, that will influence the procurement decision making process. A review of parameters, including; education, training, comfort, compatibility with other equipment, size, weight and price has been provided and their influence in the procurement process has been discussed.

A good understanding now exists of the mechanisms of noise protection and the parameters that influence it. However, noise legislation is becoming more stringent and noise environments are becoming harsher. As a consequence, new hearing protection devices that provide greater levels of protection and that have a more diverse functionality are being developed. These devices bring new challenges in terms of performance measurement and prediction, as well as understanding any associated integration mechanisms. Continued research will be required to maintain a full understanding of the associated issues.

Protection de l'ouïe –
Besoins, technologies et résultats
(RTO-TR-HFM-147)

Synthèse

Les pertes auditives provoquées par le bruit sont un problème significatif pour les nations membres de l'OTAN. Depuis des décennies, les niveaux de bruit de l'environnement militaire se sont accrus constamment et les nouveaux types de véhicules et d'armes sont souvent plus bruyants que les anciens. On observe également une meilleure prise en compte des risques auditifs associés à l'exposition à des niveaux de bruit élevés et, en conséquence, les limites d'exposition établies dans les normes et les législations (inter)nationales sont devenues plus astreignantes. C'est pourquoi, il est devenu de plus en plus difficile de protéger convenablement le personnel militaire pendant la durée du service nécessaire à la satisfaction des besoins opérationnels.

Ces dernières années, une meilleure compréhension scientifique des voies de propagation du son, y compris le bruit transmis par l'air, les os et les tissus a abouti à des technologies nouvelles et plus efficaces de protection auditive, de communication et d'évaluation de la situation. Le groupe de travail HFM-147 a été créé en avril 2005 pour étudier la technologie avancée de protection auditive personnelle et pour aborder des applications où la protection adéquate n'est actuellement pas disponible. L'objectif de ce rapport est de fournir des informations qui aideront les utilisateurs de protection auditive et les personnes dont les activités commerciales concernent l'acquisition ou les demandes de protection auditive à identifier la protection auditive la mieux adaptée pour une application ou un rôle spécifique.

Il a été procédé à une analyse détaillée des critères d'exposition au bruit et des critères de risques de dommages utilisés par les différentes nations ainsi que des types et niveaux de bruit des véhicules et des armes qui peuvent être rencontrés dans un éventail d'environnements opérationnels différents. Les informations fournies peuvent être utilisées en les combinant pour prédire le niveau de risque de dommage auditif spécifique des opérateurs et, par conséquent, obtenir le niveau de protection auditif exigé pour satisfaire aux critères d'exposition. Une revue complète des technologies de protection auditive disponibles à court terme dans le commerce a été faite, et une vue d'ensemble des techniques de tests d'évaluation en laboratoire et sur le terrain pouvant être utilisées pour évaluer les résultats d'atténuation a été fournie. Cependant, lors du choix d'un nouveau dispositif de protection auditive destiné à rendre le niveau de bruit de l'opérateur compatible avec les critères d'exposition au bruit, il existe de nombreux facteurs, autres que le niveau absolu d'atténuation assuré par l'équipement, pour influencer le processus décisionnel d'acquisition. Une revue des paramètres comprenant : l'éducation, la formation, le confort, la compatibilité avec les autres équipements, la taille, le poids et le prix a été fournie et on a débattu de leur influence sur le processus d'acquisition.

A l'heure actuelle, nous avons une bonne compréhension des mécanismes de protection auditive et des paramètres qui l'influencent. Cependant, la législation sur le bruit est devenue de plus en plus astreignante et l'environnement sonore devient plus rude. En conséquence, de nouveaux dispositifs de protection auditive fournissant des plus hauts niveaux de protection et offrant des fonctionnalités plus diversifiées sont en train d'être développés. Ces dispositifs font naître de nouveaux défis en termes de mesure des performances et de prédiction, mais aussi de compréhension des mécanismes d'intégration associés. Une recherche permanente est nécessaire pour garder une compréhension totale des problèmes associés.

Chapter 1 – INTRODUCTION

Noise-Induced Hearing Loss (NIHL) is a significant problem among member nations. Over the decades, the levels of noise in military environments have steadily increased and new vehicle and weapon types are often noisier than the ones they replace. There is also a heightened awareness of hearing damage risk associated with exposure to high levels of noise and, as a consequence, the maximum noise exposure limits set by (inter)national standards has become more stringent. Hence, it is becoming increasingly difficult to adequately protect personnel for the duty durations required to meet operational needs. As a result, there is an urgent need for an integrated approach to hearing protection and conservation.

The noise associated with the operations of a large proportion of military weapons systems can have a significant negative impact on the hearing of personnel. There are three basic approaches for mitigating these adverse affects on hearing. The first, and most preferable approach, is to reduce the noise at its source by engineering controls. Although this approach achieves close to a global reduction in noise, it may not be feasible in many military environments [1]. The second approach is insertion of a noise barrier in the path between the source and the listener [2] and, although not as preferable as reduction of noise at the source, this approach can be effective. The third approach is the use of Personal Protective Equipment (PPE) or Hearing Protection Devices (HPDs) [3].

Personal HPDs provide a cost effective and easily implemented means of reducing exposure to high-level noise both in civilian and military settings. A selection of earplug and earmuff styles is currently available and, depending on the level of protection required, they can be used effectively either as individual devices or in combination. However, their overall performance is affected by many parameters, the most important being the quality of fit or, more specifically, the size of the acoustic leak which will decrease the amount of low-frequency attenuation realized and may affect the attenuation at other frequencies.

An issue that could use more attention is the field performance of hearing protection. Some literature reports that in industrial and military environments up to half of the personnel exposed to noise do not use their hearing protection and a high proportion of those that do wear it, do not wear it correctly. Possible impediments to the use of hearing protection in the field can be the reduction of auditory detection, localization and communication capabilities, as well as comfort issues. The level of attenuation achieved in the field is affected not only by the type of hearing protection device and its condition or state of maintenance, but also by the fitting, training, education and motivation of the user.

In recent years an improved scientific understanding of sound transmission paths including air, bone and tissue conducted noise have lead to new and improved hearing protection, communication and situation awareness technologies. New technologies are mostly developed with a specific application in mind and by establishing field performance data and effective practices among member nations will help define best hearing protection / hearing conservation practices and "optimal" solutions for near future use.

This report is based on the collective experience of the HFM-147 Task Group formed in April 2005 to investigate advanced personal hearing protection technology. The purpose of the report is to inform users of hearing protection, and those in the business of hearing-protector acquisition or requirements. The requirements for hearing protection are addressed in Chapters 2 and 3 where an overview of noise policy and noise exposure in the military environment is respectively provided. Chapter 4 provides a review of hearing protection technologies that are currently available along with typical attenuation performance characteristics, costs and state-of-the-art developments. Chapter 5 details laboratory and field performance measures and Chapter 6 discuss hearing protection selection considerations. Finally, Chapter 7 summarizes the review and provides recommendations for future work. A comprehensive list of definitions of hearing protection related parameters can be found at Appendix 1. Impulse Noise Measurement Considerations are provided in Appendix 2.

Chapter 2 – REQUIREMENTS FOR HEARING PROTECTION

Although the main driver for providing military personnel with improved hearing protection is usually to help achieve compliance with legislative noise exposure criteria, minimizing unwanted noise from reaching the ear can also aid speech communication, detection of auditory warning signals, mission effectiveness, and improve the safety and the well-being of personnel. This section provides an overview of the parameters that should be considered when assessing the hearing protection system requirements for specific categories of personnel.

2.1 NOISE POLICY

Noise exposure criteria or Damage Risk Criterion (DRC) are a matter of policy. Technical experts can predict the amount of permanent hearing loss or Noise-Induced Permanent Threshold Shift (NIPTS) in a population from years of exposure to noise within a given criteria. Generally, the noise exposure criteria for a nation are a balance between acceptable levels of hearing loss and the noise exposure levels in the criteria.

2.1.1 Noise Dose Calculation

Noise dose is a combination of noise level and duration of exposure evaluated relative to a noise exposure criterion and exchange rate. The goal for noise exposed workers is to keep the noise dose to 100% or lower on a daily basis. Noise dose can also be computed/calculated for time durations longer or shorter than a standard 8-hour work day. An example would be the noise dose accumulated by a pilot during a given flight in the high noise of the cockpit. The flight might be only 1.5 hours in duration but the associated noise dose could easily exceed 100%. Another example would be the noise dose accumulated in command and control centres where the noise is at a relatively lower intensity but the durations may be significantly greater than 8 hours. Once again the allowable noise dose could easily exceed 100%. Noise dose is an aggregate or summation of several individual noise doses calculated from noise spectra/levels and times at each noise level evaluated relative to the noise exposure criterion. Equation A below provides a method for calculating noise dose from n, multiple events for any noise exposure criterion and exchange rate:

$$Dose = 100 \times \sum_{i=1}^{n} \left(\frac{t_i \times 2^{\left(\frac{l_i - L}{E} \right)}}{T} \right)$$

Equation A

where:

   Dose = Percentage dose
   t_i = Exposure time in minutes for the ith time period
   l_i = A-weighted level in dBA for the ith time period
   L = Exposure criterion A-weighted level in dBA (for example 85 dBA)
   E = Exposure criterion exchange rate in dB per doubling of exposure time (for example 3 dB/ doubling)
   T = Exposure criterion Time in minutes (for example 8 hours would be 480 minutes)
   n = Total number of exposure time periods (for example if you had 17 separate noise levels and time periods then n = 17

To illustrate different exposure criteria, two example detailed equations are given below. The first example, Equation B, is for a noise exposure criterion of 85 dBA, for 8 hours (480 minutes), with a 3 dB per doubling exchange rate. The second example, Equation C, is for a noise exposure criterion of 90 dBA, for 8 hours (480 minutes), with a 5 dB per doubling exchange rate:

$$Dose = 100 \times \sum_{i=1}^{n} \left(\frac{t_i \times 2^{\left(\frac{l_i-85}{3}\right)}}{480} \right)$$

Equation B

$$Dose = 100 \times \sum_{i=1}^{n} \left(\frac{t_i \times 2^{\left(\frac{l_i-90}{5}\right)}}{480} \right)$$

Equation C

The equations in MS Excel™ format are shown below, where A2 is the time in minutes and B2 is the exposure level in dBA. Note: 8 hours is 480 minutes:

= 100*((A2*2^((B2-85)/3))/480)

Equation B (85/8/3)

= 100*((A2*2^((B2-90)/5))/480)

Equation C (90/8/5)

Table 2-1 and Table 2-2 show the spreadsheet cells used to calculate the noise dose in the given examples. The first table is for the 85 dBA, 8-hour, 3 dB/doubling criterion while the second table is for the 90 dBA, 8-hour, 5 dB/doubling criterion.

Table 2-1: Examples of Spreadsheet Cells Used to Calculate Noise Dose – (85/8/3).

	A	B	C
1	**Time (minutes)**	**Level (dBA)**	**Dose (%)**
2	A2	B2	= 100*((A2*2^((B2-**85**)/**3**))/480)
3	A3	B3	= 100*((A3*2^((B3-**85**)/**3**))/480)
4	A4	B4	= 100*((A4*2^((B4-**85**)/**3**))/480)
5		**Total Dose**	= Sum(C2:C4)

Table 2-2: Examples of Spreadsheet Cells Used to Calculate Noise Dose – (90/8/5).

	A	B	C
1	**Time (minutes)**	**Level (dBA)**	**Dose (%)**
2	A2	B2	= 100*((A2*2^((B2-**90**)/**5**))/480)
3	A3	B3	= 100*((A3*2^((B3-**90**)/**5**))/480)
4	A4	B4	= 100*((A4*2^((B4-**90**)/**5**))/480)
5		**Total Dose**	= Sum(C2:C4)

To illustrate the dose calculation using each of the sample noise exposure criteria, two examples are given below.

Example (1): The dose is calculated for a person exposed to 85 dBA at the ear for 4 hours, 88 dBA for 1 hour, and 91 dBA for 30 minutes.

The example dose calculations for the two sample exposure criteria are shown in Table 2-3 as follows: First, on the left, the 85 dBA with 3 dB/doubling criterion; and second, on the right, the 90 dBA with 5 dB/doubling criterion.

Table 2-3: Example Dose Calculation (1).

85 dBA / 8 hrs / 3 dB			90 dBA / 8 hrs / 5 dB		
Time (mins)	Level (dBA)	Dose (%)	Time (mins)	Level (dBA)	Dose (%)
240	85	50	240	85	25
60	88	25	60	88	9
30	91	25	30	91	7
	Total Dose	100		**Total Dose**	42

Example (2): The dose is calculated for a person exposed to 95 dBA at the ear for 1 hour, 90 dBA for 2 hours, and 85 dBA for 4 hours.

The example dose calculations for the two sample exposure criteria are shown in Table 2-4 as follows: First, on the left, the 85 dBA with 3 dB/doubling criterion; and second, on the right, the 90 dBA with 5 dB/doubling criterion.

Table 2-4: Example Dose Calculation (2).

85 dBA / 8 hrs / 3 dB			90 dBA / 8 hrs / 5 dB		
Time (mins)	Level (dBA)	Dose (%)	Time (mins)	Level (dBA)	Dose (%)
60	95	126	60	95	25
120	90	79	120	90	25
240	85	50	240	85	25
	Total Dose	255		**Total Dose**	75

As can be seen the exposure criterion has a dramatic effect on the total dose. The examples and spreadsheets can be expanded/extended to add as many different noise exposure levels and time as desired for the calculation of the total noise dose. Once the noise dose is calculated for each level and time, all the noise doses are then summed to calculate the total noise dose.

2.2 DAMAGE RISK CRITERIA (DRC) FOR CONTINUOUS NOISE

DRC for continuous noise are the central core of many military and industrial hearing conservation programs. The technical relationship between DRC and incidence of long term noise inducted hearing loss has been centrally based on a large study conducted and reported by Prof Burns and Dr Robinson in 1970 [4] and supported by the work of Prof. Atherley and D. Martin on the effect of impulse noise [5]. Their work was used by the Industrial Health Advisory Committee to produce (in 1972) its Code of Practice for reducing the exposure of employed persons to noise. This code of practice led to recommendations for specific legislation on noise exposure.

Taking into account that hearing loss over a working lifetime may also occur from other causes (i.e. not just the prolonged exposure to noise) the code of practice provides an estimate of the risk of hearing loss for a given level of noise exposure, expressed as a percentage of persons exceeding a stated hearing loss.

Table 2-5 provides data for two different levels of hearing loss (30 dB and 50 dB) for periods of 10 years and a working lifetime (starting at the age of 18).

Table 2-5: Population at Risk of Suffering NIHL (1970s Data).

	50 dB	50 dB	30 dB	30 dB
	Lifetime	10 Year	Lifetime	10 Year
Noise Exposure (dBA 8 hr Leq)	Percentage Population at Risk			
100	32	17		48
95	20	10	54	39
90	11	5	42	30
85	6	3	33	25
80	3	1	27	22
75	1	0	23	20

Note: The hearing loss occurrences would be greater if the DRC used exchange rates higher than 3 dB/ doubling, i.e. 5 dB/doubling.

Table 2-6 is a collection of the continuous noise exposure criteria used in the referenced countries at the time of this report.

Table 2-6: National Noise Exposure Criteria.

Country	Department / Legislative Body	Damage Risk Criteria (DRC)
USA	Air Force, Army, DoD and EPA	85 dBA, 8 hrs, 3 dB exchange rate
	Navy	84 dBA, 8 hrs, 3 dB exchange rate
	OSHA	90 dBA 8 hrs, 5 dB exchange rate
	Air Force whole body limit	150 dB overall, 145 dB in any octave band

GBR, BEL, FRA, DEU	**EU Directive 2003/10/EC "Risks arising from physical agents"**
	
	GBR – Control of Noise at Work Regulations 2005 – adopted by MOD
	
	FRA – Statutory order n°2006-892 of Department for Employment, 19 July 2006 (Prescriptions for security and health in the event of noise exposure at work)
	
	BEL – Royal Directive 16/01/2006 N.2006 - 603
	
	DEU – Verordnung zur Umsetzung der EG Richtlinie 2002/44/EG und 2003/10/EG (23 February 2007)
	
	Decree for the implementation of the EU Directive 2002/44/EC und 2003/10/EC *(23 February 2007)*
	
	Zentrale Dienstvorschrift "ZDV 44/3 Lärmschutz"
	
	Central service regulation "ZDv 44/3 Noise Protection"
	24 August 2007
		Lower Exposure Action Value:
		
		80 dBA for 8 hrs (3 dB exchange rate) or 135 dBC peak pressure:
		
		  Risk assessment of noise environment to be conducted and hearing protection made available if requested.
		
		Upper Exposure Action Value:
		
		85 dBA for 8 hrs (3 dB exchange rate) or 137 dBC peak pressure:
		
		  Reduce noise at source or by managerial control before hearing protection is considered. Wearing of hearing protection mandatory (obliged) at this level.
		
		Exposure Limit Value:
		
		87 dBA for 8 hrs (3 dB exchange rate) or 140 dBC peak pressure:
		
		  Measured at the ear under any hearing protection worn. This is a prohibitive level, i.e. it is illegal to exceed.
		
		Germany only:
		  §1 for the purpose of the defence, exceptions can be accepted by the Ministry of Defence §6 the exposure limit value is equal to the upper exposure action value, 85 dBA continuous or 137 dBC peak

NLD	Military	Action required + limit at 80 dBA

2.3 DAMAGE RISK CRITERIA FOR IMPULSE NOISE

DRC for impulse noise that have been proposed or are currently used in different countries can be divided in three categories, with the Criteria based on the:

   I) Peak pressure level and a duration, i.e. A, B, C, D duration;

   II) Noise dose delivered by the impulse noise, i.e. L_{Aeq} or L_{Aex}; and

   III) Pressure time history of the noise impulse, Auditory Damage Units, AHAAH model.

Damage risk criteria for impulse noise have been the focus of two previous NATO research study groups, RSG.6 and RSG-029, and a Lecture Series LS219. Below is an excerpt for the RSG-029 technical report TR-017, Reconsideration of the Effects of Impulse Noise (RTO TR-017 / HFM-022) RSG-029 [6].

This report contains the main outcome of the work constituted by NATO Research Study Group RSG-029 "Reconsideration of the effects of impulse noise". RSG-029 followed RSG.6 on the effects of impulse noise. The first RSG started its activities in 1980. Its final report appeared in 1987; NATO document AC/243(Panel 8/RSG.6) D/9. The activities of RSG.6 resulted in specific recommendations for additional research. This RSG was disbanded awaiting new data.

In 1994 the NATO Defence Research Section concluded that the evaluation of the effects of impulse noise on man should be reconsidered in view of the new data that had become available. Consequently, RSG-029 was established. RSG-029 has accommodated very effective cooperation.

Two RSG meetings were organized in 1997 and 1998 (UK and The Netherlands), and a Lecture Series on damage risk from impulse noise (LS-219) was held in two locations in 2000 (USA and Germany) and in two locations in 2002 (Russia and Kyrgyzstan). RSG-029 was formally disbanded by the end of 1998.

In producing this final report, it turned out that RSG-029 could not reach agreement on all issues. Hence, the present report cannot be considered as a consensus report. Different chapters were contributed by different members, and the text sometimes tends to reflect the view of the author, and not necessarily that of the entire RSG. Given this situation, the name of the author is explicitly mentioned in the respective chapters.

One particularly difficult topic concerns a model to predict the risk of hearing damage from impulse sound based on physiological data (AHAAH model by Price and Kalb)...

More elaborate contributions on a number of subjects (hearing protection performance, medical treatment, cost effectiveness, non-auditory damage risk) can be found in the proceedings of RTO Lecture Series 219 "Damage risk from Impulse Noise" (RTO-ENP-011, June 2000).

Clearly, there has been and continues to be a robust scientific debate regarding damage risk criteria for impulse noise. The scope of this debate is extensive. NATO TR-017 is a good reference relative to establishing damage risk criteria for impulse noise.

I) Peak Pressure Level and Duration Based Criteria

Four major DRC can be found in this category:

- The CHABA (Committee on Hearing, Acoustics, and Bioacoustics – USA National Research Council) criterion, which is mainly used in the USA, distinguishes between impulse noise generated in the free sound field and in a reverberant area. When considering noise in the free sound field, the A-duration is used. In a reverberant environment, or in the case of rapid (automatic) firing, the B-duration is used. The method for the determination of these durations is shown in Figure 2-1.
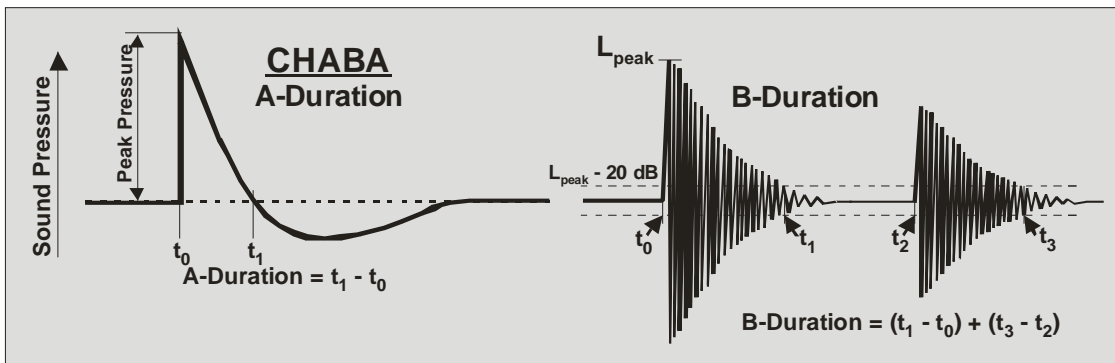
**Figure 2-1: Calculation Methods for the CHABA "A" and "B"
Exposure Durations for Impulse Noise.**

- The Pfander criterion uses a different way to determine the action time called C-duration (see Figure 2-2). It does not distinguish between reverberant or free field exposures.
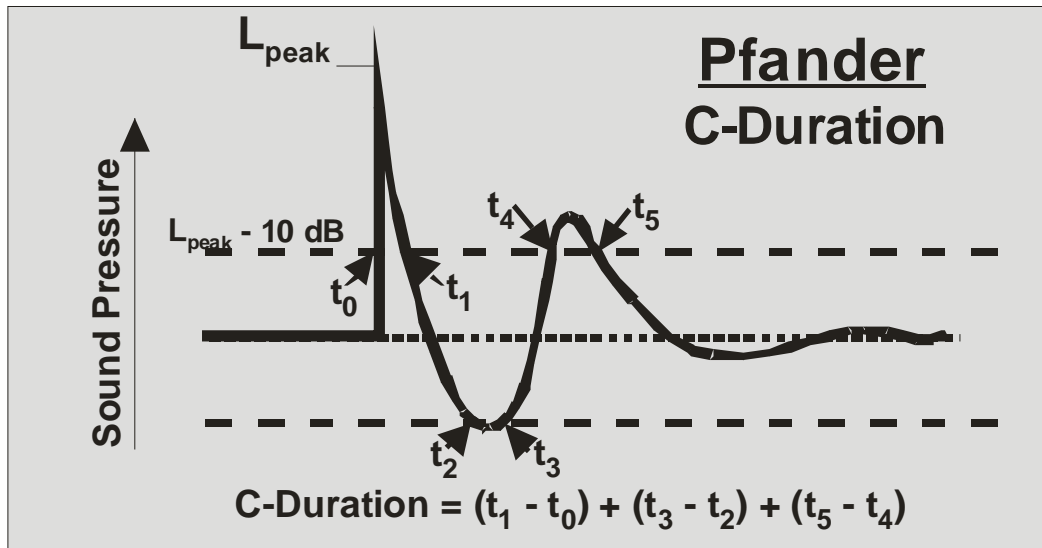
Figure 2-2: Calculation Methods for the Pfander "C" Exposure Durations for Impulse Noise.

- The Smoorenburg criterion uses the D-duration for the determination of the exposure duration (see Figure 2-3) and, again, does not distinguish between free field and reverberant conditions.
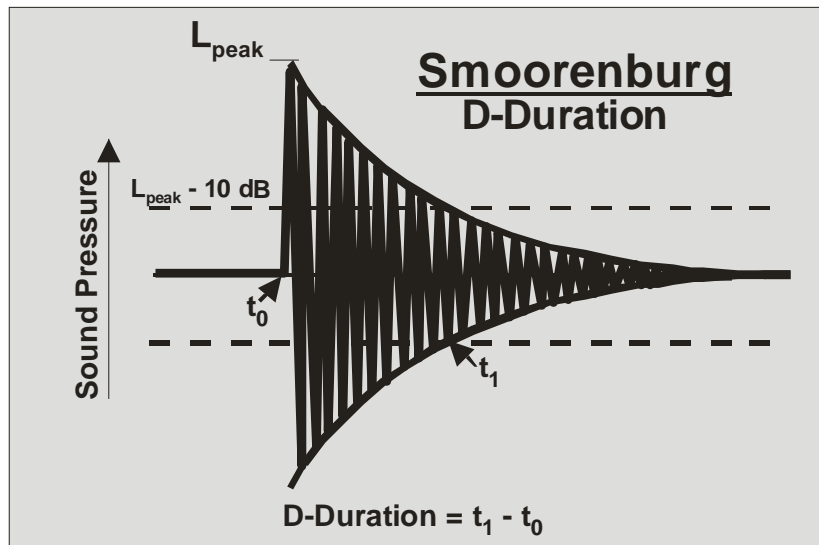
**Figure 2-3: Calculation Methods for the Smoorenburg "D"
Exposure Durations for Impulse Noise.**

- The USA Military Standard 1474D [7] uses the B-duration (as shown in Figure 2-1) and the number of impulses (see Figure 2-4).

MIL-STD-1474D
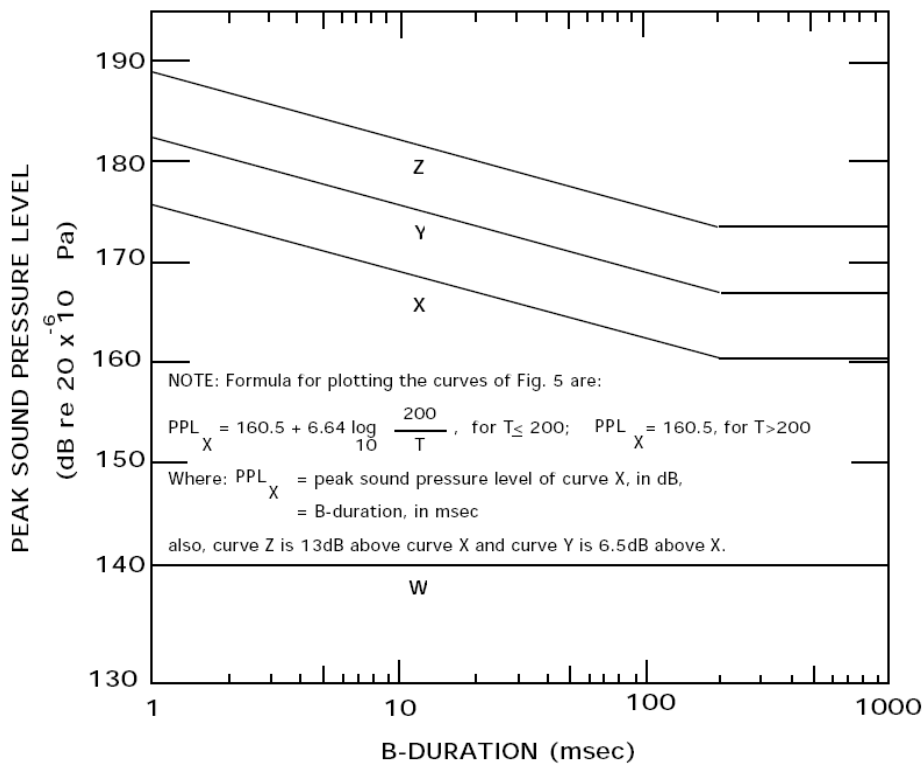
Figure 2-4: USA Military Standard 1474D.

The chart in Figure 2-5 presents the limits for all three criteria. It shows that the Pfander and the Smoorenburg criteria are almost identical (~ 1 dB difference) and both of them roughly correspond to the equal energy principle. This means that for each doubling of the duration, the peak pressure of the impulse must be reduced by 3 dB (factor = $\sqrt{2}$). However, these equal energy oriented criteria don't take into account the modification of the spectral shape if the duration of the noise increases. The CHABA criterion is not equal energy orientated and instead of decreasing by 3 dB per doubling of the exposure duration it decreases by 2 dB, to allow for the changes in the spectrum when the duration of the impulse increases.
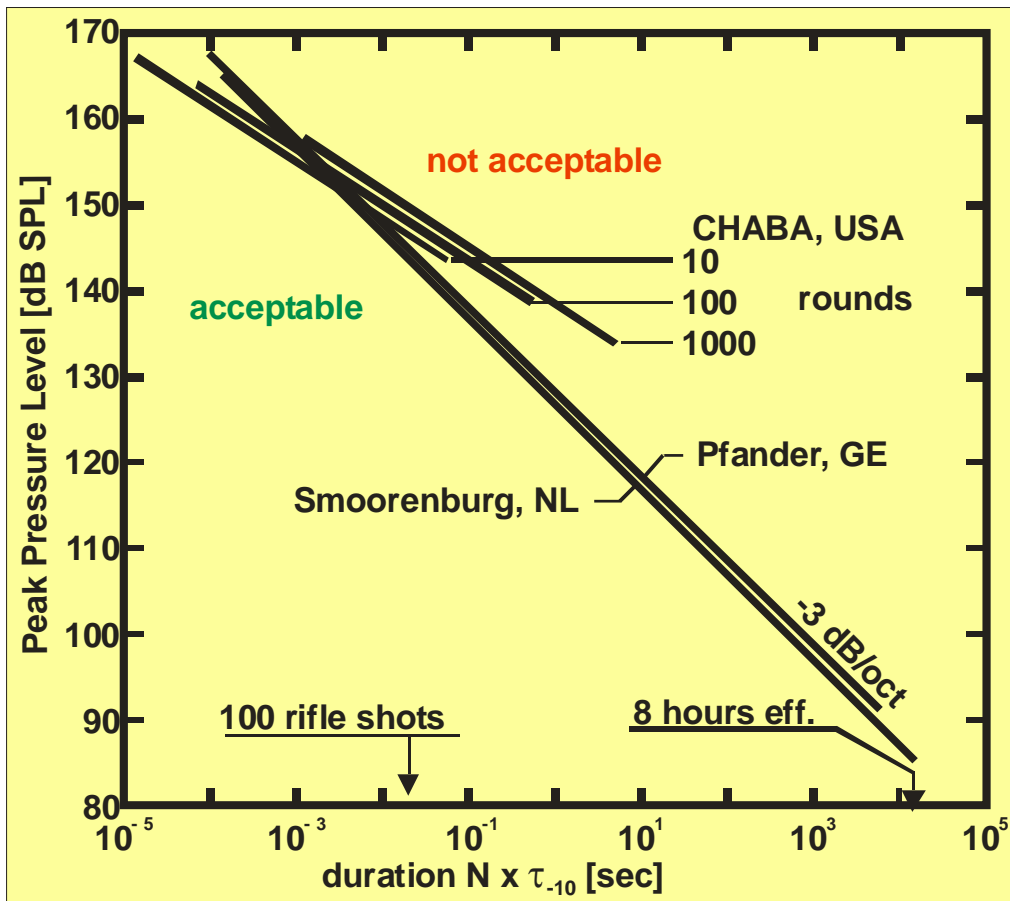
Figure 2-5: The Graphical Determination of the Auditory Damage Risk. All three criteria, CHABA, Pfander, and Smoorenburg are represented on this chart.

As these four criteria have been developed and verified by using small arms, they tend to overrate the danger of large calibre weapons. It has been shown [8,9] that this overestimation can be as much as 20 dB. Another problem associated with these criteria is that they cannot predict risk from exposure to impulse noise combined with continuous noise, which is a major problem in the military community where the soldier is exposed to high-level continuous noise (e.g. Armoured Personnel Carrier) and weapon noise.

II) Noise Dose (Lex) Based Criteria

Atherley and Martin [5] as well as Dancer [10] have proposed that weapon noise be evaluated in the same way as continuous noise (comparable to ISO 1999 [11]). They propose that for every round fired an A-weighted equivalent noise level for 8 h (L_{Aex},8h) be determined. The maximum daily exposure is reached for a L_{Aex},8h of 85 dBA. The advantage of this proposal is that it aligns well with the noise

protection standards for continuous noise (ISO 1999, NIOSH, etc.) and therefore allows the combined risk of continuous and impulse noise to be assessed.

III) Pressure Time History Based Criteria

Price and Kalb [12] have developed the Auditory Hazard Assessment Algorithm for the Human (AHAAH) which takes into account the whole signal transmission from the free sound field to the cochlear structures. Auditory Hazard Units (AHUs) are determined based on the calculated time-history of the displacement of the basilar membrane (mechanical stress, elongation, number of cycles, etc.). For a single event a maximum of 500 AHUs is allowed and if this limit is exceeded permanent hearing loss may occur. The technique requires a very precise measure of the pressure time history of the weapon noise and, as a consequence, this method is quite difficult to implement. Moreover, the validity of the model is still controversial inside the scientific community.

2.4   DRC FOR COMBINED IMPULSE AND CONTINUOUS NOISE

Currently, separate Standards and DRC exist for the prevention of hearing damage in continuous noise and for impulse noise. This is because different metrics are used for the continuous noise DRC (usually TWA or L_{Aeq}), and for the impulse noise DRC (peak pressure combined with a duration). However, soldiers are often exposed to a combination of these two types of noise and therefore a DRC should be able to handle both. The only current DRC that was specifically designed to handle the combined exposure was proposed by Atherley and Martin, and by Dancer. This DRC is based on the A-weighted noise dose and treats all types of noises in the same way, making the assumption that for impulse noise the level for physical destruction of the hair cells is not reached.

2.4.1   Impulse Noise Legislation

The EU Physical Agents Directive (2003/10/EC) [13] introduces exposure action and limit values for both continuous and impulse noise. For continuous noise, the limits are expressed in A-weighted equivalent noise levels and take account of the effectiveness of any hearing protection worn. However, for impulse noise the exposure limits are determined from a C-weighted pressure time history of the impulse measured under the hearing protector. When applied to this measure the directive only takes account of the peak pressure level. Hence, neither the spectral composition (C-weighting doesn't reflect the sensitivity of the auditory organ), nor the energy of the impulse are taken into account when determining the hazard.

2.5   CONSEQUENCES OF NON-COMPLIANCE

Noise exposure regulations generally place a responsibility on the employer to protect his employees by providing adequate levels of protection against noise encountered in the workplace. If suitable palliative measures are not introduced (for example, the provision of HPDs that are fit for purpose) some operators will experience hearing damage. Noise-Induced Hearing Loss (NIHL) is an insidious process. The person is generally unaware of the slow degradation of hearing thresholds and speech perception in noise until the losses are significant and permanent. In the military many specialist and safety critical roles require the operator to have good hearing acuity and if this is compromised it may be necessary to downgrade personnel. There will not only be costs incurred in the re-training of these personnel and the associated training of new recruits to replace them (in the case of aircrew this could amount to 12 m US$ a head) but there are the added costs of disability pensions and possibly compensation and litigation costs.

Most countries provide monetary compensation for hearing loss as a disability. The costs are both monetary and functional. A person with a compensable hearing loss is truly disabled. Their speech perception in even low level noise is severely degraded when compared to a person with normal hearing thresholds.

The monetary costs for disability payments, treatment (audiograms, hearing aides, etc.), and retraining can easily exceed 5,000 US\$ (3,400 Euros) per person per year.

In 2002 the cost to the UK MOD from litigation claims exceeded £ 200 m, a figure that is doubling every four years. Of this total, some 20% is directly related to noise and vibration, i.e. some £ 40 m. If this trend continues, claims relating to noise and vibration could potentially rise to over £ 160 m per annum by 2010. A similar situation is found in the US. Figure 2-6 shows how the costs associated with hearing loss for all US Veterans have escalated between 1977 and 2006 when the disability pensions paid out touched 9 billion US\$.

Figure 2-6: Cost of Hearing Loss for All US Veterans (1977 – 2006).

2.6   ENFORCEMENT FOR COMPLIANCE WITH EXPOSURE CRITERIA

Regulations governing noise exposure and use of hearing protection can be ineffective if users are not motivated for consistent and high quality use of the devices. The overall message sent with enforcement of hearing protector use is that use of the protective equipment is important enough that penalties will be incurred for non-compliance. One method to encourage hearing protector use in the military has been employed by the US Army where the hearing protector has been made part of the soldier's uniform. Therefore, if the hearing protection is not on the soldier, or if the hearing protector is not being worn in a noisy environment, the soldier is technically "out of uniform" and is subject to disciplinary action. Additionally, military leaders/commanders could be made responsible for ensuring the proper use of hearing protection by those in their command. Industrial users have the capability to dismiss/fire personnel for non-use and/or improper use of hearing protection.

Chapter 3 – MILITARY NOISE ENVIRONMENTS

The previous section detailed the noise exposure limits imposed by different nations. Most NATO member nations have, to a greater or lesser degree, conducted reviews of the noise environments to which they expose their personnel. Reviews have covered internal and external vehicle noise, weapons/ explosives exposure and the electrical communications load. However, these reviews have not routinely been exchanged or published, which means that insight into noise exposure in the armed forces exists, at best, at a national level. Moreover, the procedure used to measure noise data and subsequently calculate daily noise dose, varies from nation to nation.

Probably the most useful and common parameter quoted across the various noise surveys is the overall A-weighted sound pressure level monitored at the various positions occupied by different personnel for different operational scenarios. Nearly all surveys report this measure and it provides a fairly good first-order indicator of noise exposure. Unfortunately, the collection of spectral information has been less prevalent. Hence, it is the aim of this section to provide an overview of the types of noise levels that different categories of military personnel of the NATO nations are exposed to and to provide some typical spectral information that may be used, along with a knowledge of any communications load, to predict the risk of hearing damage when wearing different types of hearing protection.

3.1 CONTINUOUS NOISE ENVIRONMENTS IN VEHICLES

3.1.1 Aircraft

In fast jets the internal cockpit noise spectrum is generally random in nature with high energy levels spread over a broad frequency band [14]. The noise is generated from two predominant sources. One is from the external airflow around the aircraft canopy and the front structure of the aircraft (boundary layer flow noise), and the other is from internally generated noise from the pressurisation and cockpit conditioning systems. The boundary layer flow noise is dependent upon the dynamic pressures on the aircraft and thus the speed and height. This is clearly demonstrated in Figure 3-1 that shows a comparison of the cockpit noise measured in a Harrier during high-speed, low-level flight and during flight at altitude. A difference in cockpit noise levels of some 10 dB is exhibited across the frequency band.

Harrier
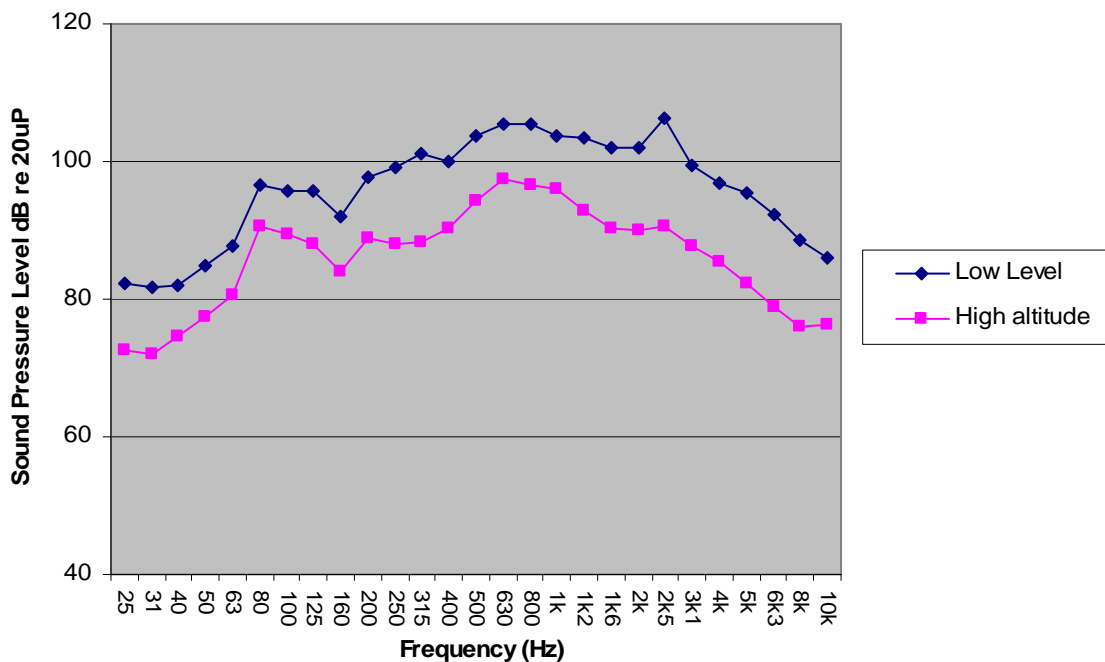
Figure 3-1: Comparison of Cockpit Noise in Harrier During High and Low Altitude Flight.

Cockpit conditioning noise is mainly generated through turbulent flow from the outlet sprays. The noise levels associated with the flow are nominally constant with speed and height, although the cockpit noise spectrum will vary with conditioning mode. Figure 3-2 compares the cockpit noise in an F-16A with the ECS on normal and maximum defog settings. The plot shows that with the ECS on there is a large increase in high frequency energy that increases the overall sound pressure level by some 10 dBA and, if experienced for any length of time, will contribution to the dose received.

F16
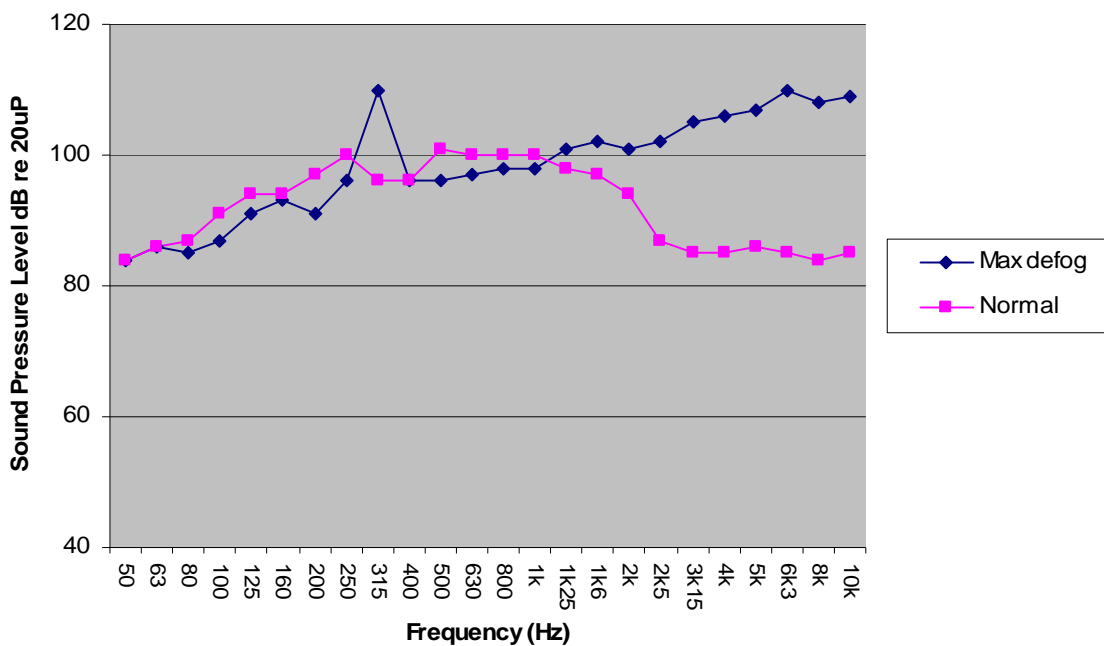
Figure 3-2: A Comparison of Cockpit Noise in the F-16A with ECS Switched On and Off.

For helicopters the sources of internal cockpit and cabin noise are both aerodynamic and mechanical. The cockpit or cabin noise is predominantly narrow band discrete tones with associated harmonics superimposed on a low-level, broadband background noise. Aerodynamically induced noise is generated from the main and tail rotors, including interactions between the rotors in a twin rotor design (e.g. Chinook) and interactions between the rotors and fuselage. The mechanical noise originates from revolving systems connected to the rotors in the form of gearboxes, transmission shafts, transfer gears, auxiliary systems, drive shafts, etc. Figure 3-3 shows a narrow band analyses for a Lynx helicopter and the sources of the noise peaks.

Lynx
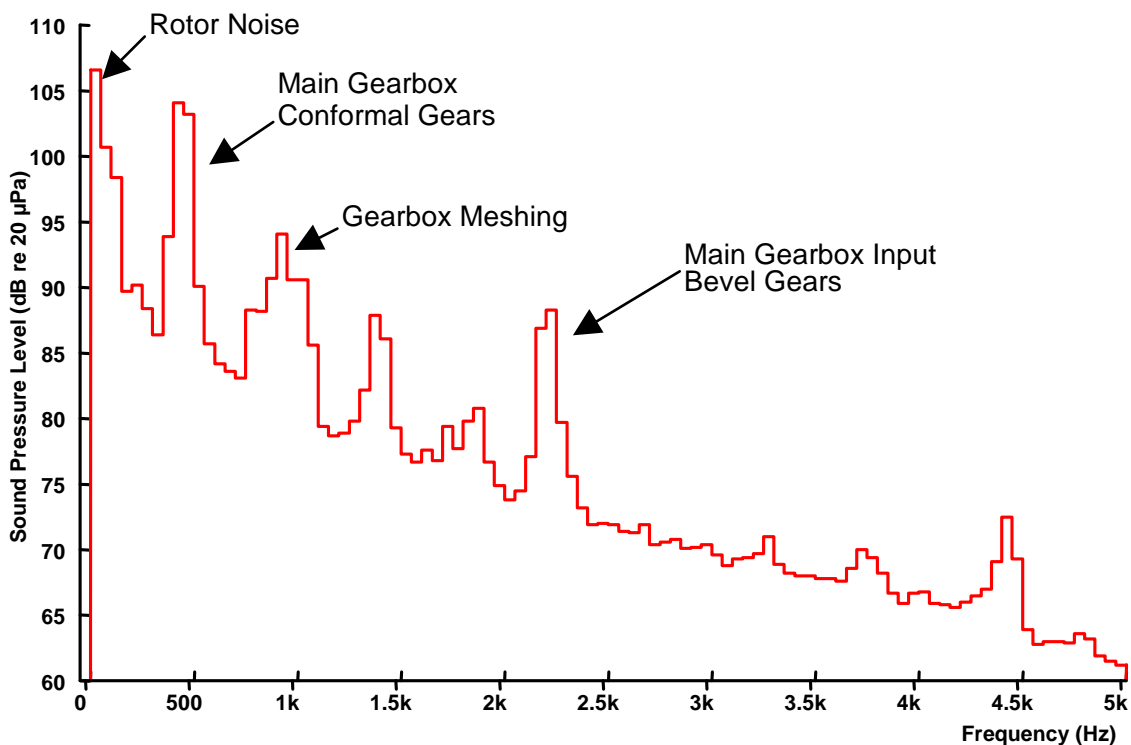
Figure 3-3: Narrowband Analysis of Cockpit Noise in the Lynx Helicopter (100 knots).

The cockpit and cabin noise in transport aircraft of the Hercules (turbo-prop) or C17 (turbo-fan) type, or those that use the Tilt Rotor approach, can have a number of sources. Some noise will be generated from the propellers, rotors or wing mounted gas turbines, some from boundary layer flow and some from equipment cooling and cockpit conditioning systems. The overall cockpit and cabin noise levels are a differing combination of discrete and random noise. Figure 3-4 compares the cockpit noise environment for the 4-bladed propeller driven Hercules C130K and the 6-bladed propeller driven C130J. The plot shows how the blade passing frequency (68 Hz and 102 Hz for the C130K and C130J respectively) dominates the whole cockpit noise spectrum. Similarly, passengers transported in the cargo compartment of this type of aircraft will also be exposed to high noise levels. In the C130J, noise levels of up to 118 dB are experienced in the forward cargo compartment just forward of the propeller plane.

Hercules C130K
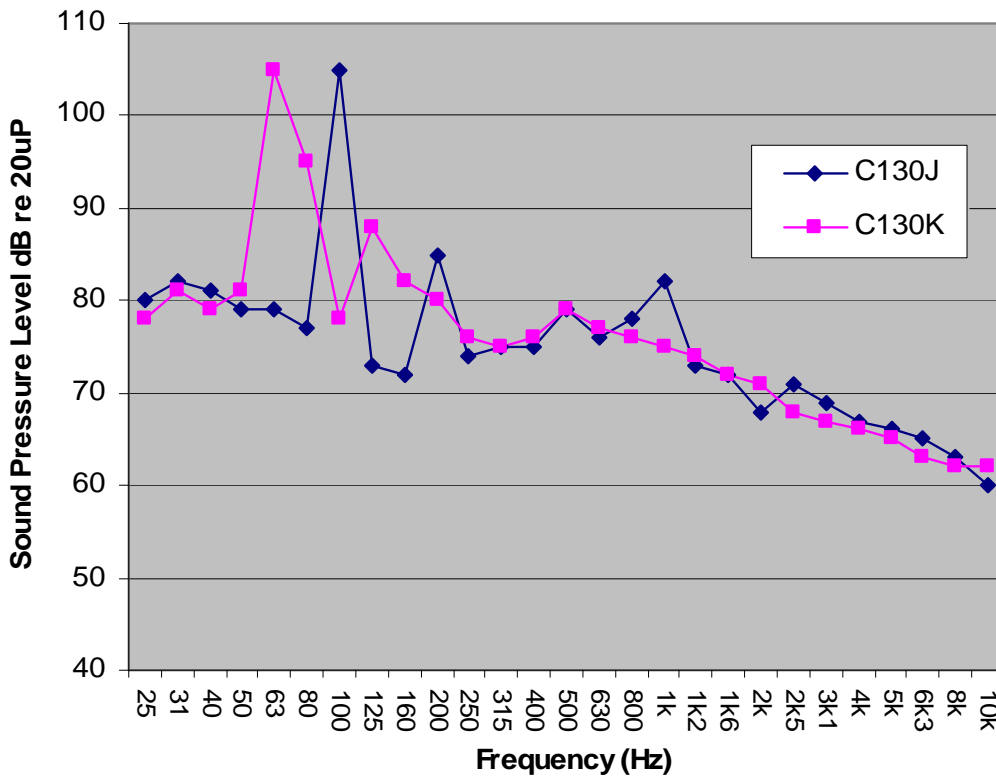
Figure 3-4: Cockpit Noise in the C130K and C130J Variants of the Hercules.

3.1.2   Land Vehicles

The extent of noise exposure in land based vehicles will be influenced by the vehicle type and variant, the vehicle propulsion system, the use of any weapons, communication or other equipment mounted in the vehicle, the interaction between the vehicle and the terrain, the vehicle speed, the driver skill, experience and driving style, the position of the crewmember within the vehicle, the vehicle loading, the state of any hatches, doors or windows and a range of other factors.

To provide an indication of the types of levels that may be experienced in the range of vehicles used by the NATO nations a review of unpublished and published noise survey data for land vehicles was collected from

various sources [15]. National surveys from BE, CA, FR, NL, UK and US were included. For each vehicle type the worst-case noise conditions were chosen and the combined data are presented in Figure 3-5. The dark coloured bars in the middle section of each bar span two standard deviations around the mean A-weighted sound level (the mean + one standard deviation). Statistically, 68% of all vehicles in each category are expected to have an A-weighted sound level that falls within this region. For the combined length of the dark and lighter parts of the bars (the full length, corresponding to four standard deviations), this expected percentage is increased to 95%. However, it should be noted that given the small number of observations in some categories, the estimate of these 68% and 95% confidence intervals may be inaccurate.
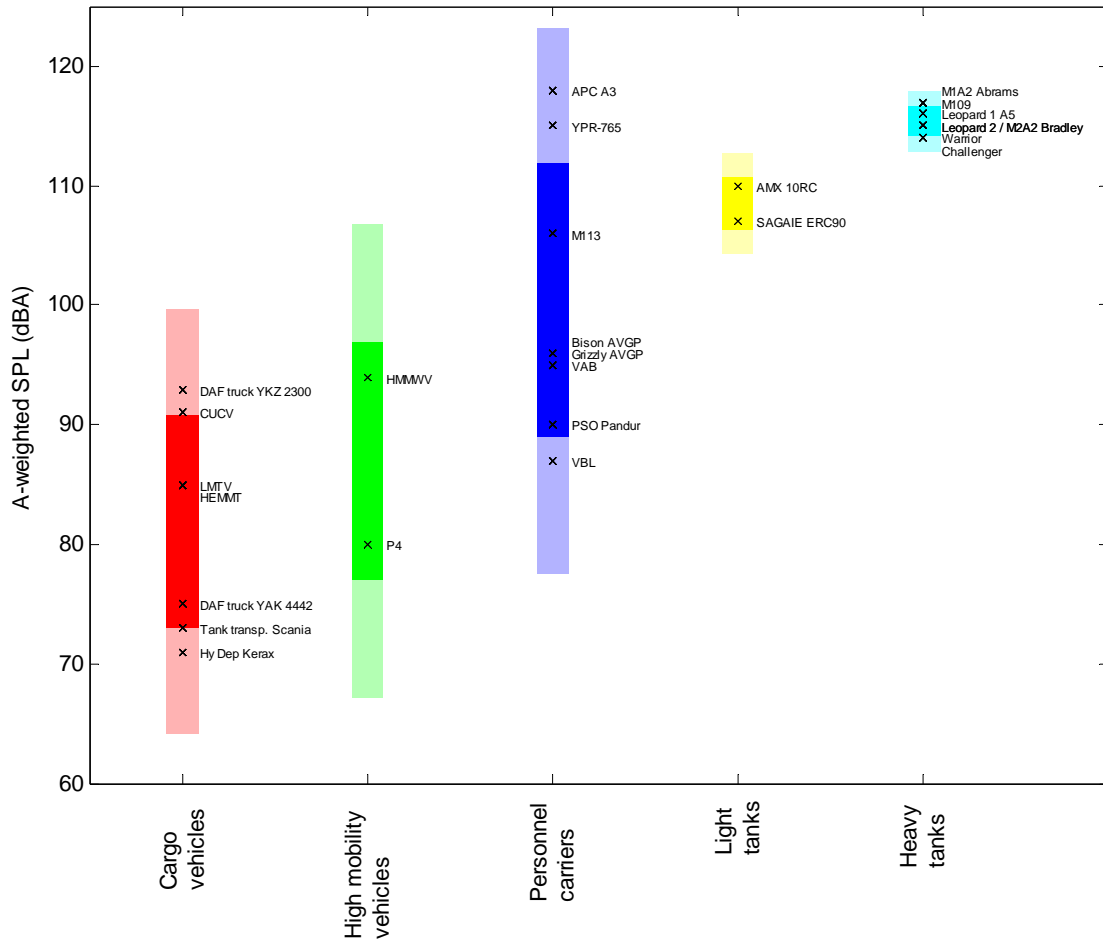
Figure 3-5: A-Weighted Interior Noise Levels for 26 Land Vehicles.

Figure 3-6 compares the worst case noise conditions measured in the UK's Warrior and Challenger tanks. The plots show the linear noise spectra to be dominated by the tonal parameter around 100 – 125 Hz. This is associated with the metal linked tracks striking the ground and the noise being transmitted through the running gear and shell of the vehicle. The worst case noise condition occurs during running on hard surfaces (such as tarmac) and at high speed.

Challenger II Tank
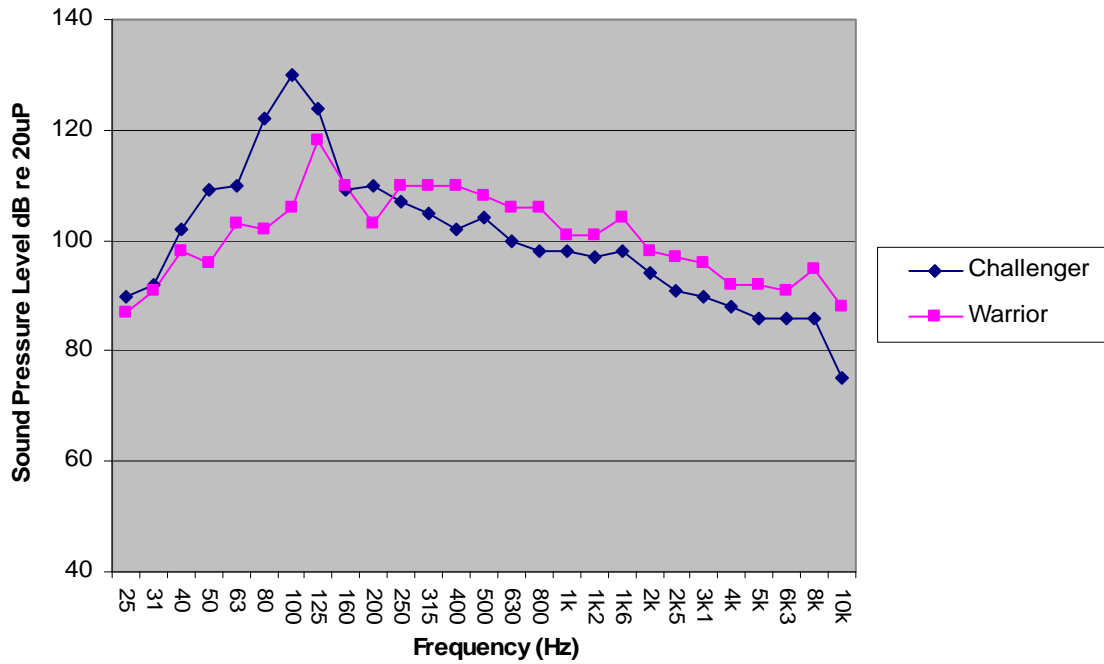
Figure 3-6: Comparison of Worst Case Noise in Warrior and Challenger Tanks.

In wheeled armoured vehicles such as the Pandur 6 x 6 family, noise levels are not as high as experienced in the tracked vehicles but measurements made by the Belgium Army (Table 3-1) show that they are still significant.

Table 3-1: Noise Measurements Made in a Pandur Vehicle.

Person	Driving Conditions	Time	Level (dBA)	Dose (%)
Driver	Fast and hard underground	13'41"	101.3	388
	Slow and soft underground (forest)	10'05"	100.3	222
		LEX,d	**87.9**	**611**
Cargo	Fast and hard underground	13'28"	90.5	31
	Slow and soft underground (forest)	14'26"	85.7	11
		LEX,d	**76.3**	**42**

3.1.3   Sea Vessels

The power and transmission requirements of ships, their mass and speed when moving through water, the systems and equipment carried (e.g. weapons, aircraft, domestic machinery, maintenance equipment and tools) may require and generate substantial energy, significant components of which may appear as noise [16]. When considering the overall level of hearing damage risk, emphasis is placed on the need to consider both the magnitude and the period of exposure. This is especially relevant for sea-going personnel, as legislation normally uses standard 8-hour equivalent exposure limits, with a 16-hour recovery period that effectively contains no additional noise exposure. This conventional shift pattern may not be in line with the work patterns used by embarked crew, and it may not be possible to move into a sufficiently quiet area for any part of a 24-hour period.

Unlike the internal noise of aircraft and land vehicles, where the noise levels are generally high throughout the vehicle, the noise levels experienced on ship will vary significantly depending on the compartment occupied. Hearing damage risk will therefore be role specific and will require knowledge of the duration ship crew spend in the different compartments whilst fulfilling their daily duties, i.e. hearing damage risk should be calculated against a typical Battlefield Day (BFD) specified for each crewmember role.

In the UK the noise exposure levels published for ship crew have generally been monitored through Occupational Noise Surveys or Habitability studies and Table 3-2 shows the overall A-weighted sound pressure levels monitored in a number of compartments for a range of sea-going vessels.

Table 3-2: Noise Levels in Different Compartments in a Range of Sea-Going Vessels.

Ship	Compartment	Leq dBA
Aircraft Carrier (CVS)	Engine Room	99
	Gear Room	92
	Flight Deck	123
Type 23 Frigate	Engine Room	107
	Flight Deck	104
Type 42 Destroyer	Aft Engine Room	99
	Mess	84
River Class Patrol vessel	Engine Room	105
	Generator Room	103
T-Class Submarine	Engine Room	94

For the majority of craft the Engine Room is the noisiest internal compartment and time spent in this area needs to be carefully managed. It may also be noted that the mess area on board a Type 42 destroyer exhibits noise levels of about 84 dBA. Although this is below the upper exposure action value of the European Legislation, when considering noise exposure over a 24-hour period (at sea) this "quiet" area may be sufficiently noisy to be contributory to the daily dose.

Table 3-2 shows that the most extreme noise environment on ship is the flight deck. For deck crew the major noise source will probably be the high levels of direct aircraft noise experienced through the take-off, landing and taxiing events. However, they will also be exposed to other noise such as communications signals (comprising of speech, noise transmitted down the speech line and auditory warnings), any other extraneous noise outside of the main take-off and landing events (e.g. other aircraft manoeuvring, generator noise) and noise exposure outside of the shift. All of this noise will contribute to the overall daily noise dose received. However, the actual daily dose received will be mainly determined by the number of aircraft operations managed during a working shift and how many shifts occur in a 24-hour period.

A joint US/UK trial conducted in 2001 [17] to assess the deck noise environment during Sea Harrier operations for use in the modelling of noise patterns for the JCA/JSF, showed the noise levels experienced on deck during the vertical landing of a Sea Harrier on deck reached 131 dB. Similar measurements made for a wider range of aircraft operating on US aircraft carriers showed deck crew are exposed to levels as high as 150 dB with afterburner (A/B) (Figure 3-7).
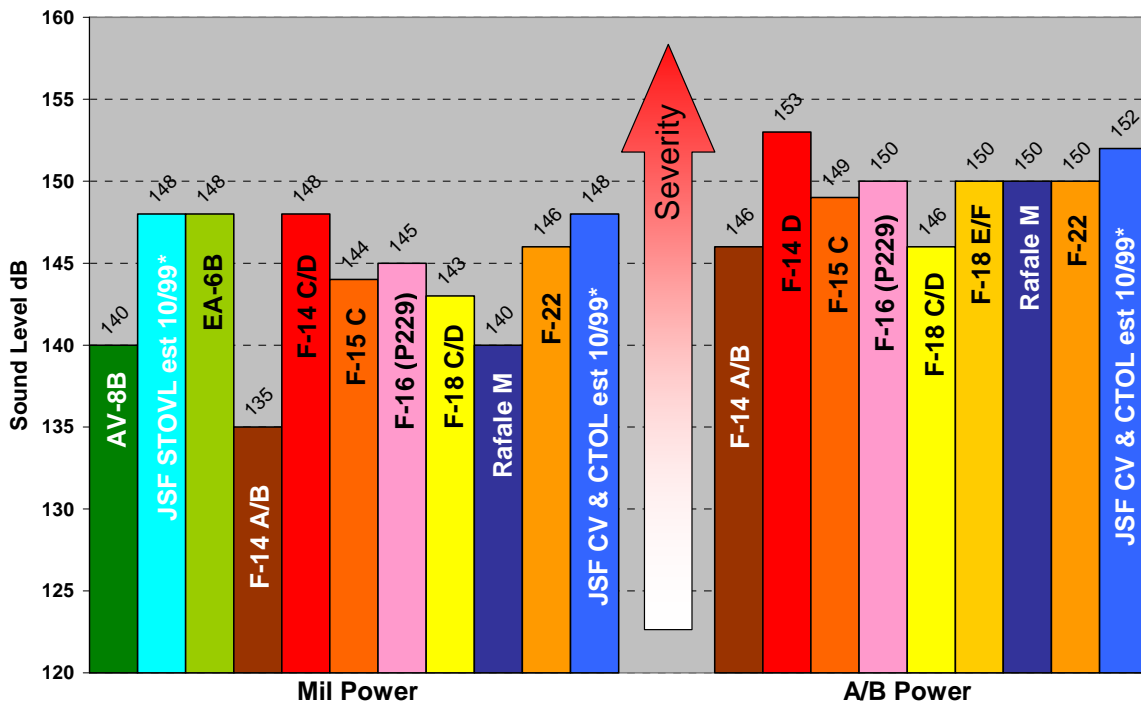
Typically 135 degrees off nose or 45 degrees off plume

Figure 3-7: Worst Case Aircraft Noise Levels at 50 ft.

3.2 IMPULSE NOISE FROM WEAPONS

The vehicle noise discussed in the previous sections may be considered "continuous noise" as personnel are generally exposed to the sound energy over a period of time spanning from possibly just a few seconds

up to a number of hours. However, "impulse noise events", such as those experienced during the firing of a weapon or the discharge of an explosive are characterised by a sharp initial pressure rise followed by an exponential decay which is determined by the absorbing character of the environment in which it is heard. The energy from most impulse noise is normally focussed into just a few milliseconds (ms) and can be sufficiently high to produce auditory impairment in an unprotected ear. In exceptional cases it may even result in damage to other organs of the human body, such as the lungs, the windpipe, the stomach, etc.

3.2.1 Weapon Impulse Noise Characteristics

For small calibre weapons, like handguns or assault rifles, a typical signature is shown in the left graph of Figure 3-8. The peak pressure level for these weapons is in the order of 160 dB and the A-duration is quite short, typically 300 to 600 µs. For large calibre weapons like howitzers or mortars, (right graph of Figure 3-8) the peak pressure at the firer's ear can reach up to 190 dB and the A-duration can exceed 2 ms.
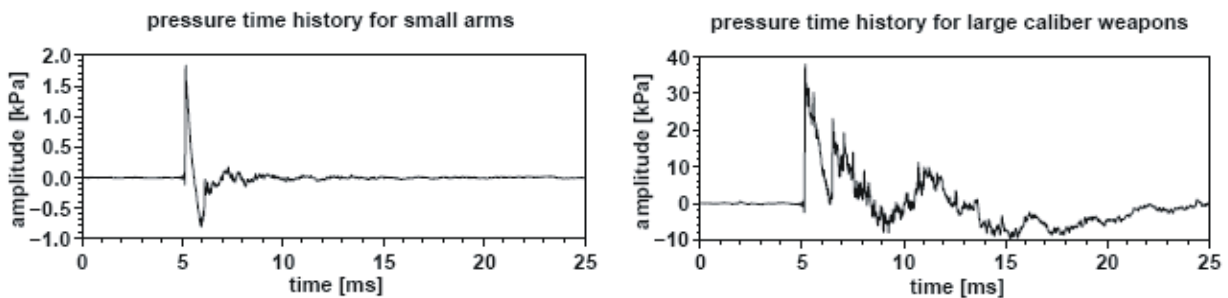
Figure 3-8: Typical Time Pressure History of a Small (left) and a Large (right) Calibre Weapon.

Such differences in peak pressure level and A-duration have an impact on the spectral composition of these signals. Figure 3-9 shows that only the amplitude of the spectrum (but not its shape) changes when the peak pressure is modified without modifying the A-duration.
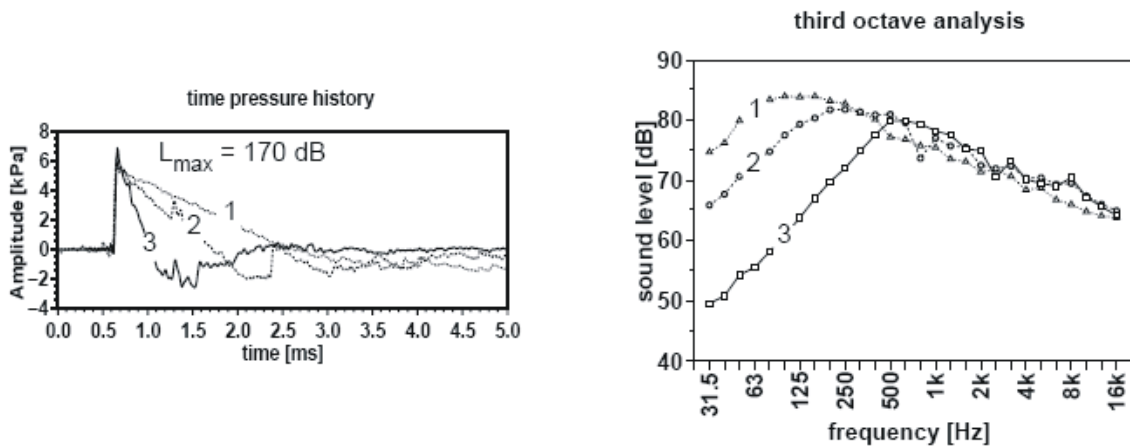
Figure 3-9: Spectral Compositions (Third Octave Analysis) for Weapon Noise with Constant A-Duration and Different Peak Pressure Levels.

When the peak pressure is kept constant (Figure 3-10) only the lower spectral components increase with increased A-duration. The high frequency components remain unchanged. As the damage risk to the auditory organ depends on the frequency, this should be taken into account, for exposure criteria.
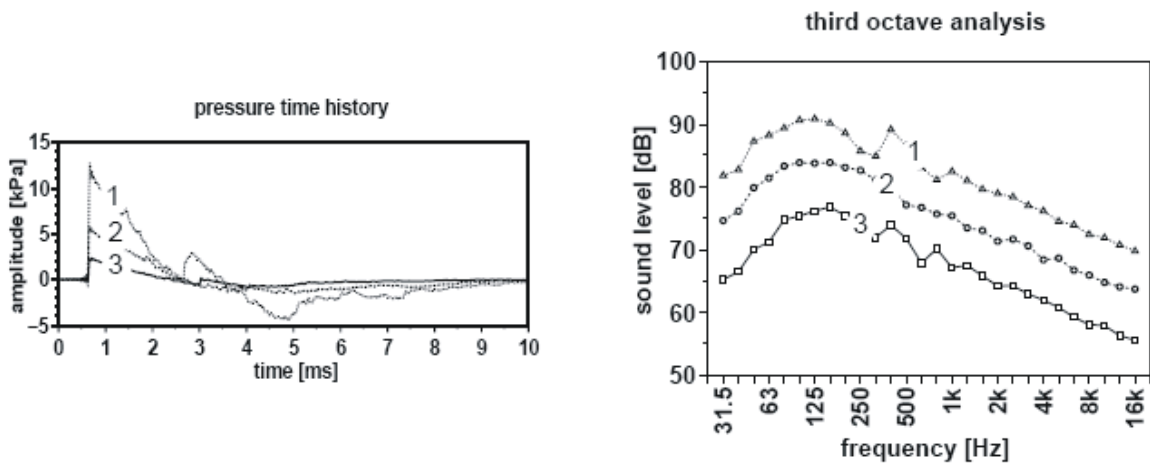
**Figure 3-10: Spectral Compositions (Third Octave Analysis) for Weapon
Noise with Constant Peak Pressure Level and Different A-Durations.**

3.2.2 Measurement of Weapon Noise

Considering the sharp rise times, short durations and high peak pressure levels which are specific to weapon noise (Figure 3-8 to Figure 3-10) and the fact that some of the used Damage Risk Criteria (DRC) are based on the precise measurement of peak pressure level and duration, additional considerations have to be taken into account for the measurement of impulse noise which might not be of importance for the measurement of continuous noise. In particular the choice of the transducer, the manner of the deployment, the sampling rate (when digital system acquisition is used) and the filtering of the electrical signal will have a major impact on the precision of the measurement. An overview of the parameters that need to be considered is given in Appendix 2 but more detailed information about the measurement procedures can be found in the 'International Test Operations Procedure (ITOP) 4-2-822 (2000)'.

3.2.3 Weapon Noise Exposure Levels

Figure 3-11 and Figure 3-12 below show the time pressure histories and the spectral characteristics for a single shot from a small assault rifle and a large Howitzer weapon and demonstrate the peak levels an unprotected shooter would experience. The peak pressure levels measured are 158.4 dB and 175.5 dB respectively and both exceed the Upper Exposure Action Value of the EU legislation for Impulse noise exposure which is set at 137 dB(C) when the wearing of hearing protection becomes mandatory.

Assault Rifle 5.56 mm
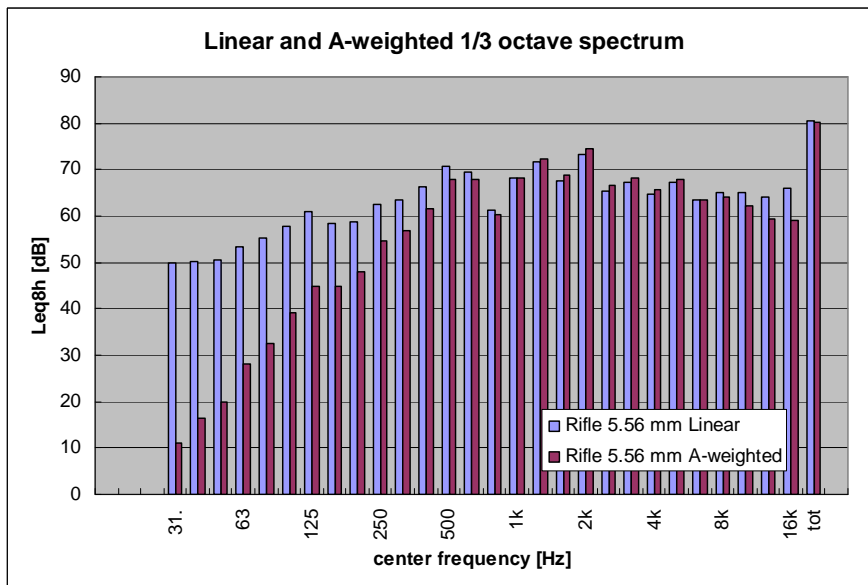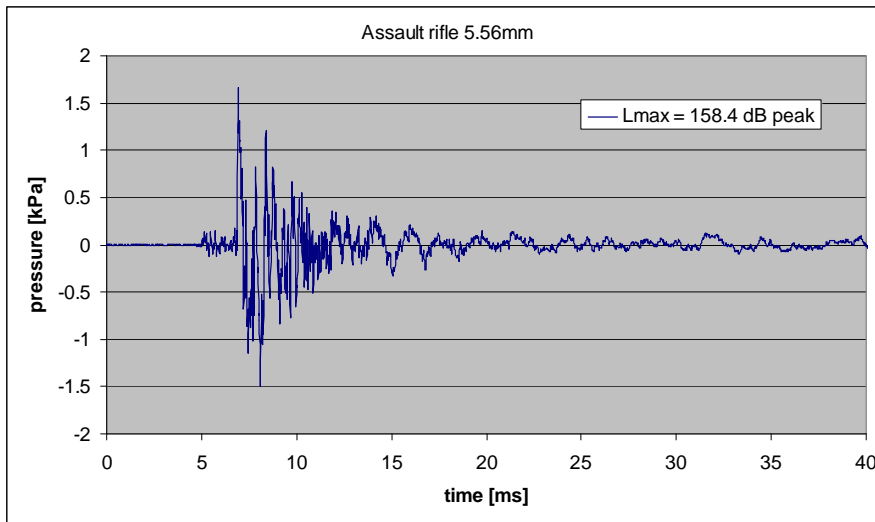
Figure 3-11: Time Pressure History and Spectrum for the Firing of a 5.56 mm Rifle.

Howitzer 155 mm
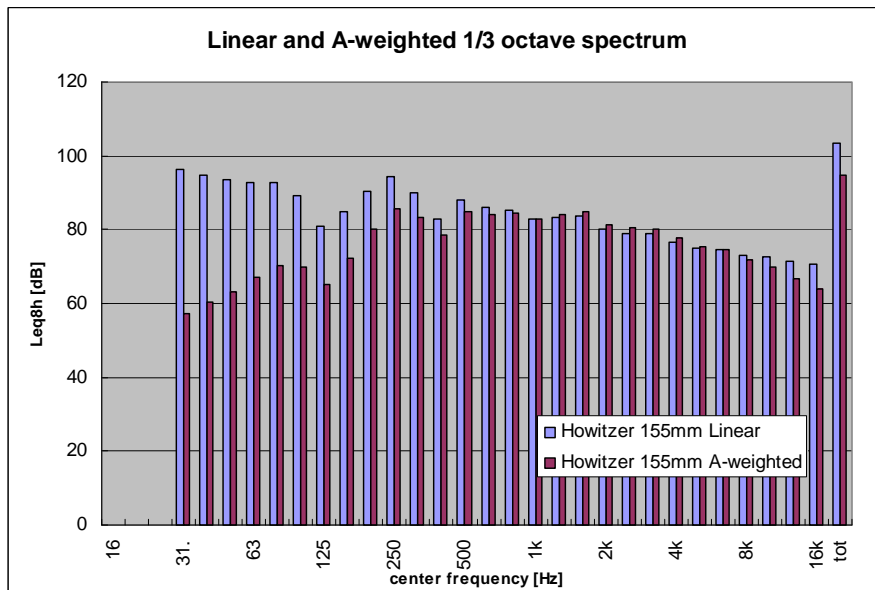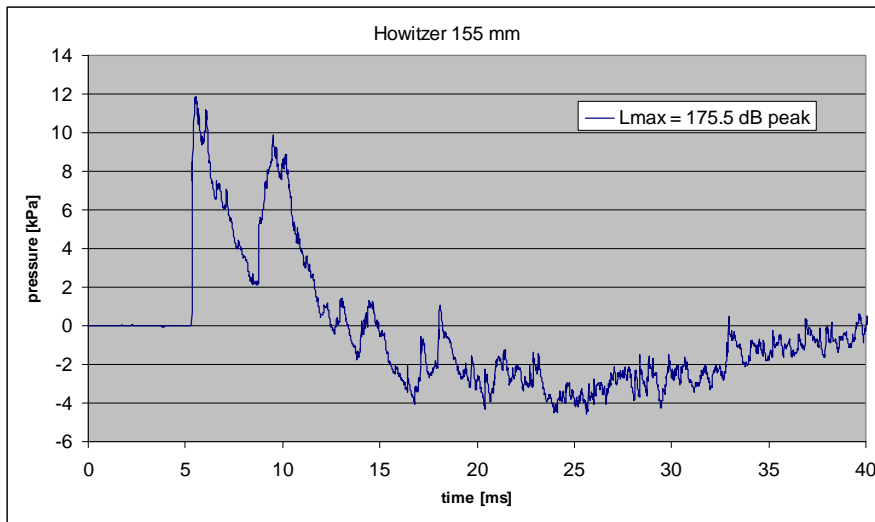
Figure 3-12: Time Pressure History and Spectrum for the Firing of a 155 mm Howitzer.

Table 3-3 and Table 3-4 have been compiled from measurements made by the Institute St. Louis (ISL) in France and the US Army Centre for Health Promotion and Preventative Medicine (CHPPM) in the USA. Both provide peak pressure levels measured for a range of other weapon types and all can be seen to exceed the Upper Exposure Action Value (UEAV) of the European legislation.

Table 3-3: Peak Pressure Levels for a Single Firing of a Range of Weapons Measured by the ISL.

Weapon Type	Lmax dB (peak)	L_{Aeq}8h dB
Assault Rifle 5.56 mm	158.4	80.6
Rifle 7.62 mm	151.9	75.5
Machine Gun 12.6 mm	177.2	97.8
Mortar 81 mm	164.5	89.0
Mortar 120 mm	183.8	
Howitzer 155 mm	175.5	103.4

Table 3-4: Peak Pressure Levels for a Single Firing of a Range of Weapons Measured by US Army.

Model	Name	Location	Sound Level dB (peak)
M16A2	5.56 mm rifle	Shooter	157
M9	9 mm pistol	Shooter	157
M249	5.56 mm squad automatic weapon fired from a HMMWV	Gunner	159.5
M60	7.62 mm machine gun fired from a HMMWV	Gunner	155
M2	0.50 caliber machine gun fired from a HMMWV	Gunner	153
MK 19 Mod 3	Machine gun fired from a HMMWV	Gunner	145
M26	Grenade	At 50 ft	164.3
M3	MAAWS recoilless rifle	Gunner	190
M72A3	Light Anti-tank Weapon (LAW)	Gunner	182
M119	10 5 mm towed Howitzer at charge 8	Gunner	183
M198	155 mm towed Howitzer firing M203 propellant	Gunner	178
M109A5/6	Paladin, 155 mm self-propelled Howitzer firing M4A2 zone 7 charge	Fighting compartment, hatches open	166.1
M110A2	8" self-propelled Howitzer firing M106 projectile with a M188A1 zone 9 propelling charge,	Gunner	176.9

3.2.4   Effects of Ammunition on Impulse Noise Levels

When considering a specific weapon a specific type of ammunition must also be considered. The type of ammunition used may also influence the level of impulse noise and risk to which military personnel are exposed. The use of blank ammunition during tactical training exercises is common practice and this training may be conducted without the use of hearing protection to maintain situational awareness. However, the number of blank ammunitions fired during these types of training exercises can be quite high and although the peak pressure levels measured for the firing of blank ammunition is almost 10 dB lower than real ammunition, there is still a significant risk of hearing loss if no hearing protection is used. As an example, the FNC rifle used by the Belgian Army produces an impulse of 159 dB peak ($L_{Aeq}8 = 76$ dBA) for real ammunition and 147 dB peak ($L_{Aeq} = 65$ dBA) for blank ammunition.

3.2.5   Exposure to Communications

It is important to note that hearing damage occurs in the early stages of the hearing process, i.e. as damage to the hair cells in the cochlea of the inner ear (Figure 3-13). Assuming that speech is equally as damaging as noise then the exposure to speech communication signals should be considered in calculating noise exposure. (NB: Experimental evidence is lacking showing the dose/hearing loss function for speech.) A conservative procedure considers that during operational duties the noise dose received by many personnel is a combination of both the ambient environmental noise transmitted through their Hearing Protection Device (HPD) and the electrical communication signal that is delivered directly to the ear via the communications telephone mounted in the HPD.
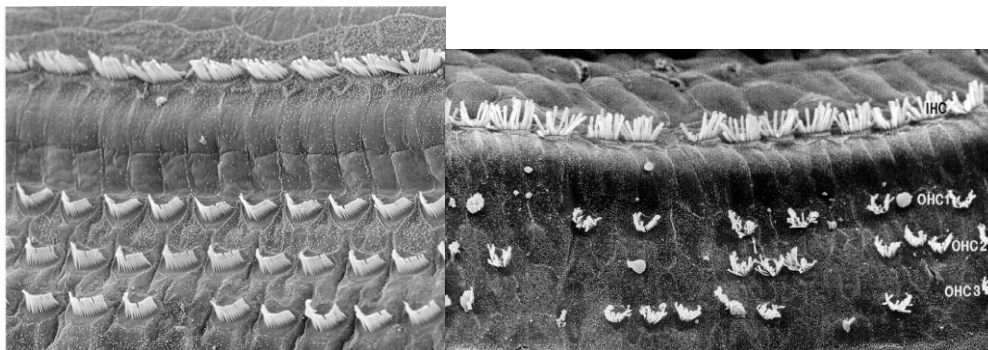
Figure 3-13: Hair Cells in the Inner Ear in a Healthy and Damaged Condition (NIHL).

For most operators speech communications are generally converted into electrical signals by a 'noise-cancelling' boom microphone, a microphone built into the oronasal oxygen mask or by throat/bone conduction microphones. In a high noise environment noise is often introduced into the speech communications line through the microphone of the speaker and then the transmitted signal becomes a combination of the intended signal (i.e. speech) and the unwanted noise. This combination signal is transmitted to the ear of the listener via radio or intercom and may be further contaminated with noise pick-up from the electronic systems or from radio interference (e.g. HF radio transmissions). This contamination of the intended signal will reduce its intelligibility and clarity and the additional noise will add to the overall noise dose received by the listener. Hence, when considering the total noise hazard it is important to address methods for reducing the levels of "unwanted" noise on the communications line as well as improved HPDs.

Table 3-5 has been compiled from a series of noise surveys conducted in a range of UK military aircraft and provides an indication of the contribution the communications load makes to the overall noise dose received by aircrew for the various aircraft types.

Table 3-5: Comms Contribution to Sortie Noise Dose Calculated for a Range of UK Aircraft.

Aircraft Category	Aircraft Type	Mean Comms Dose dBA	St.dev Dose dBA
Helicopters	Sea King Mk5	6.3	2.2
	Sea King Mk4	7.9	1.4
	Sea King Mk6	7.1	2.0
	Lynx Mk7 and Mk9	9.8	2.5
	Chinook HC1	8.6	2.6
	Tiger HAP	2.1	1.0
Fast Jet	Harrier GR5	10.0	4.3
	Jaguar GR1	9.9	4.2
	Tornado	10.4	2.9
	Hawk	9.1	3.2
	Sea Harrier	9.1	2.7
Training	Tucano	8.5	1.8
Transport	Hercules C1/C3	8.4	3.0
	HS125	10.6	4.8

3.3   SUMMARY OF MILITARY NOISE ENVIRONMENTS

The data provided in this section shows that many military personnel are exposed to extreme noise levels during the course of their duties and the level of hearing protection provided must be carefully chosen to minimize the risk of hearing damage without overprotecting and reducing situational awareness. For many operators the major noise sources are well defined and bounded. For aircrew and land vehicle drivers the predominant noise source that will largely determine the daily dose received will be the continuous internal vehicle noise. For ground crew and deck crew the dose received will be mainly due to external vehicle noise and aircraft take-off and landing events. However, for many other operators the situation is more complex as during a typical battlefield day noise exposure will be to many different sources of noise and the total dose received will be very dependent on the specific role and whether it is training or battlefield operations that are being considered.

For example, ground based troops may transit to the point of operation in a vehicle (APC, helicopter or landing craft) where their exposure will be mainly to high-level, continuous noise. At the point of operation (battlefield) soldiers may at one extreme be sitting in a quiet environment listening for enemies approaching where they need the full advantage that their own natural hearing and localization capability offers, unencumbered by hearing protection. But at the other extreme, in the midst of a gun battle, they may be subjected to the impulse noise from the firing of their own weapons, or weapons fired by other members of their unit or the enemy, mortars, grenades, explosives, etc., and the continuous noise of helicopter fly-over, tanks and other heavy equipment being operated in the near vicinity. Ultimately, they may again transit from the point of operations in a vehicle or helicopter. All these different noise sources and hearing requirements need to be considered, along with any communications load the operators receive, when looking to address suitable hearing protection for ground based troops (see Section 2.4).

For many operators, such as ground based troops, it is not possible to monitor noise exposure throughout a complete and representative working shift. However, a good prediction can be made of the dose likely to be received by developing typical Battlefield Days (BFDs) or Battlefield Missions (BFMs) for the different operator roles and vehicle types involved. This prediction can, in turn, then be used to determine the level of extra protection required to meet noise exposure standards and criteria or legislative criteria.

Chapter 4 – HEARING PROTECTOR TECHNOLOGIES

There is a wide range of hearing protection technologies currently on the market and many new concepts are under development that may become commercially available in the near future. The technologies include: passive earplugs and earmuffs, earplugs and earmuffs incorporating Active Noise Reduction (ANR), sound restoration devices and helmet mounted systems. Communications earplugs (including wireless versions) and headsets are being developed into operationally deployable products. For noise conditions where substantial attenuation is needed, such as flight decks, reducing the influence of bone conducted noise has recently received increased attention. Other hearing protection developments are aimed at maintaining audibility, localizability and communication ability. Some of these systems are based on analogue and/or digital electronics and have the potential to offer increased noise attenuation compared to conventional passive technologies. However, not all devices are equally suitable for all acoustic environments. Reduction in hearing damage risk will depend on matching the most appropriate hearing protection device to the specific noise environment and, in some cases, double hearing protection (using earplugs and headsets/ helmets in combination) may be required.

The following sections detail the individual hearing protection technologies and provide, in overview, a description of the device, typical laboratory and field performance figures (where appropriate), life cycle costs and state of the art developments.

4.1 CURRENTLY AVAILABLE HEARING PROTECTION DEVICES

The types of hearing protector devices will be presented in an order approximating the level of technical complexity. The order of presentation is noted below:

- 4.1.1 Passive Earmuffs
- 4.1.2 Passive Earplugs
- 4.1.3 Combination Passive Earmuffs and Earplugs
- 4.1.4 Communication Earmuffs
- 4.1.5 Communication Earplugs
- 4.1.6 Active (ANR) Earmuffs
- 4.1.7 Active (ANR) Earplugs
- 4.1.8 Non-Linear Earplugs
- 4.1.9 Level Dependent, Sound Restoring, Acoustically Transparent Earmuffs and Earplugs – Passive
- 4.1.10 Level Dependent, Sound Restoring, Acoustically Transparent Earmuffs and Earplugs – Active
- 4.1.11 Tactical Hearing Protectors
- 4.1.12 Helmets
- 4.1.13 Other Devices – Bone/Tissue Conduction Communication with HPD

4.1.1 Passive Earmuffs

4.1.1.1 Description

A passive earmuff consists of hard plastic cups which fit over and surround the ears (circumaural), and are sealed to the head by cushions filled with soft plastic foam or viscous liquid. Tension to assist the seal is provided by a headband (or neckband). They are clearly visible and therefore easily monitored.

4.1.1.2   Performance

The noise attenuation afforded is dependent on the size of the acoustic leak (which is dependent on the quality of the seal), the volume of the earcup, the mass of the earcup, the stiffness of the cushion, any absorptive liner provided and the headband tension.

4.1.1.3   Typical Laboratory Attenuation

For a passive earmuff the attenuation afforded ranges from 5 – 10 dB in the low frequencies, 63 Hz to 250 Hz, and up to 20 – 30 dB in the mid and higher frequencies, 500 Hz to 8 kHz.

Figure 4-1: Typical Laboratory Attenuation – Passive Earmuffs.

4.1.1.4   Typical Field Attenuation

The attenuation afforded by an earmuff in the field can be up to 90% of that measured for the same device in the laboratory. Earmuffs are easy to use and to (re)fit with consistent performance. Deterioration of performance may occur as a consequence of:

- Hardening or cracking of the cushion.
- Reduced tension of the headband.
- Deterioration of the absorptive liner inside the earcup.
- Use in combination with other head gear (eyeglasses, respirator, balaclava, sweat covers on the cushions).
- Hair, ear jewellery.

4.1.1.5   Life Cycle Costs

Acquisition costs for a passive earmuff device is dependent on the level of performance required but is typically 10 – 80 US$ per unit. The main life cycle costs associated with passive earmuffs is the replacement of the cushions every 1 – 2 years.

4.1.1.6   State-of-the-Art

The attenuation afforded by passive earmuffs may be enhanced by using one or more of the following features:

- Double-walled cups.

- Innovative cushions (materials, design).

- Custom-moulded cushions.

- Foam concha cushions.

4.1.2   Passive Earplugs

4.1.2.1   Description

A passive earplug is inserted and worn in the earcanal to form a seal. They are sometimes equipped with a cord or neckband to prevent loss. Universal earplugs are either disposable or reusable and available in different forms (pre-moulded, user-formable, semi-insert), materials (foam, silicone rubber), and different sizes. Alternatively, custom moulded earplugs are individually moulded to fit the shape of the user's earcanals. Comfort is frequently an issue with earplug users and leads to poor user fit and lower field attenuations, especially for use periods exceeding 2 hours. Choice of earplug materials can be driven by ambient weather conditions. For example, earplugs use/fit in hot and humid environments maybe compromised by loosening of the earplug by sweat. Additionally, earplugs also introduce a hygiene issue. Any dirt or oil on the hands of the user can be transferred to the earplug and the earcanal.

4.1.2.2   Performance

The attenuation afforded by earplugs is dependent on the quality of fit and the earplug material characteristics. The correct fit is often difficult to check by observation. For custom-moulded earplugs, the attenuation is mainly determined by the depth of the plug and the material characteristics. Compared to universal fit earplugs, custom moulded earplugs are becoming increasing popular with military hearing conservation programs because their attenuation performance is more repeatable due to more consistent, correct fittings by wearers in real-world operations. Custom earplugs match earcanal tortuosity making them more comfortable when the two fit together as puzzle pieces than when worn askew [18].

4.1.2.3   Typical Laboratory Attenuation

For a passive earplug the attenuation afforded ranges from 10 – 20 dB in the low frequencies to 30 – 40 dB in the mid and higher frequencies (deep insert).
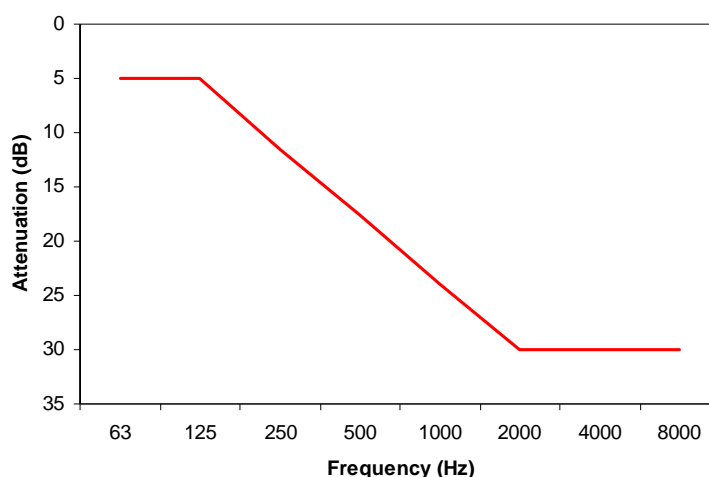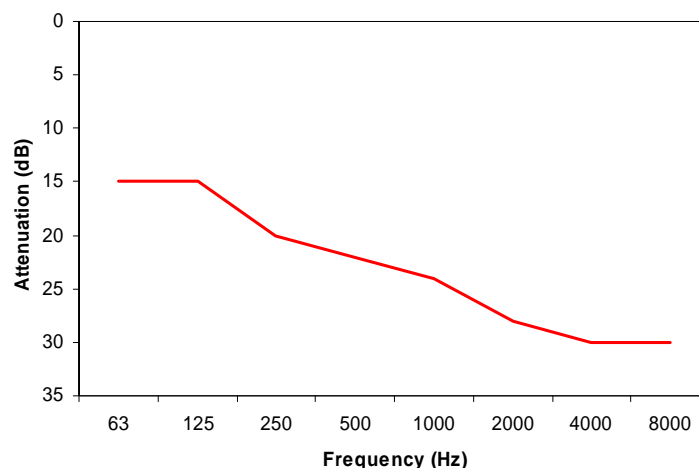

Figure 4-2: Typical Laboratory Attenuation – Passive Earplugs.

4.1.2.4   Typical Field Attenuation

The attenuation afforded by a passive, universal fit earplug is typically 33% of the attenuation measured for the same device in the laboratory [19]. While longitudinal studies of deep insert custom moulded earplugs have not been completed in the military, preliminary studies and repeated-trial fittings indicated near 100% repeatability of laboratory attenuation over periods of several months. Deterioration in performance may occur as a consequence of material degradation with time (especially with foams) and changes in fitting and loosening over time.

4.1.2.5   Life Cycle Costs

Acquisition costs for universal reusable or disposable earplugs are typically a few US$ (or fraction) per pair. The most commonly used devices are foam earplugs. They frequently become soiled in a single use and should be replaced. Therefore the annual cost (2 – 3 pair per day x number of workdays per year x cost of the foam earplugs) can easily exceed the cost of earmuffs and/or custom moulded earplugs. Acquisition costs for custom moulded earplugs is about 30 – 200 US$ depending on construction and may be a cost that has to be made every 1 – 3 years to maintain a high level of attenuation performance.

4.1.2.6   State-of-the-Art

Passive earplugs in pre-moulded and universal fit designs are commonly available in different shapes and materials. Field attenuation and comfort may be enhanced by using some form of custom fit procedure. Military research investments are further improving both comfort and attenuation performance of custom earplugs by transitioning from skilled artisan styling to near-prescription designs. Future custom earplug designs will be based off digital maps of earcanal shapes and sub-anatomy that will allow earplug depths and girths to be optimize for each and every earcanal independently [20].

4.1.3   Combination Passive Earmuffs and Earplugs

4.1.3.1   Description

A combination hearing protection system is where earmuffs (or helmet) and earplugs are worn in combination and may be required in extreme noise environments of more than 110 – 115 dBA, or when impulse peak sound pressure level exceeds 150 dB.

4.1.3.2   Performance

Double protection is a complex process and the overall attenuation achieved is always lower than the addition of the attenuation afforded by the two devices worn individually and frequently only a few dB more than the attenuation of the better performing device. Various empirical techniques have been used to attempt to predict the total attenuation achieved by double protection, but the most accurate method is still that of direct measurement. The overall performance is frequently limited by the Bone Conduction (BC) pathway. The most sensitive frequency band is usually around 2 kHz and is limited to approximately 40 – 45 dB of attenuation due to the bone conduction path.

4.1.3.3   Typical Laboratory Attenuation

The attenuation afforded by a double hearing protection system ranges from 15 – 25 dB in the low frequencies up to 30 – 50 dB in the mid and higher frequencies [21].
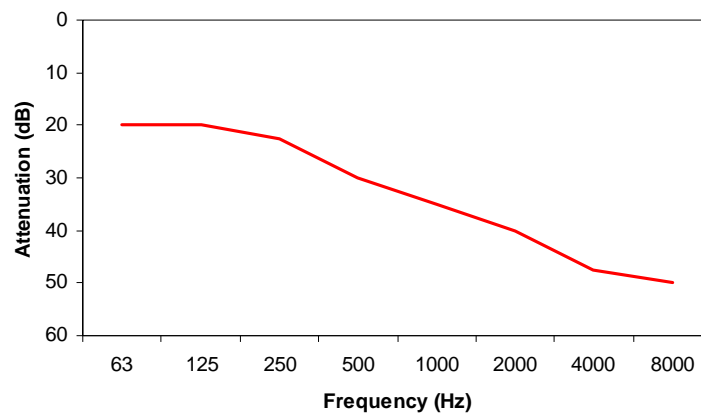
Figure 4-3: Typical Laboratory Attenuation – Combination Passive Earmuffs and Earplugs.

4.1.3.4 Typical Field Attenuation

In practice (field performance), of combination or double hearing protection is better than the 33% for the earplug and not as good as the 90% for the earmuff. It is most likely nearer the higher end of this range but there are very little data available on the field attenuation performance of combination or double hearing protection.

4.1.3.5 Life Cycle Costs

Acquisition cost is typically for passive technology 10 – 300 US$ per unit, generally depending on the price of the earmuff and earplug. Life cycle costs are the costs of replacements for each device's individual components.

4.1.3.6 State-of-the-Art

The key to high performance double or combination protection is prevention of direct mechanical coupling of the earmuff/helmet to the earplug and interaction of the earmuff/helmet directly with the head and/or ear (pinnae). New technologies, such as damping foams, are being investigated to reduce or eliminate the direct mechanical coupling of the acoustic energy to the head and/or tissues and should improve the performance of combination/double hearing protection systems by reducing the bone conduction pathway. Wireless Communications Earplugs (w-CEPs) are also being developed which can overcome some of the integration issues associated with routing earplug cables around the helmet and headset. There are a number of methods for achieving a wireless link between the communication system and earphone in the earplug, including: optical infrared, Bluetooth, and magnetic induction.

4.1.4 Communication Earmuffs

4.1.4.1 Description

A communication earmuff consists of hard plastic earcups with an earphone installed which fit over and surround the ears (circumaural) and are sealed to the head by cushions filled with soft plastic foam or viscous liquid. Tension to assist the seal is provided by a headband (or neckband).

4.1.4.2 Performance

The noise attenuation afforded is dependent on the size of the acoustic leak (which is dependent on the quality of the seal and any cable penetrations), the mass of the earphone element, the volume of the earcup

minus the volume of the earphone, the mass of the earcup, the stiffness of the cushions, any absorptive liner provided and the headband tension.

4.1.4.3 Typical Laboratory Attenuation

For a communication earmuff the attenuation afforded are similar to those for passive earmuffs with ranges from 5 – 10 dB in the low frequencies, 63 – 250 Hz, and up to 20 – 30 dB in the mid and higher frequencies, 500 Hz to 8 kHz.

Figure 4-4: Typical Laboratory Attenuation – Communication Earmuffs.

4.1.4.4 Typical Field Attenuation

The attenuation afforded by a communication earmuff in the field can be up to 90% of the attenuation measured for the same device in the laboratory. Communication earmuffs are easy to use and easy to (re)fit with consistent performance. Deterioration of performance may occur as a consequence of:

- Hardening or cracking of the cushion.
- Reduced tension of the headband.
- Loss of grommet sealing the cable penetrations.
- Deterioration of the absorptive liner inside the earcup.
- Use in combination with other head gear (eyeglasses, respirator, balaclava, sweat covers on the cushions).
- Hair, ear jewellery.

4.1.4.5 Life Cycle Costs

Acquisition costs for a communication earmuff device is dependent on the level of performance required but is typically 100 – 300 US$ per unit. The main life cycle costs associated with communication earmuffs are the replacement of the cushions every 1 – 2 years and the monthly checking of the earphones with occasional replacement of an earphone.

4.1.4.6 State-of-the-Art

The attenuation afforded by communication earmuffs may be enhanced by using one or more of the following features:

- Double-walled cups.

- Innovative cushion (materials, design).

- Custom-moulded cushions.

- Foam concha cushion.

4.1.5   Communication Earplugs

4.1.5.1   Description

A communication earplug is inserted and worn in the earcanal to form a seal. They normally have an acoustic tube to deliver the communication signal directly to the eardrum (tympanic membrane) from a miniature earphone. When designed for pilot use, they sometimes have another acoustic tube for pressure equalization. The communication signal to the earphones may be delivered via a cable. They are sometimes equipped with a cord or neckband to prevent loss. Universal earplugs are either disposable or reusable and available in different forms (pre-moulded, user-formable, semi-insert), materials (foam, silicone rubber), and different sizes. Alternatively, custom moulded communication earplugs are individually moulded to fit the shape of the user's earcanals. Comfort is frequently an issue with communication earplug users and leads to poor user fit and lower field attenuations, especially for use periods exceeding 2 hours. Choice of communication earplug materials can be driven by ambient weather conditions. For example, communication earplugs use/fit in hot and humid environments maybe compromised by loosening of the earplug by sweat. Additionally, communication earplugs also introduce a hygiene issue. Any dirt or oil on the hands of the user can be transferred to the earplug and the earcanal.

4.1.5.2   Performance

The attenuation afforded by communication earplugs is dependent on the quality of fit, the size of the pressure equalization port, the connection of the miniature earphone, and the earplug material characteristics. The correct fit is often difficult to check by observation. For custom-moulded communication earplugs, the attenuation is mainly determined by the depth of the plug, the pressure equalization tube (if present), and the material characteristics. Communication earplugs are becoming increasing popular due to their communication enhancement properties and capability of operating as part of a double hearing protection system.

4.1.5.3   Typical Laboratory Attenuation

For a communication earplug the attenuation afforded ranges from 10 – 20 dB in the low frequencies to 30 – 40 dB in the mid and higher frequencies (higher attenuations can be achieved with a deep insert custom earplug).
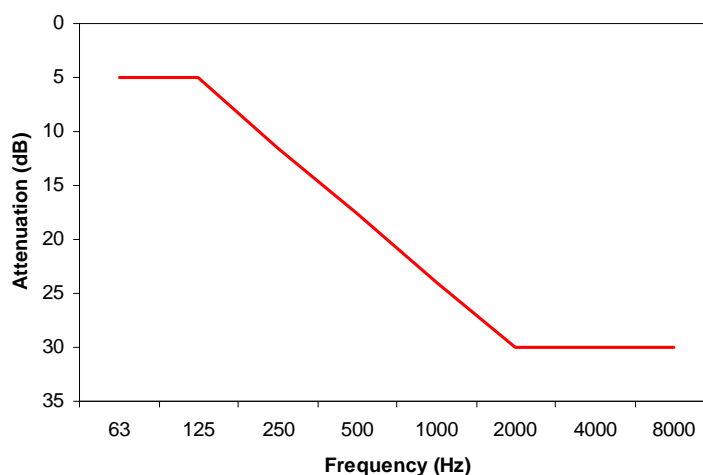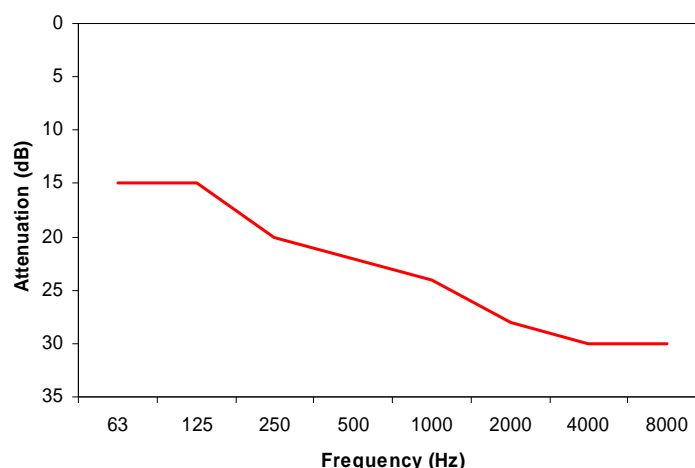
Figure 4-5: Typical Laboratory Attenuation – Communication Earplugs.

4.1.5.4   Typical Field Attenuation

The field attenuation afforded by communication earplugs has not been studied and no data was available at the time of this report. However, it is expected that the field performance would be similar to the field performance of passive earplugs.

4.1.5.5   Life Cycle Costs

A universal fit communication earplug can have an acquisition cost of 100 – 150 US$ per pair. The commonly used universal fit designs include foam earplugs tips. They frequently become soiled in a single use and should be replaced. Therefore the annual cost (1 pair per day x number of workdays per year x cost of the foam earplugs tips). Acquisition costs for custom moulded communication earplugs is about 200 – 500 US$ depending on construction and there may be an additional cost (30 – 100 US$) that has to be made every 1 – 3 years to replace the custom earplug to maintain a high level of attenuation performance.

4.1.5.6   State-of-the-Art

Communication earplugs in pre-moulded and universal fit designs are commonly available in different shapes and materials. Field attenuation and comfort may be enhanced by using some form of custom fit procedure. Military research investments are further improving both comfort and attenuation performance of custom communication earplugs by transitioning from skilled artisan styling to near-prescription designs. Wireless communication links are emerging for communication earplugs. These designs typically use a coil or optical couple to relay the communication signal wirelessly to the earplug.

4.1.6   Active (ANR) Earmuffs

4.1.6.1   Description

Active Noise Reduction (ANR) earmuffs incorporate an electronic sound cancelling system ("anti-noise") that typically provides additional noise attenuation at the lower frequencies. ANR earmuffs can be achieved using both analogue and digital designs. There is no clear advantage of one implementation over the other. Active cancellation can be achieved using either a feedback (typical) or feed-forward (rare) design.

4.1.6.2 Theory of Operation

ANR earmuff systems generate anti-noise through a loudspeaker in the earmuff (Figure 4-6). Systems can either be feed-forward, feedback, or a hybrid of both. Feed-forward systems make use of available information about the noise to be attenuated. This requires a microphone at the noise source. Feed-forward ANR systems are especially suited to use with narrowband, predictable noises. Feedback systems do not make use of information about the noise source. Inside the earmuff, near the loudspeaker, a microphone registers the noise and generates the anti-noise via a correction filter and amplifier. Feedback systems work well for random noises, which is of great importance for use in hearing protectors. Hybrid systems are a combination of feed-forward and feedback systems. The objective is to handle random noise and tonal components of the noise to achieve an optimal overall noise reduction. The electronic circuitry can in principal be extended to add communications and to compensate for a specific hearing loss, in order to have optimal speech intelligibility.
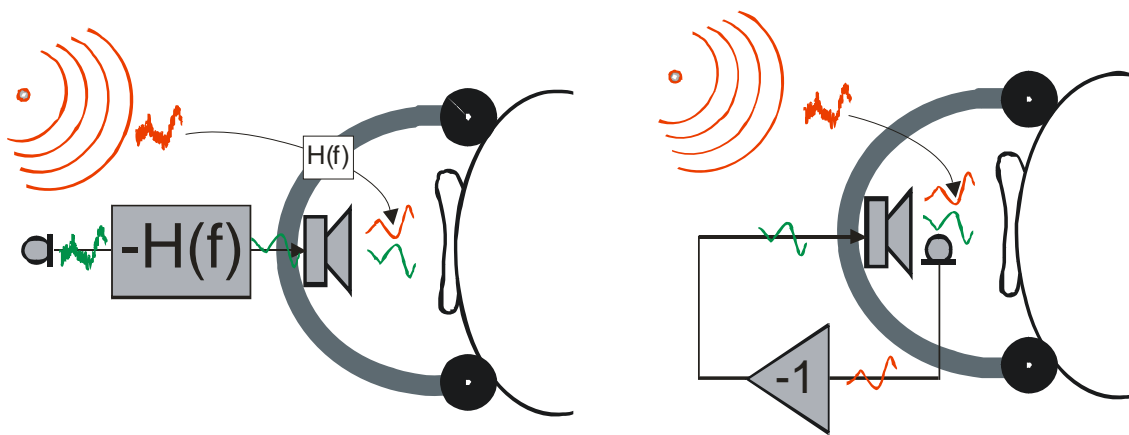
Figure 4-6: Simplified Principle of a Feedforward (left) and a Feedback (right) ANR Control.

4.1.6.3 Performance

An ANR earmuff affords higher levels of low frequency attenuation (up to about 1 kHz) compared to a standard communication earmuff. The performance of the ANR and standard earmuff is similar at the mid and high frequencies. ANR earmuff systems exhibit a wide range of active and passive attenuation performance. Additionally, all ANR systems have a maximum noise level (approximately 130 dB for the best systems) at which they can no longer actively attenuate the noise. Some systems will no longer attempt to actively cancel noise once the maximum noise limit is reached and only provide passive attenuation above these levels. A crucial issue for ANR earmuffs is stability of the system (risk of oscillation). Heavily fluctuating noises (e.g. helicopter noise) or impulsive sounds may cause instability in some ANR systems. Instability can cause some ANR systems to generate additional noise. All ANR systems will have some portion of the noise signal that may be amplified by a small amount. Typically this occurs in the octave above the cross-over frequency and is about 3 dB. This factor usually does not normally add to the noise exposure since the passive attenuation is typically more than adequate at these frequencies.

4.1.6.4 Typical Laboratory Attenuation

For an ANR earmuff In active mode, the total attenuation will typically be 15 – 20 dB in the low frequency range (<1 kHz), rising to 20 – 30 dB for the mid and higher frequencies. The active component is typically highest, 15 – 20 dB, in the 125 – 250 Hz bands and is approximately 0 dB at 1 kHz. Typically, ANR earmuffs can reduce the overall A-weighted noise at the ear by 3 – 12 dB depending on the noise spectrum, with the better performance occurring in noise spectra which are predominately low frequency noise.

Figure 4-7: Typical Laboratory Attenuation – Active (ANR) Earmuffs.

4.1.6.5 Typical Field Attenuation

As for passive earmuffs the passive attenuation achievable in the field with ANR earmuffs can be up to 90% of the passive attenuation achieved in the laboratory for the same device. However, most of the active attenuation will be achieved in the field. For most ANR earmuffs it is essential that a good seal is achieved (i.e. a good fit around the ear), to avoid oscillation or instability. Eyeglasses can introduce an acoustic leak and may marginally or severely degrade the active and passive attenuation according to the size of the temple piece of the eyeglasses and design of the ANR earmuff.

4.1.6.6 Life Cycle Costs

ANR earmuff systems are more expensive than passive earmuffs. Typical acquisition cost are 250 – 1000 US$ per system. Many ANR systems are powered via vehicle power (with associated cost to wire some vehicles) although some are powered by batteries which must be replaced on a regular basis. Additional life cycle costs are incurred in the replacement of cushions and earcup foam.

4.1.6.7 State-of-the-Art

Latest developments in ANR earmuffs use a digital implementation of the feedback or feed-forward design. There are no inherent performance advantages in a digital ANR earmuff design when compared to an analogue design. However, digital systems make it possible to use adaptive filtering and to easily vary the extent of active attenuation depending on the ambient noise spectrum.

4.1.7 Active (ANR) Earplugs

4.1.7.1 Description

ANR earplugs are not yet in common use and are normally in a (sometimes well advanced) development stage. The basic active noise reduction principles are the same as those in ANR earmuffs. The volume and the distance between the loudspeaker and the microphone play an important role in ANR devices. The smaller distances in ANR earplugs allow a greater maximum bandwidth of attenuation than ANR earmuffs. Figure 4-8 shows the two possible physical implementations of these earplugs.

- **Close to the earcanal (left):** In this case, the electro-acoustic elements are placed outside of the earcanal. This allows the use of larger receivers (loudspeakers) and microphones. The advantage

of these receivers is that they are able to deliver higher levels at the lower frequencies. Another advantage of such a configuration is that the air volume in the plug is large and it is therefore less sensitive to the inter-individual differences of the middle ear volume.

•   **In the earcanal (right):** In this configuration both, receiver and microphone are installed inside the part of the earplug that is introduced in the earcanal. Using such a scheme, the smaller receiver usually has a larger bandwidth which, together with the small volumes involved, should provide ANR over a broader bandwidth than can be achieved with an ANR earmuff.

"Close to the Earcanal"   "In the Earcanal"
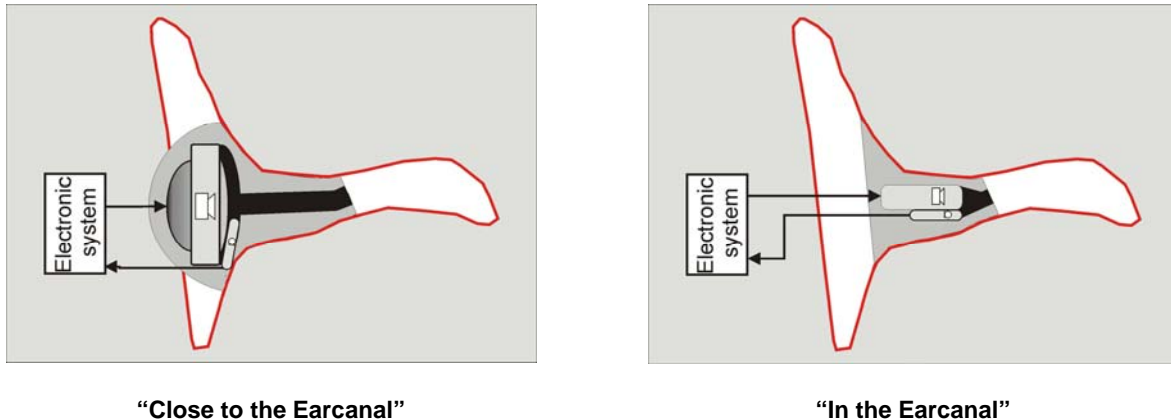
Figure 4-8: Possible Implementations of an ANR Earplug.

4.1.7.2   Performance

An ANR earplug affords higher levels of total attenuation (up to about 3 kHz) compared to a standard ANR earmuff. ANR earplug systems exhibit a wide range of active and passive attenuation performance. Additionally, all ANR systems have a maximum noise level (approximately 130 dB for the best systems) at which they can no longer actively attenuate the noise. For ANR earplugs this maximum level can be raised by using a passive earmuff in a double hearing protection system to reduce the maximum noise level seen by the ANR earplug.

4.1.7.3   Typical Laboratory Attenuation

For an ANR earplug in active mode, the total attenuation will typically be 15 – 20 dB in the low frequency range (<1 kHz), rising to 20 – 30 dB for the mid and higher frequencies. The active component is typically highest, 15 – 20 dB, in the 250 – 500 Hz bands and is approximately 0 dB at 3 kHz. Typically, ANR earplugs can reduce the overall A-weighted noise at the ear by 3 – 10 dB depending on the noise spectrum.

Different controller implementations are possible with an ANR earplug and may achieve broader bandwidth active attenuation. Different control schemes also allow the earplug system to target different parts of the spectrum.
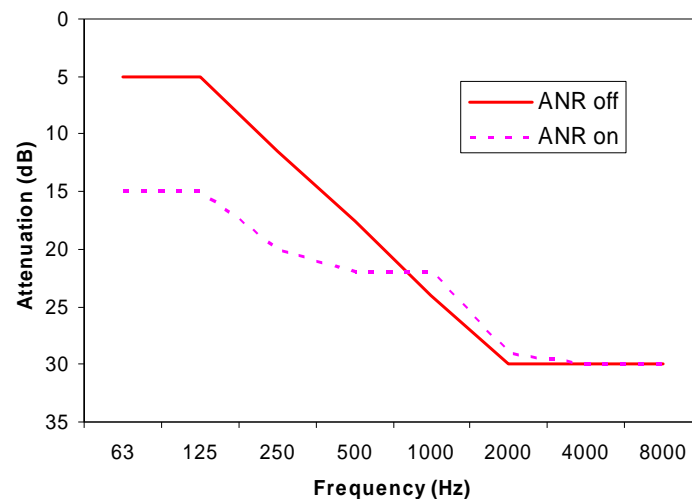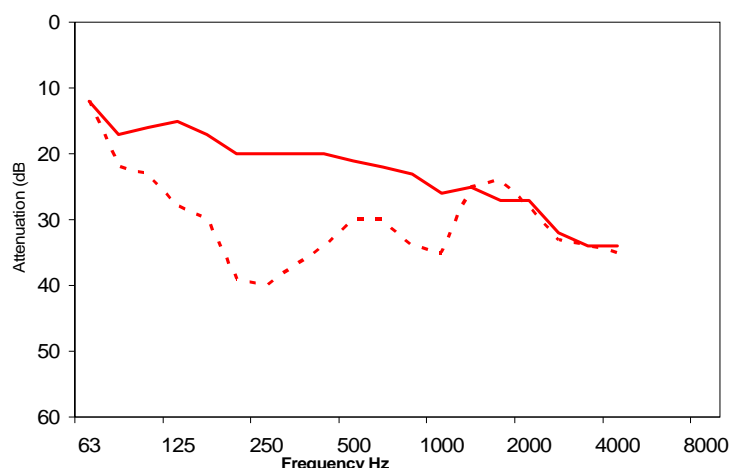
Figure 4-9: Typical Laboratory Attenuation – Active (ANR) Earplugs.

4.1.7.4   Typical Field Attenuation

As for passive earplugs the attenuation achievable in the field with ANR earplugs can be dependent on the acoustic seal. However, with active earplugs most of the active attenuation will be achieved in the field. For some ANR earplugs it is essential that a good seal is achieved in the earcanal, to avoid oscillation or instability. Eyeglasses are not a factor with ANR earplugs.

4.1.7.5   Life Cycle Costs

ANR earplug systems are generally more expensive than ANR earmuffs. Typical acquisition cost are 150 – 3500 US$ per system. It is expected that when ANR earplugs are produced in large volumes that their cost should be comparable to ANR earmuffs and less than hearing aids. Many ANR systems are powered via vehicle power (with associated cost to wire some vehicles) although some are powered by batteries which must be replaced on a regular basis. Additionally life cycle costs are incurred in the replacement of the custom or universal fit earplugs.

4.1.7.6   State-of-the-Art

ANR earplugs are an emerging technology. Just like ANR earmuffs they can use a digital or analogue implementation of the feedback or feed-forward design. There are no inherent performance advantages in a digital ANR earplug design when compared to an analogue design. However, digital systems make it possible to use adaptive filtering and to easily vary the extent of active attenuation depending on the ambient noise spectrum. The digital systems are also easier to tune to the individual user.

4.1.8   Non-Linear Earplugs

4.1.8.1   Description

Level dependant earplugs are designed to afford the protection needed against impulse (weapon) noise which may be encountered for the majority of weapons used. During periods without impulse noise, they allow vocal communication as well as detection and localization of noise sources present in the environment. Due to the little attenuation that is delivered by these devices when moderate (up to 110 dB) levels are present, these devices are not meant to be used as protection against loud continuous noise exposure.

4.1.8.2   Theory of Operation

Two basic principles are used for level dependent earplugs:

- **Mechanic Occlusion of the Sound Canal:** These systems use the sudden increase of the air particle flow due to the initial impulse to displace a membrane in the sound canal and to stop any further raise of the pressure in the ear canal. This type of systems acts in a way that is comparable to a switch. Figure 4-10a shows schematically the effect of this principle where the residual peak pressure behind the small hole in the plate (in the ear canal) is a function of the peak pressure at the other side of the plate.

- **Aerodynamic Properties of Small Holes:** The level dependency of these systems is related to the changes in acoustic impedance that occur due to the increasing velocity of airflow in a small hole through the earplug. Figure 4-10b shows schematically the modification of the insertion loss with increasing peak pressure.

$$L_{peak} \qquad L_{peak} \cdot k(L_{peak})$$

| (a) | (b) |
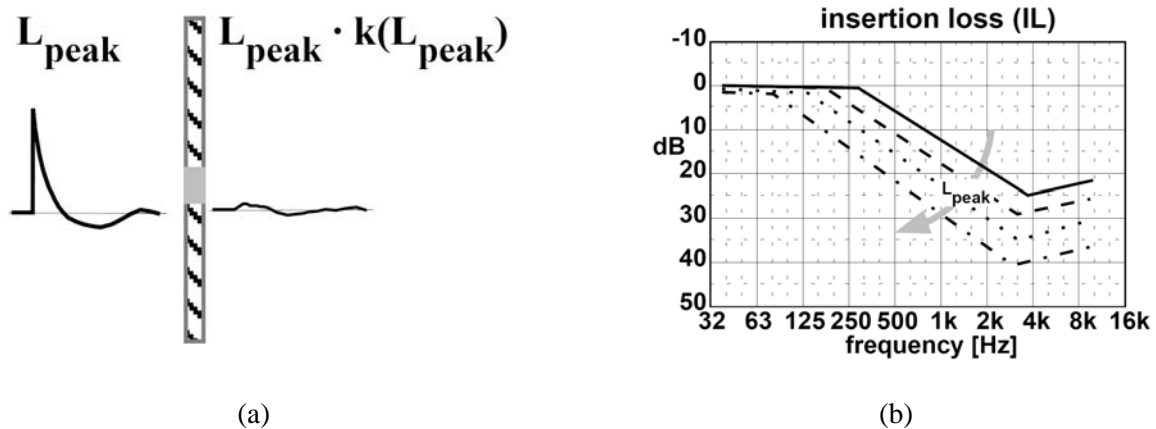
Figure 4-10: Non-Linear Earplug Performance.

4.1.8.3   Performance

Level dependant earplugs should ideally have no (or very little) noise attenuation if used in quiet environments. It is especially important that the frequency range necessary to allow speech communication should not be attenuated. When the user is exposed to weapon noise, the noise attenuation should increase and give appropriate protection for the given noise exposure. For the highest exposure level the earplug should perform like a linear earplug of the same type.

4.1.8.4   Typical Laboratory Attenuation

As the performance of these types of devices can only be measured using high-level impulse noise created with explosive charges or shock tubes, it can only be evaluated on artificial test fixtures. The graph below shows the insertion loss of a level dependent earplug equipped with the ISL non-linear element. It can clearly be seen how the protection increases gradually with the increasing peak pressure level.
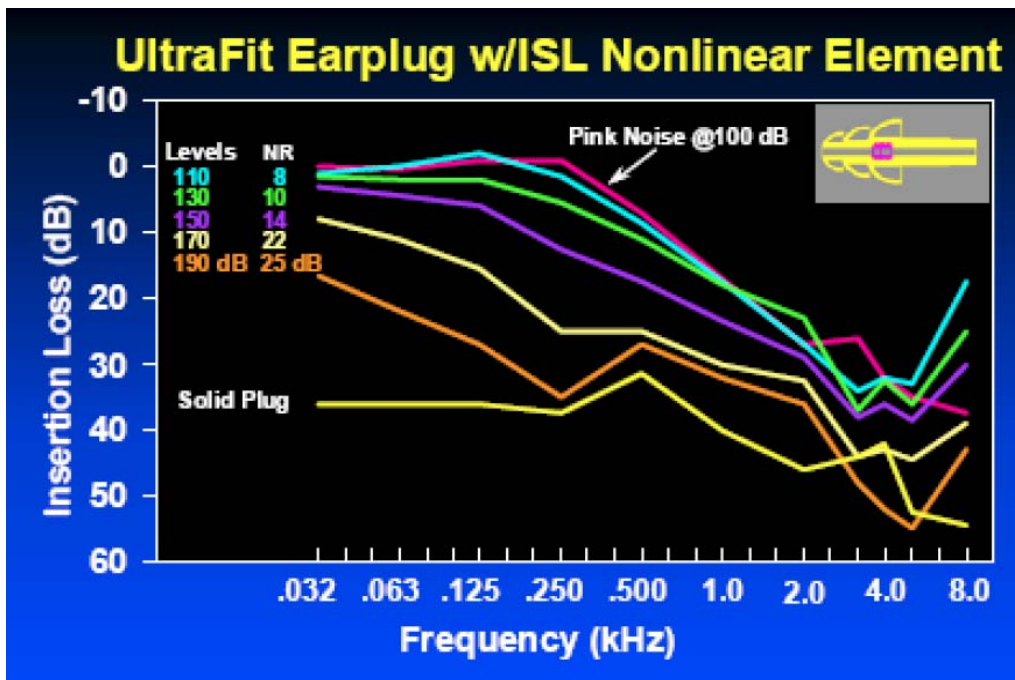
**Figure 4-11: Insertion Loss of Combat Arms Earplug (CAEP) in Impulse Noise from 110 dB
to 190 dB Peak (http://chppm-www.apgea.army.mil/documents/fact/51-004-0204.pdf).**

4.1.8.5   Typical Field Attenuation

It is important that a level dependent earplug is properly fitted into the ear canal if optimum performance is to be achieved. With a poorly fitting earplug the attenuation of even high-level impulses may be lower than the 110 dB-curve. In the case of a misfit of the plug, the non-linear behaviour will be lost.

4.1.8.6   Life Cycle Costs

The cost of a non-linear passive earplug is, if the non-linear element is inserted in a remoulded earplug, between 5 and 15 US$ per pair. If individually moulded plugs are used, the price will be close to that of the moulded plug.

4.1.8.7   State-of-the-Art

The design of the non-linear element is mature and can be used in all types of earplugs. New emerging designs are being developed in order to overcome the limitation of use in loud continuous noise. These devices use mechanical elements to block the airflow through the non-linear element when used in continuous noise.

4.1.9   Level Dependent, Sound Restoring, Acoustically Transparent Earmuffs and Earplugs – Passive

4.1.9.1   Description

Sound restoring protectors are level dependent devices, which are designed to protect against hazardous noise while allowing communication during quiet periods. These devices usually incorporate a Venturi of some kind to achieve the desired non-linear attenuation. At the time of this report, none of these devices were truly acoustically transparent or sound restoring.

4.1.9.2 Theory of Operation

Level dependent implies a non-linear attenuation function, i.e. one that varies with level. Passive level dependent earmuffs and earplugs typically rely on a Venturi or valve to achieve this non-linear attenuation. At low sound pressure levels the flow thru the Venturi or valve is linear and laminar and the acoustic signal is attenuated only a small amount. As the sound pressure increases to high levels, the flow thru the Venturi becomes turbulent and the flow is reduced lowering the sound pressure level downstream of the Venturi or valve. The attenuation increases with sound pressure level. Typically, this non-linear effect does not become a factor until the sound pressure level is greater than 130 dB.

4.1.9.3 Performance

These types of hearing protectors typically provide only small amount (<6 dB) of passive attenuation for any noises except impulse noises (typically over 130 dB) and high level (>110 dB) continuous noises. The passive level dependent earmuffs frequently are subjectively preferred by users in a test or demonstration while the scientific attenuation and temporary threshold shift data demonstrate that normal passive earmuffs provide better attenuation and protection from temporary threshold shifts. The better of the passive level dependent earplugs, when well inserted, typically provide about 6 dB of attenuation for low level noise and up to 25 dB of attenuation for large impulses (190 dB peak).

4.1.9.4 Typical Laboratory Attenuation

Earmuff, passive, level dependent

	Low Level (<130)	High Level (>150)
Continuous Noise	6 dB	15 dB
Impulsive Noise	6 dB	15 dB

Earplug, passive, level dependent

	Low Level (<130)	High Level (>150)
Continuous Noise	6 dB	25 dB
Impulsive Noise	6 dB	25 dB

4.1.9.5 Typical Field Attenuation

The attenuation afforded by a passive, universal fit level dependent earplug is typically 33% of the attenuation measured for the same device in the laboratory [19]. Deterioration in performance may occur as a consequence of material degradation with time (especially with foams) and changes in fitting and loosening over time. The attenuation afforded by this type of earmuff in the field can be up to 90% of that measured in the laboratory.

4.1.9.6 Life Cycle Costs

The cost of the combat arms earplug for a single pair on the commercial market is about 9 US$ in 2009. In large numbers, the combat arms earplug may be purchased for significantly less than that number. Like any earplug, the combat arms earplug should be periodically replaced. The time is dependent on use. A rough estimate would be one to two pairs per year per user. Level dependent active earmuffs are significantly more expensive. When available, single units are approximately 100 US$.

4.1.9.7 State-of-the-Art

The only passive level dependent earplug or earmuff in use in large numbers is the Combat Arms Earplug (CAEP). Therefore, this device represents the state-of-the-art. This earplug is actually two earplugs, one is a traditional passive earplug to be used in continuous noise and the second is a passive level dependent earplug for use in ambient listening and impulsive noise.

4.1.10   Level Dependent, Sound Restoring, Acoustically Transparent Earmuffs and Earplugs – Active

4.1.10.1   Description

Sound restoring protectors are level dependent devices, which are designed to protect against hazardous noise while allowing communication during quiet periods. Devices incorporate an electronic sound reproduction system. At low noise levels the sound picked up by the microphone is relayed to a loudspeaker inside the muff or plug. With increasing noise levels above threshold, the electronics gradually reduce transmission. An example is miners' earmuffs which allow the miners to listen to the sounds of the cracking sounds of the "roof" while protecting the user from the noise of the mining machine.

4.1.10.2   Theory of Operation

Level dependent implies a non-linear attenuation function, i.e. one that varies with level. The system uses an external microphone connected via an active electronic circuit to the earphone. The electronics control the attenuation or insertion loss up to the limit of the passive attenuation of the earmuff or earplug. The active systems use an electronic circuit or computer to define/provide the non-linear function. This non-linear function can be as simple as a hard limit of the overall level provided to the user or as complicated as an exponential compression function based on noise exposure or dose. Some systems also have both an attack and decay function on the non-linear portion of the system. In some cases, the attack and decay functions are very rapid and can allow an intelligible conversation to be conducted during rapid firing of weapons.

4.1.10.3   Performance

Attenuation or insertion loss performance is dependent on the design of the electronics circuitry and on the mechanical design as for passive earmuffs or earplugs (see under passive devices above). Issues of the electronics design:

- Appropriate circuitry to limit the noise exposure so that criterion levels are met for different types of noise (low, mid, or high frequency).

- Approach input/output gain functions that preserve transparent hearing while protecting the user from noise exposure.

- Power consumption that allows a minimum of one duty day without recharging or changing batteries.

- Transducers, both earphones and microphones that will perform in the noise environments of use. These levels can be up to 195 dB in impulsive noise environments.

4.1.10.4   Typical Laboratory Attenuation

The attenuation or insertion loss in passive mode (sound restoration switched off) is the same as for a passive muff or plug. Attenuation is varying and only relevant for noise levels above threshold. Some examples are shown below:

Earmuff, active, level dependent

	Low Level	High Level (>150)
Continuous Noise	0 dB	15 – 25 dB
Impulsive Noise	0 dB	15 – 25 dB

Earplug, active, level dependent

	Low Level (<130)	High Level (>150)
Continuous Noise	0 dB	40 dB
Impulsive Noise	0 dB	40 dB

4.1.10.5   Typical Field Attenuation

The field attenuation of these active level dependent devices, in the limit, is controlled by the passive attenuation of the base earplug or earmuff as previously stated. However, the active nature of these devices enhances the capability for the ambient listening condition to be 0 dB loss or they can actually provide enhancement/amplification. Likewise, they more easily accomplish reaching the passive attenuation limit of the earplug or earmuff by completely attenuating the active transmission path.

4.1.10.6   Life Cycle Costs

Due to the electronics, acquisition costs are higher compared to passive devices. The costs for an active level dependent earplug or earmuff typically begin at over 100 US$ per set and can be significantly higher.

4.1.10.7   State-of-the-Art

The state-of-the-art active level dependent systems aim to provide three dimensional sound restoration by providing unity gain (or better) ambient listening. They can afford 15 – 40 dB of attenuation in continuous and/or impulsive noise. However, they disrupt many auditory localization cues and therefore decrease localization performance. They provide better localization than traditional earmuffs or earplugs, but fall short of transparent hearing.

4.1.11   Tactical Hearing Protectors

4.1.11.1   Description

Ground warfare is dependent on effective communications for command and control. Loss of effective communications, due to temporary hearing loss (Temporary Threshold Shift – TTS) from gunfire, explosions, etc., can lead to loss of command and control. Tactical hearing protectors are a special case of active level dependent hearing protector systems designed to prevent loss of hearing and enhance communication capability in tactical ground warfare environments.

Tactical hearing protection systems generally have been designed to attenuate both impulse noise and continuous noise while providing some ambient listening capability while enhancing communication capability with interfaces to radio communication. These devices mostly are level dependent electronic earplugs or electronic earmuffs with interfacing capabilities with radio communication systems.

4.1.11.2   Theory of Operation

Tactical hearing protectors include the functions of an active level dependent earplug or earmuff, with additional circuitry to provide integration with single or multiple radio systems. These systems can also add active noise reduction capability to reduce continuous noise. Some systems also have both an attack and decay function on the non-linear portion of the system. In some cases, the attack and decay functions are very rapid and can allow an intelligible conversation to be conducted during rapid firing of weapons.

4.1.11.3   Performance

The protection afforded by tactical devices is nearly identical to the level dependent active earmuffs and earplugs. The performance of tactical hearing protection systems can be characterized by the passive attenuation of continuous noise as measured by a real-ear attenuation at threshold test, the active attenuation (if applicable) of continuous noise as measured by a microphone in real-ear attenuation test, the impulse noise reduction typically measured with an Acoustic Test Fixture (ATF) (dummy head), speech intelligibility measured with a standardized speech intelligibility test, and ambient listening capability as measured with an auditory localization test and auditory detection tests.

4.1.11.4   Typical Laboratory Attenuation

Typical tactical hearing protection systems as measured in the laboratory can provide approximately 20 dB of continuous noise attenuation, 0 – 10 dB of active attenuation, 15 – 40 dB of impulse noise attenuation, speech intelligibility of 70% – 90%, and combined azimuth and elevation auditory localization errors of 15 – 30 degrees. Some examples are shown below:

Tactical Earmuff

	Low Level	High Level (>150)
Continuous Noise	0 dB	15 – 25 dB
Impulsive Noise	0 dB	15 – 25 dB

Tactical Earplug

	Low Level (<130)	High Level (>150)
Continuous Noise	0 dB	40 dB
Impulsive Noise	0 dB	40 dB

4.1.11.5   Typical Field Attenuation

Typical tactical hearing protection systems have not been included in any field attenuation studies. It is expected that the typical field performance of tactical earmuffs will achieve about 90% of attenuation achieved in laboratory studies and can provide approximately 0 – 10 dB of active attenuation, 15 – 40 dB of impulse noise attenuation, speech intelligibility of 70% – 90%, and combined azimuth and elevation auditory localization errors of 15 – 30 degrees.

4.1.11.6   Life Cycle Costs

Acquisition costs for tactical hearing protectors are typically in the 800 – 2000 US$ range for systems that provide active and passive noise attenuation, electronic ambient listening capability, and interfacing to communications radios. Life cycle costs include replacement of cushions, earplugs, batteries, etc., analogous to the ANR earplugs and earmuffs.

4.1.11.7   State-of-the-Art

Tactical hearing protectors are an emerging technology. Improvement in communications signal clarity, localization performance with ambient listening, and human factors considerations of the control are all being pursued. These systems may improve the use compliance rates by eliminating or greatly reducing the over protection typically experienced by users of traditional passive hearing protection in tactical environments.

4.1.12   Helmets

4.1.12.1   Description

A helmet consists of a hard or soft shell that provides protection against shock and penetration. The helmet will generally have an integrated earmuff assembly that provides noise protection and supports the communication system but it can also play a primary role in helmet stability. Hard-shell helmets provide the best shock and penetration protection and are generally made in several sizes (e.g. aircrew helmets). Soft-shell helmets allow the number of helmet sizes to be minimized when lower impact protection levels are required (e.g. flight deck, ground vehicles). In some lightweight, hard shell helmets the earmuff consists of a soft leather or plastic cup and cushion supporting a communication transducer (earphone). An edge roll around the helmet shell can provide an additional acoustical seal to the head. The soft earmuff mainly provides attenuation at the higher frequencies.

Most hard or soft shell helmets use hard cup passive earmuffs that provide better levels of attenuation of the lower frequencies. To assist the seal of the earmuff to the head tension is provided by foam spacers positioned between the helmet shell and the earcup, a neckband or strap suspension system. Generally, the position of the earmuff inside the helmet is adjustable by means of self-adhesive fabric or straps. When there is no earmuff position adjustment, comfort drives the position of the helmet on the head. The fit of the earmuff is not easily monitored under the helmet shell.

4.1.12.2 Performance

The attenuation afforded by a helmet is dependent on the size of the acoustic leak on the earmuffs and the helmet, the quality of the seal, the volume of the earcup, the mass of the earcup, the stiffness of the cushions and of the helmet shell, softness of the link between the earmuff and the shell, pressure of the shell on the earmuff and the softness of the inner helmet liner.

4.1.12.3 Typical Laboratory Attenuation

For a helmet the attenuation afforded ranges from 5 – 20 dB in the low frequencies up to 30 – 50 dB in the mid and higher frequencies.
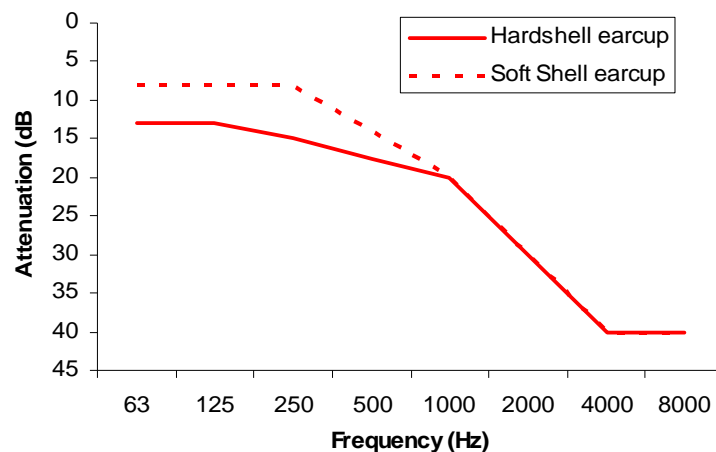
Figure 4-12: Typical Laboratory Attenuation – Helmets.

4.1.12.4 Typical Field Attenuation

The field attenuation can be up to 90% of the laboratory attenuation; however it is usually less due to difficulty in fitting the helmet and earcups. Once well fitted, it is easy to use and easy to (re)fit with consistent performance. Deterioration of attenuation performance may occur as a consequence of:

- Hardening or cracking of the cushions.
- Reduced tension of the earcups due to deteriorating foam spacers.
- Deterioration of the foam inside the earcup.
- Use in combination with other head gear (eyeglasses, respirator, balaclava, sweat covers on the cushions).
- Hair, ear jewellery.

4.1.12.5   Life Cycle Costs

Acquisition costs for a helmet is dependent on the level of performance required but is typically 500 – 1500 US$ per unit. The main through life costs associated with passive earmuffs is the replacement of the cushions every 1 – 2 years.

4.1.12.6   State-of-the-Art

Helmet attenuation may be enhanced by using one or more of the following features:

- Enhanced passive earmuffs.

- Active earmuffs.

- Passive face shields or breathing masks.

- Passive or active earplug.

- Bone vibration cancellation.

4.1.13   Other Devices – Bone/Tissue Conduction Communication with HPD

4.1.13.1   Description

Bone/tissue conduction communication headsets with hearing protectors are composed of suitable bone/tissue conduction vibrators that send signals to the listener (the equivalent of headphones) and a bone/tissue conduction or air conduction microphone to transmit the wearer's voice to others. The noise attenuation of the hearing protectors used with bone/tissue conduction headsets does not change with the use of the headset. However, it may be preferable to use earplugs as they make the bone/tissue conduction headset more efficient.

Chapter 5 – LABORATORY AND FIELD PERFORMANCE

There are a number of internationally recognised techniques for measuring the attenuation performance of hearing protectors. These include objective test methods that use a Manikin or Acoustic Test Fixture (ATF), semi-objective methods such as the Microphone in Real Ear (MIRE) technique that uses human subjects in a passive role and, subjective methods such as the Real-Ear Attenuation at Threshold technique where measurements are based on subjective judgment. These different test methodologies all have different advantages and disadvantages. Not all techniques are equally suitable for measuring all types of hearing protection devices or, indeed, are suitable for measuring both in the laboratory and in the field. For some of the more advanced hearing protection devices with high functionality, such as Tactical Hearing Protectors, standardised test protocols still need to be developed. When assessing the acoustic attenuation of a HPD it is important to choose a relevant test procedure or, if resources and capability are limited, to understand what limitations are associated with the test procedure adopted and to interpret measurements accordingly.

The following sections describe the most commonly used laboratory methodologies and how those techniques are being adapted to provide meaningful measurements of attenuation levels actually achieved in the field.

5.1   STANDARD LABORATORY ATTENUATION MEASURES

5.1.1   Real-Ear Attenuation at Threshold (REAT) Technique

The REAT test method is a subjective technique (described in ANSI S12.6 [22] BS EN 24869-1:1993 [23] and ISO 4869-2:1994) where the subject responds to very low levels of noise to establish their threshold of hearing. The subject is seated in a diffuse noise field of white noise, band-limited to specific 1/3 octave frequency bands. The subject indicates by pressing a button when the noise is just audible and a measurement of the threshold is obtained both with and without the hearing protector in place. The difference between the two threshold measurements is the attenuation of the device under test. The 1/3 octave frequency bands that the REAT standard specifies for test are 63 Hz (optional), 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz and 8 kHz.

The REAT technique is, by its nature, a measure of the SPL at the cochlea and therefore is the preferred technique when assessing the attenuation of earplugs and in any hearing protection system where bone conducted noise is likely to be a consideration. However, it should be noted that:

- The technique is based on subjective opinion and consequently there is a wide variance in the attenuation measured across subjects.

- The standard method only presents ten, 1/3-octave bands of noise, generally spaced about an octave apart. This means that no attenuation information is provided for the frequencies between the test bands.

- The technique may over estimate the occluded threshold at 63 Hz and 125 Hz due to physiological noise masking the test frequencies.

- The hearing protection device is only tested at threshold and not in the high noise environment it is intended for use in.

- The procedure is lengthy and requires subjects to have a good attention span.

The REAT technique is not suitable for measuring the attenuation performance of HPDs that incorporate ANR as these devices generate electronic noise when switched into their active mode of operation.

This residual noise ranges from 80 Hz to 2 kHz and is audible when the system is worn in the quiet and will mask the REAT test signals. Hence, the REAT technique will over-estimate sound attenuation in this frequency range.

5.1.2   Microphone In Real Ear (MIRE) Technique

The MIRE method is a semi-objective technique (detailed in ANSI S12.42 [24] and BS EN ISO 11904-1:2002 [25]) that requires the use of miniature microphones placed at the entrance to the subject's ear canal. The subject is seated in a reverberant chamber within which diffuse broadband noise is generated. The Sound Pressure Level (SPL) is measured at the subject's ear canals both with and without a hearing protector in place. The difference between the occluded measurement and the unoccluded measurement is the insertion loss (or attenuation) of the device under test.

The MIRE method can be used to quickly obtain the full frequency spectrum of the SPL at the entrance to the ear but it cannot be used with standard earplugs as it is difficult to insert a microphone to the occluded side of the ear canal. However, the MIRE method measures the SPL at the entrance to the ear canal and does not take account of any BC noise reaching the subject's cochlea. As a consequence, it is possible that in high noise the MIRE technique may overestimate the level of attenuation achievable above 2 kHz.

Figure 5-1 provides a comparison of the attenuation measured for a flight helmet using both the REAT and MIRE test techniques. The plot shows how the REAT measure overestimates the low frequency performance of the device.
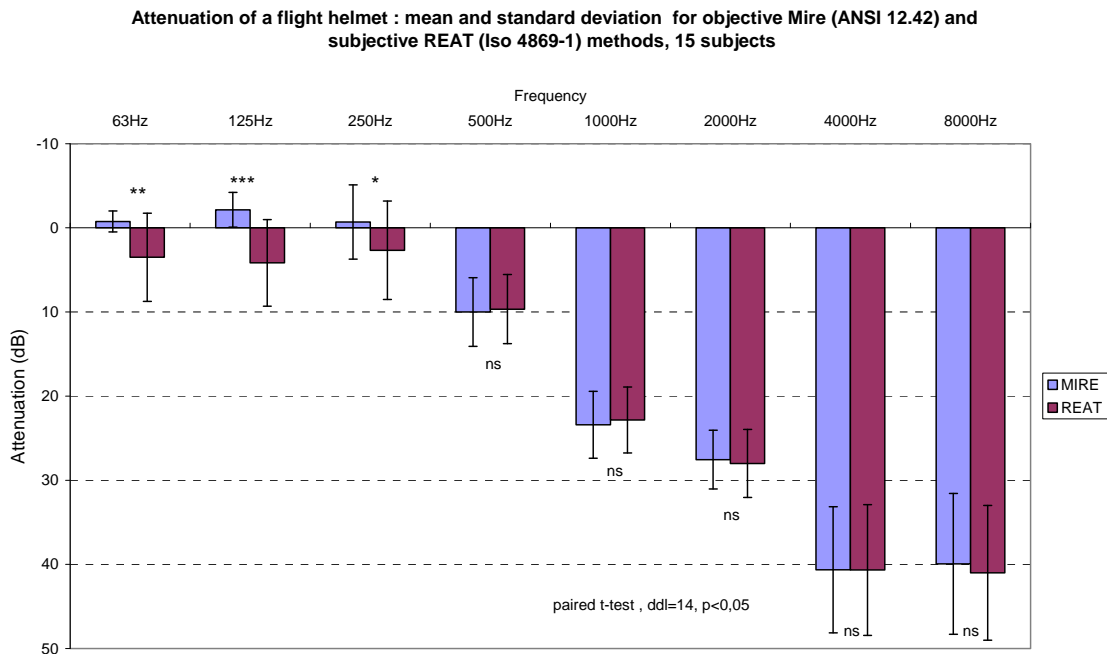
Figure 5-1: A Comparison of the Attenuation Afforded by a Flight Helmet Measured Using the MIRE and REAT Techniques.

5.1.3   Acoustic Test Fixture / Manikin Measurements

Objective techniques detailed in ANSI S12.42 [24] and BS EN ISO 11904-2:2004 [26]) use an ATF fitted with standardised artificial ears positioned on either one or both sides of a head simulator. For assessment of HPDs in high-level noise the ATF must provide adequate levels of isolation (no less than 60 dB)

determined as the difference in each frequency band between the output of the microphone uncovered and covered with a heavy, thick walled, metal earcup. The sound level is measured using laboratory standard microphones placed at the eardrum position. Some ATF will be covered with an artificial skin which will provide similar compliance to that of real skin and, hence, measurements will provide a good representation of those measured on a real head. However, for an ATF that does not provide a skin like cover measurements may overestimate the low frequency attenuation achievable.

5.2   FIELD PERFORMANCE BACKGROUND, METHODS, AND STUDIES

5.2.1   Background

Measuring the attenuation performance of hearing protectors in the field setting is an important but technically challenging task. It is important to measure the performance of hearing protectors when they are fitted by users in the workplace and to correlate the field attenuation with laboratory attenuation. The most technically challenging part of measuring attenuation in the field is the acoustics, specifically the noise floor of the test room. The measured attenuation is directly dependent on the open and closed auditory thresholds of the test subject. The open thresholds increase (decreasing the measured attenuation) as the noise floor of the test room increases. In the laboratory setting, great care is exercised in constructing the test rooms used for attenuation measurement. Frequently, the room construction involves rooms within rooms, mechanically and acoustically isolated from each other, with walls, floors, and ceilings made of concrete and special noise attenuated air handling systems. Most laboratory test rooms using these techniques, satisfy the attenuation test standard with little margin. It is extremely difficult to nearly impossible in a field setting to achieve the noise floor required by the attenuation test standards. Therefore, much of the field attenuation data for hearing protectors has been confounded by the noise floor of test rooms. However, field attenuation studies should be conducted and the noise floor of the field test rooms should be reported along with the estimated effects on open hearing thresholds of the test subjects.

Numerous studies have shown that the sound attenuation achieved in the field, that is, when users fit the devices themselves, generally falls short of both manufacturers' specifications (optimum performance) and the attenuation achieved when fitted by trained personnel in laboratory studies [27]. As a result, various schemes have been suggested for correcting the values given in specifications to predict real-world outcomes [22,3] The reasons for the discrepancies include the previously described unsatisfactory noise floor of the test room, poor sizing and fitting technique, inadequate maintenance, length of time worn, and integration with other gear. Also, the quality of the field attenuation measurement system must also be considered. The precision measuring equipment and sound fields are usually not available and not achievable in a field setting. In civilian and military settings, users often report that they have access to only a limited number of devices which have no provision for sizing. Earplugs, even if initially well fitted, may work their way out of the earcanal with extended wearing. Leakage of sound under an earmuff may result if the device is worn in combination with other head gear such as safety glasses, a respirator, or cold weather balaclava.

Typically, the training provided on fitting technique is poor and limited to the scant information on the packaging. With no oversight, compliance with hearing conservation initiatives tends to be low. One measure of the training, education, and motivation of users in a hearing conservation program can be the percentage of the laboratory attenuation that is achieved by a group of users in the field.

5.2.2   Methods

Clearly, the most direct method of measuring field attenuation of hearing protectors is by using a standard Real-Ear Attenuation at Threshold method with laboratory quality instrumentation and a high attenuation test room. Field attenuation facilities have included portable booths, trailers, and truck mounted test

rooms. These mechanizations normally have problems in attenuating low frequency noise found in the field. As stated in the background, the goal of achieving a noise floor in the test room as required by the test standards is very rarely achieved. Therefore, several alternate methods have been suggested for use.

The first is the objective measures of insertion loss using the Miniature Microphone In Real Ear (MIRE) methods. This method typically works only for earmuffs. The MIRE insertion loss values generally agree with the REAT attenuation values in the mid-frequencies but there are differences at both the high and the low frequencies due to small space acoustics and physiological masking respectively. Additionally, the MIRE method does not account for the flanking path via bone and tissue conduction and therefore can over estimate attenuation for high performance hearing protectors.

A second alternative method is by visual inspection of the depth of insertion of a pre-moulded earplug. The attenuation achieved is highly correlated with the depth of insertion and therefore a reasonable estimate of attenuation can be made by measuring the portion of the earplug which is not in the earcanal. This measurement is subtracted from the total length of the earplug and the difference is the depth of insertion [20].

Finally, the largest problem with hearing protector attenuation in the field is compliance. A hearing protector that is not worn does not provide any attenuation to the user. A surprise survey of users will indicate the compliance rate. Previous studies in industry and the military have shown typical compliance rates of approximately 50%.

5.2.3   Field Performance Studies

5.2.3.1   Field Performance of Hearing Protection Used by US Deck Crew

A recent survey [28] by the US Navy of 301 flight deck personnel included detailed assessments of earplug use and insertion depth; cranial helmet fit and maintenance condition (e.g. earmuff headband tension, earcup cushion and foam insert integrity); anthropometric head size measures; and personal/historical data. Based on these data, field attenuation performance of the HPDs was estimated. Data analysis of survey findings showed that 79% of surveyed flight deck personnel received an estimated 0 – 6 dB of noise attenuation from either shallow earplug insertion depths or not wearing earplugs at all. Some 47% self-reported never wearing earplugs while just 14% reported always wearing earplugs with their cranials (the required double hearing protection is earplugs plus cranial). For subjects who reported they sometimes or always wore earplugs, only 7% inserted the earplugs deeply enough in both ears to achieve the maximum noise attenuation of 22 dB (mean minus two standard deviations). Figure 5-2 provides the percentage of those surveyed who wore their earplugs at each of four depths and the estimated hearing protection they would receive at that insertion depth.
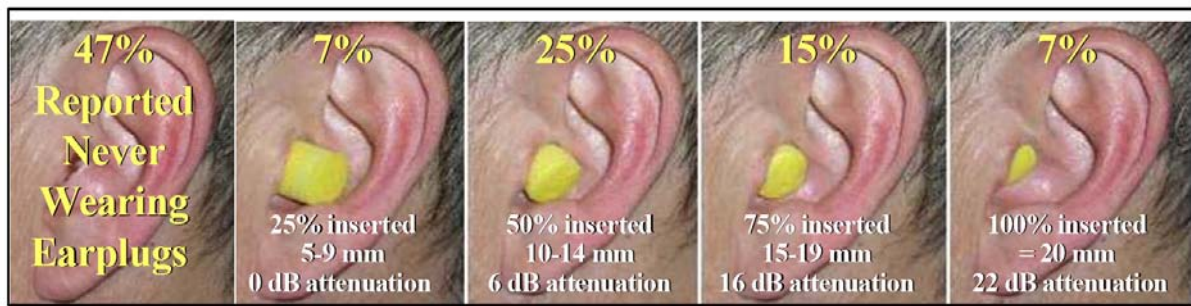

Figure 5-2: Earplug Insertion Depth, Related Noise Attenuation, Percentage of Earplugs at Each Depth (extrapolated from 202 ears of sometimes and always earplug users).

All survey subjects reported wearing a cranial helmet with earmuffs. U.S. Air Force Research Laboratory attenuation testing of the cranial showed the cranial provides 22 dB (mean minus two standard deviation) of hearing protection when sized and fitted properly, and when earcup cushions and foam inserts are in good condition. During the survey conducted, however, 75% of subjects were issued a questionable cranial size; most were issued the largest of four sizes available regardless of head size or shape. Further, 41% of earcup cushions and foam inserts were deteriorated, hard, creased, or missing. It has been reported since the 1950s [29-33] that air (acoustic) leaks between earcups and wearers' heads can reduce noise attenuation 3 – 15 dB across a broad range of frequencies but predominantly in lower frequencies. From the US Navy survey, it is surmised that 79% of the flight deck crews surveyed were reliant solely on earmuffs for hearing protection; yet questionable helmet/earmuff fitting and maintenance practices indicated these crews likely received far less hearing protection than the 22 dB found in laboratory testing.

5.2.3.2   Field Performance of Hearing Protectors in Impulse Noise of Mortar Firing

A field performance test using an Artificial Test Fixture (ATF) was conducted to evaluate the Insertion Loss (IL) of different classic hearing protectors in order to calculate the number of rounds that may be fired on a daily basis if the noise exposure of the shooter is to comply with damage risk criteria. Figure 5-3 shows 3 artificial heads in the neighbourhood of a mortar (120 mm) firing with charge 6.
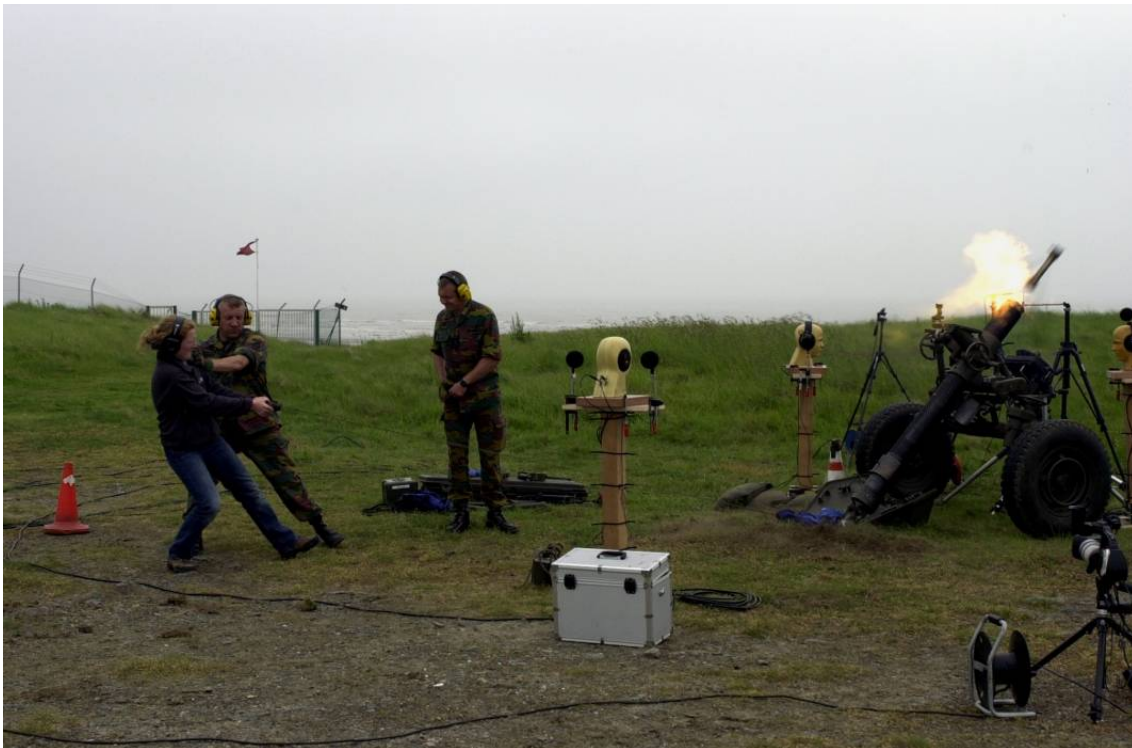
**Figure 5-3: Array of 3 Artificial Heads Used for the Measurement of
Mortar (120 mm) Noise with Various Headsets and Earplugs.**

Three earplug designs and 3 different headsets were tested individually. Each headset was also tested in combination with the ISL earplug. Figure 5-4 shows the devices that were fitted to the artificial heads illustrated in Figure 5-3 above.

Earplug ISL	Peltor Comtac / Bilsom Impact Sport
Improved Combat Arms Ear Plug	Bilsom Thunder 3
Bilsom Smartfit	Bilsom Leightning 2

Figure 5-4: Different Types of Hearing Protectors Tested on the ATFs.

The graphs in Figure 5-5 illustrate the results obtained for the ISL earplug and the Bilsom Smartfit earplug. The graphs presented are as follows:

- **Upper Graph:** Attenuation (IL) of the earplug;

- **Middle Graph:** Impulse measured in the free field; and

- **Lower Graph:** Impulse measured under the hearing protection.

Head N°2   **MORTAR 120mm Charge 6**   **LX0061**   Head N°2   **MORTAR 120mm Charge 6**   **LX0061**

Protector Left Ear2:   **Ultrafit ISL**   **Protector Right Ear2:**   **Bilsom Smartfit**
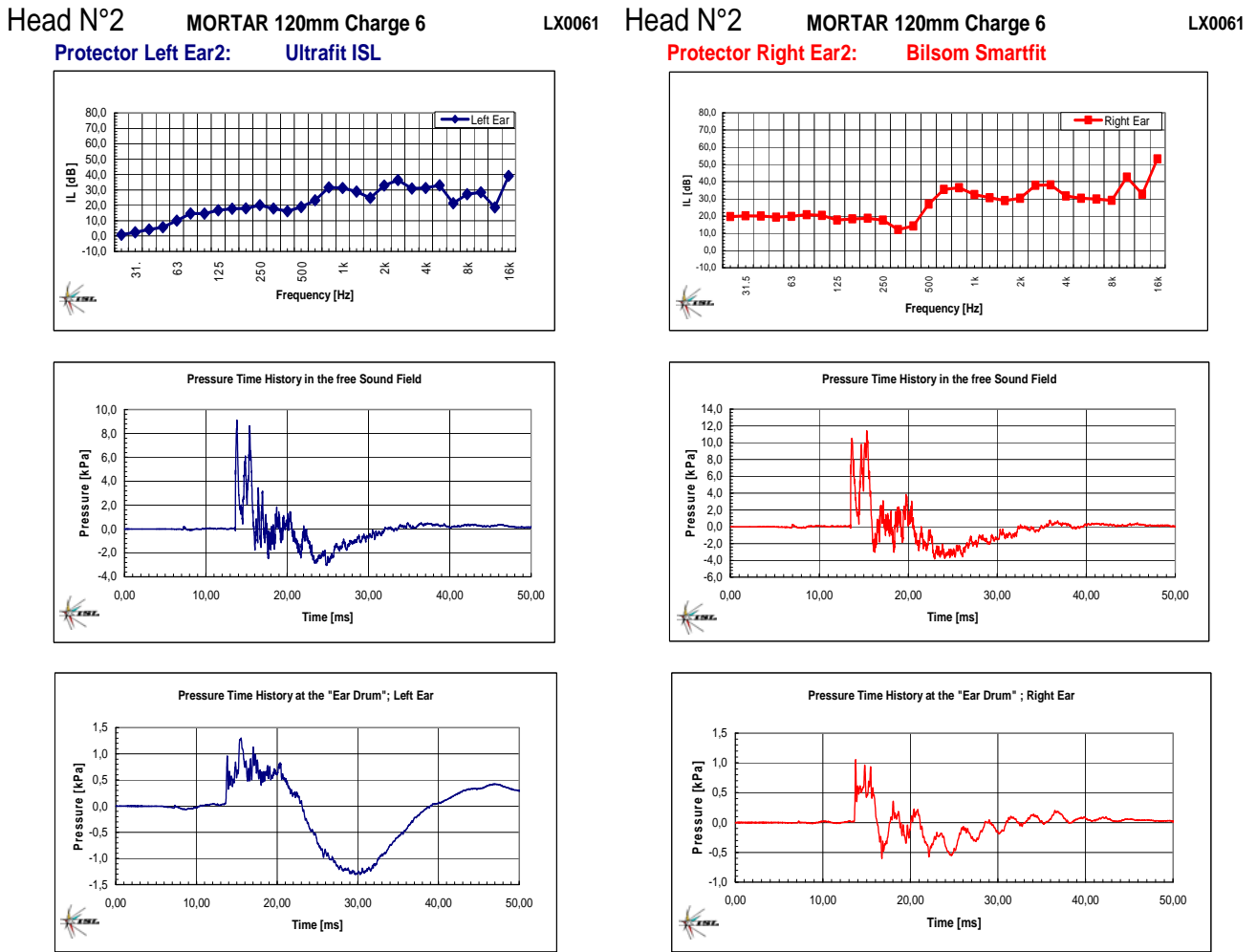
Figure 5-5: Measurements Made for the ISL and the Bilsom Smartfit Earplugs.

Table 5-1 shows the following measurements and calculations:

- Lpeak FF, Lpeak LE: sound pressure in the free field (FF) and under the hearing protection (LE).

- NRpeak: attenuation of the impulse (Noise Reduction).

- L_{eq} FF, L_{eq} LE: equivalent sound pressure in free field (FF) and under the hearing protection (LE).

- L_{Aeq} FF, L_{Aeq} LE: A-weighted equivalent sound pressure in free field (FF) and under the hearing protection (LE).

- IL: attenuation of the hearing protection (Insertion Loss).

- N (85 dBA) WP, P: daily number of impulses allowed by the DRC (criteria based on the noise dose delivered by the impulse noise) without protection (WP) and with hearing protection (P).

Table 5-1: Measurements and Calculations for the ISL and Bilsom Smartfit Earplugs.

	Lpeak FF	173,2	L_{Aeq} FF	93,1
	Lpeak LE	156,3	L_{Aeq} LE	68,6
	NRpeak	16,89	IL	25
	Leq FF	98,2	N (85 dBA) WP	0
	Leq LE	90,7	N (85 dBA) P	2
	Lpeak FF	175,1	L_{Aeq} FF	95,58
	Lpeak LE	154,4	L_{Aeq} LE	71,66
	NRpeak	20,68	IL	24
	LeqFF	101,58	N (85 dBA) WP	0
	Leq LE	81,78	N (85 dBA) P	1

The insertion loss calculated for all the hearing protection considered during the trial is presented in Figure 5-6.
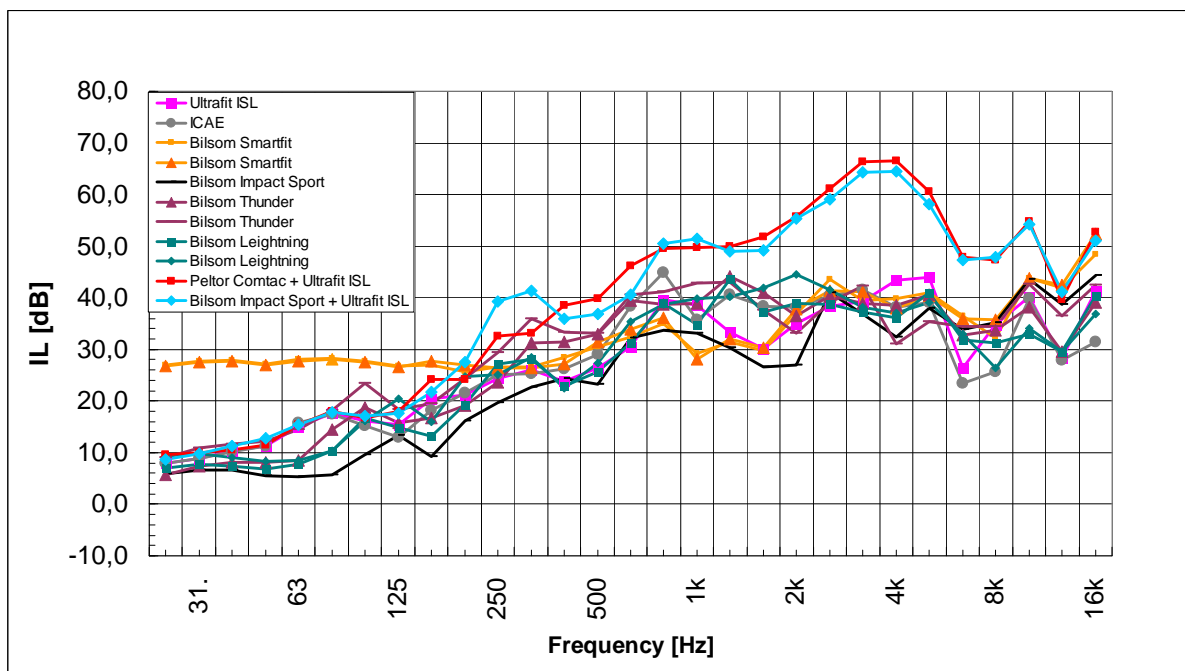
Figure 5-6: Insertion Loss of the Hearing Protection Under Study.

The field measured performance of the hearing protectors in mortar noise shows that any of the existing classic hearing protectors used either individually or in combination can reduce the peak levels to under 140 dB peak at all positions round a mortar. The attenuation (IL) of the earplugs (classic and combat arms earplug) (IL = 25 – 33 dB) were better than the classic (IL = 25 – 29 dB) and much better than the talk through headsets (IL = 11 – 19 dB) in mortar noise.

When the equal energy principle ($L_{Aeq}8$) with a limit of 85 dBA was applied, all of the protectors under study showed that the number of allowable daily exposures to mortar fire is very small and may place unacceptable constraints on operational use.

Chapter 6 – HEARING PROTECTION SELECTION CONSIDERATIONS

When procuring a new hearing protection device to bring operator noise dose in line with noise exposure criteria there are many factors, other than the absolute level of attenuation a device affords, that will influence the decision making process. For many situations the issue will not be that the exact levels of attenuation are provided, rather just that a HPD is actually used. Due consideration should also be given to the impact the extra noise attenuation may have on an operators ability to maintain detection of any natural audio cues used, the effect it may have on the audibility and discriminability of speech and non-speech communications and the localization of sound sources in the immediate vicinity. It is also important that the chosen device is comfortable to wear for long duration, easy to fit, easy to use and compatible with all other operator equipment. Some of the parameters are discussed further in the following section.

6.1   EDUCATION, TRAINING AND MOTIVATION

Hearing protection will only provide good protection when used properly and fitted correctly. The first requirement is to follow the instructions of the manufacturer for proper fitting, use, maintenance, and replacement of parts. Secondly, further training may be necessary to educate the user of the dangers of exposure to loud noise. Particular issues that should be considered during training include:

- Motivate users to wear protection correctly and at all times in a noisy environment by highlighting the consequences of irreparable hearing loss;

- Instruct users on wearing protectors in combination with other protective equipment;

- Provide advice on avoiding any potential interference due to long hair, eyeglasses, earrings, etc.;

- Provide instruction on how to store protectors correctly;

- Instruct users on regular inspection of the devices; and

- Inform users where to report damage and where to find replacements.

By conducting annual health surveillance the performance of hearing protectors may be assessed over a longer period of time. This will give feedback about the effectiveness of education and training and about actual field performance of the hearing protector itself.

6.2   OVERPROTECTION

Hearing protectors must limit the noise exposure for the user, without reducing the overall sound level too much. If the sound level is reduced too much, the result is overprotection which may negatively affect other auditory cues. A user should not feel "acoustically isolated" from the environment but instead should, as much as is possible, be kept in touch with the outside world (ambient listening). Proper attenuation, not over-protection or under protection through use of a hearing protector ensures that there is an appropriate balance between attenuation of noise and perception of other auditory cues. The concept of matching hearing protection to noise exposure is illustrated in Figure 6-1.

Figure 6-1: Matching Hearing Protection to Noise Exposure.

6.3 LOCALIZATION AND SITUATIONAL AWARENESS

For many military operators, situational awareness is dependent on being able to locate sound sources in the immediate environment. Hearing protectors can reduce the ability of a listener to localize sounds. High frequencies are particularly important for perceiving elevation, and the outer ear (pinna) is also a determining factor for directional hearing. Use of earmuffs or earmuffs result in a small degradation of localization performance in azimuth or the horizontal plane and a significant degradation of localization in elevation or the vertical plane. Use of double hearing protection, earmuffs and earplugs results in the almost complete loss of localization cues and a very severe degradation of localization performance.

6.4 SPEECH COMMUNICATION

Speech communication is of utmost importance in military environments. For listeners with normal hearing, the use of hearing protectors will not impair their ability to understand speech in noise. The levels of both the speech and noise at the listener are reduced, and the signal-to-noise ratio is therefore unchanged. In some situations, with dominant low-frequency noise, the use of hearing protection can (slightly) improve intelligibility in noise. For listeners with impaired hearing (assumed to be a minority in active military), the use of hearing protection could have a negative effect on speech intelligibility, as critical parts of the speech signal could fall below the hearing threshold.

A natural reaction of people wearing hearing protectors is to drop the level of their voice due to the increased perception of their own voice when they speak attributed to the occlusion effect. So, when wearing a protector, it is important to maintain or even slightly increase the level of one's voice to improve speech communication with others. It is assumed that the listener in the same environment is also wearing hearing protection. If this is not the case, e.g. when communicating over a radio to someone in a quiet environment (command centre), the need to raise your voice is less important.

Generally, the optimal choice of hearing protection in terms of speech intelligibility is to use protectors with a flat attenuation characteristic. That is, a hearing protector that provides equal sound attenuation for the low, mid, and high frequencies. In this way the protector acts as an overall volume control, without changing the frequency components or spectrum (timbre) of sounds too much. Earplugs are better suited

for flat attenuation than earmuffs. Some types of custom moulded earplugs, equipped with special filters, have shown to give a near-perfect flat attenuation.

Apart from the positive aspects for intelligibility, a flat attenuation characteristic will also contribute to better speech quality and perhaps better acceptance from the user. The usually sloping curve of hearing protectors (more attenuation toward higher frequencies) makes everything sound dull to the user, thus reducing the perceived speech quality.

## 6.5 RECEPTION OF AUDITORY WARNINGS (SPEECH AND NON-SPEECH)

The same issues for speech communication apply to audibility (and identification) of auditory warnings. As long as the warning signal is well designed in relation to the background noise (10 – 15 dB signal-to-noise ratio as a general rule), nothing changes when using hearing protectors. That is, the audibility of the warning signal under the hearing protector must be assured by generating a sufficiently high signal level. This is primarily an issue of warning signal design.

6.6 COMFORT

Wearer comfort depends on many different factors. Comfort is a critical issue for the acceptance of hearing protection by the user because if something is not comfortable, the user will not wear it. Aspects to consider for earmuffs are mass, cushion pressure, headband force, adjustability, material used, construction and compatibility with other protective gear. For earplugs, comfort and ease of fitting and removal are additional relevant factors. Uncomfortable plugs, muffs or (flight)helmets can distract users from their primary activities in situations where concentration is of the utmost importance.

Lack of comfort is likely to induce a negative attitude towards the job. Also, when experiencing physical discomfort, people will try to eliminate the cause of it. This means that uncomfortable hearing protectors are more likely to remain unused. Improper use of these protectors may also occur; e.g., chin straps are left loose, or earplugs are only half inserted into the earcanal. This will compromise the performance of the hearing protector.

If discomfort results in removing hearing protection for some time, even when loud noise is present, the effects can be very serious. The maximum exposure time rapidly decreases when intervals without protection are introduced (Figure 6-2). For example, removing protection 5% of the time, the maximum daily exposure time is reduced by a factor of 5 (approx. 40 minutes instead of 3 hours). Even if the hearing protection is removed for only 2 minutes during a 3-hour flight, the maximum exposure time is reduced by one hour. These examples underline the importance of comfort.
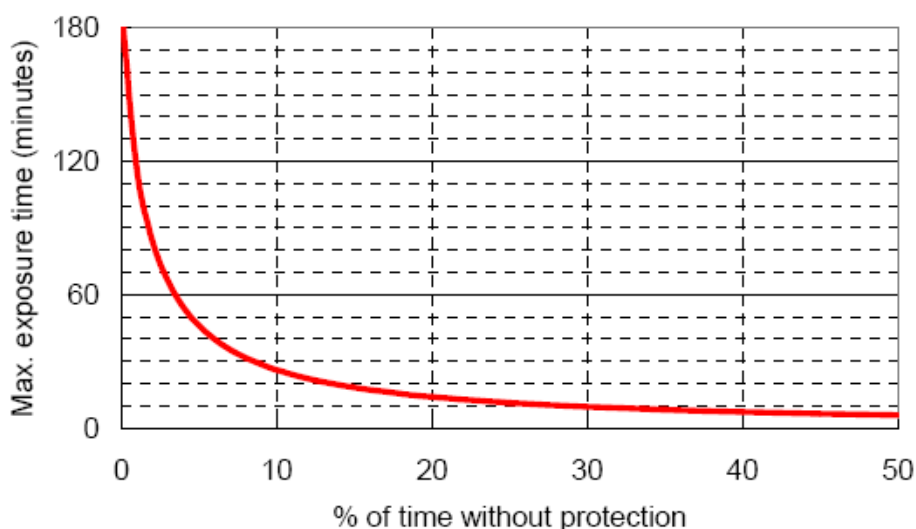
Figure 6-2: Maximum Exposure Time when Hearing Protection is Taken Off Temporarily for a Percentage of the Total Exposure Time – in this example the maximum exposure time is 3 hours if the HPD is worn consistently but drops rapidly if the HPD is removed.

6.7   COMPATIBILITY TO OTHER EQUIPMENT

When selecting hearing protectors one should take account of any other equipment that users (must) wear which may impair the performance of the hearing protector. In general, earplugs will be more compatible with other equipment than earmuffs (or helmets). Examples of other equipment are given below:

- Protective clothing – should be worn over any hearing protector and not underneath.

- Eyeglasses – should have side arms with low profile so as not to disturb the seal of the earmuff against the head.

- Goggles – should have a lens housing and head-straps that do not interfere with the earmuff cushion and seal.

- Face shields – must be designed not to interfere with hearing protection.

- Hoods – should be worn over the hearing protector.

- Helmets – if not part of an integrated design, helmet shells should be designed to be compatible with hearing protectors or hearing protectors should fit comfortably under helmets.

- Respiratory protection devices (NBC masks) – must be designed not to interfere with hearing protection.

6.8   SIZE/WEIGHT

Currently, the headsets and helmets worn by many military operators are designed to not only provide protection against high levels of ambient noise but also to provide a communication link (via earphones mounted in the earshells) and, for some helmets, to play a primary role in ensuring helmet stability.

In addition to the requirement to provide increased levels of noise protection, for many operators there is also a requirement to reduce the size and mass of the HPD. However, the acoustic performance of the circumaural hearing protection devices used in most helmets and headsets is governed by its physical

characteristics and reducing the size and mass of conventional styled earmuffs will generally have a detrimental effect on the attenuation afforded, for the following reasons:

- Low frequency attenuation (up to about 250 Hz) is determined by the volume of the earshell and the stiffness of the cushion. Low frequency ambient noise will cause the earmuff assembly to pump on the flexible cushion and skin. This pumping will cause fluctuations in the internal volume of the earmuff which, in turn, generates a sound pressure level within the earshell cavity. Consequently, the apparent attenuation of the device is reduced at these frequencies. The amount of sound generated within the earshell is proportional to the changes in internal volume. Therefore, for a large volume earshell where the volume changes are relatively small, the SPL generated inside the earshell will be small and attenuation levels will be retained. However, for an earshell of smaller dimensions the changes in volume will be relatively high causing greater SPLs to be generated within the cavity and consequently, the small earmuff will afford a much reduced attenuation.

  For similar reasons the stiffness of the cushion effects the attenuation afforded. A really stiff cushion could be used to minimise the degree of pumping on the head but a certain amount of compliance will always be necessary to ensure a good seal to the various facial contours of individual aircrew.

- In the mid frequency range the attenuation afforded by the earmuff is governed by a mass rule where, for every doubling of mass of the earshell the attenuation between about 250 Hz and 2 kHz will increase by some 6 dB. By reducing the mass of the helmet there will be an associated loss in the attenuation afforded.

- At frequencies above 2 kHz the attenuation is governed by the absorptive lining inside the earshell (e.g. Bilsom wool, foam), although it should be noted that at these frequencies relatively high levels of attenuation are afforded by a circumaural protector compared to the low/mid frequencies.

Ideally, the aim would be to reduce the mass of the HPD whilst retaining acoustic performance. However, in reality it will probably be necessary to examine trade-offs in acoustic performance with size and weight requirements.

6.9   EASE OF FITTING

Hearing protectors should always be fitted in accordance with the manufacturer's instructions in order to maximize their effectiveness. In general, earmuffs are relatively easy to fit properly (providing other equipment does not impair fitting). Headbands or neckbands must be correctly positioned and adjusted to the user. Earplugs should be correctly inserted into the earcanal (deep enough). Inserting only halfway will result in a considerable loss of attenuation. If earplugs are sized, the proper size (usually S, M or L) per ear should be used. Custom moulded earplugs are fitted to the individual's ears, but this does not imply that fitting will automatically be correct. The user must be instructed in how to insert their earplugs correctly to maximize attenuation. Additionally, over time fitting may decrease, due to slight changes in the shape of the earcanal or changes in the material of the earplug.

6.10   MAINTENANCE

All hearing protectors must be monitored for wear and damage and must be replaced when necessary. Visual inspection is a simple first check. Protectors should be maintained and cleaned to avoid loss of attenuation and/or comfort. Re-usable earplugs must be cleaned after use and kept in a clean container. The same earplugs should not be worn by different people. When the same earmuff is to be used by a number of people, the muffs should be cleaned between uses.

The wearer should have clean hands when handling hearing protectors (especially earplugs) which is not always easy in a military environment. Contamination by foreign materials, solutions, liquids, dust, etc. must be prevented at all times. Devices with electronic components may need special care (instructions will be provided by the manufacturer), for example, some devices require the timely replacement of batteries.

6.11   PRICE

Good hearing protection has its price. The most advanced devices such as systems with built-in communication (wired or wireless), level-dependent attenuation, active noise reduction or any other electronic components tend to be the most expensive. Disposable, universal fit earplugs are probably the cheapest protection based on unit price, but ultimately it may be more cost effective to purchase reusable earplugs. Earmuffs are generally more expensive than earplugs but the more sophisticated custom moulded earplugs can cost as much, if not more, than a good earmuff device. As the performance of some HPDs decrease with time it is important during the procurement process to investigate those devices that guarantee a level of protection over a given time scale.

In many military settings, the cost of hearing protection competes with the costs of fuel, tires, and other consumables. Currently, the unit commander sets the priority and decides whether his operators are going to be better trained or provided with improved hearing protection. As the commanders do not currently incur any of the costs associated with hearing loss, their decision usually falls in favour of better training and the provision of cheaper, and sometimes less effective, hearing protection. In order to influence the decision making process it has been proposed that a portion of the hearing loss disability compensation costs be charged back to the individual units. This would give the commanders a 'pay now or pay more later' option to consider regarding hearing protection and noise exposure.

Table 6-1 provides some typical costs for hearing protection devices that are currently available as Commercial Off-The-Shelf (COTS) items.

Table 6-1: Typical Costs for Hearing Protection Devices.

Hearing Protectior Type	New Unit Price Band		Through Life Costs				
	min $	max $	Replace entire unit	Replace cushions	Replace earphone	Replace tips	Batteries
Circumaural Passive Earmuff	7.50	45.00	x	every 1-2 yrs	x	x	x
Circumaural Communications Headset	250.00	630.00	x	every 1-2 yrs	occasional	x	x
Circumaural ANR Headset	630.00	1010.00	x	every 1-2 yrs	occasional	x	per mission
Universal Fit passive Earplugs	0.20	3.50	after each use	x	x	x	x
Universal Fit Communications Earplugs	25.00	900.00		x	occasional	after each use	x
Custom Molded Communications Earplugs	50.00	900.00	every 2-3yrs	x	occasional	x	x
Tactical HPD - earplugs (universal fit)	830.00	1500.00	x	x	occasional	after each use	x
Tactical HPD - headset	165.00	330.00	x	every 1-2 yrs	occasional	x	per mission
Helmets	500.00	1500.00	x	every 12 wks	occasional	x	x

Chapter 7 – SUMMARY AND RECOMMENDATIONS FOR RESEARCH

This aim of this report has been to provide information that will support users of hearing protection and those in the business of hearing-protector acquisition or requirements in identifying the most suitable hearing protection for a specific application or role. Detailed reviews have been provided of the noise exposure criteria and Damage Risk Criteria (DRC) used across the different nations, and the types and levels of noise that may be experienced in a range of different operational environments. This information may be used in combination to predict the level of hearing damage risk specific operators may be exposed to and, consequently, the level of hearing protection required for compliance with exposure criteria. A wide range of COTS and near-term hearing protection technologies have been reviewed and an overview has been provided of suitable laboratory and field evaluation test techniques that may be used to assess attenuation performance. However, when choosing a new hearing protection device to bring operator noise dose in line with noise exposure criteria there are many factors, other than the absolute level of attenuation a device affords, that will influence the procurement decision making process. A range of parameters that should also be considered as part of this process have also been discussed.

A good understanding now exists of the mechanisms of noise protection and the parameters that influence it. However, noise legislation is becoming more stringent and noise environments are becoming harsher. As a consequence, new HPDs that provide greater levels of protection and that have a more diverse functionality are being developed. These devices bring new challenges in terms of performance measurement and prediction, as well as understanding any associated integration mechanisms.

Further research will be required to maintain a full understanding of noise protection issues and research areas that are of initial importance include:

- Understanding the contribution speech communications make to operator noise dose by establishing the relationship between speech dose and hearing loss.

- Development of standardised test protocols for tactical hearing protectors.

- Understanding the effects of high levels of protection on situational awareness.

- Agreement on DRC for impulse noise.

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Appendix 1 – DEFINITIONS

A, B, C and D Weighting of Sound – Illustrated in the figure below.
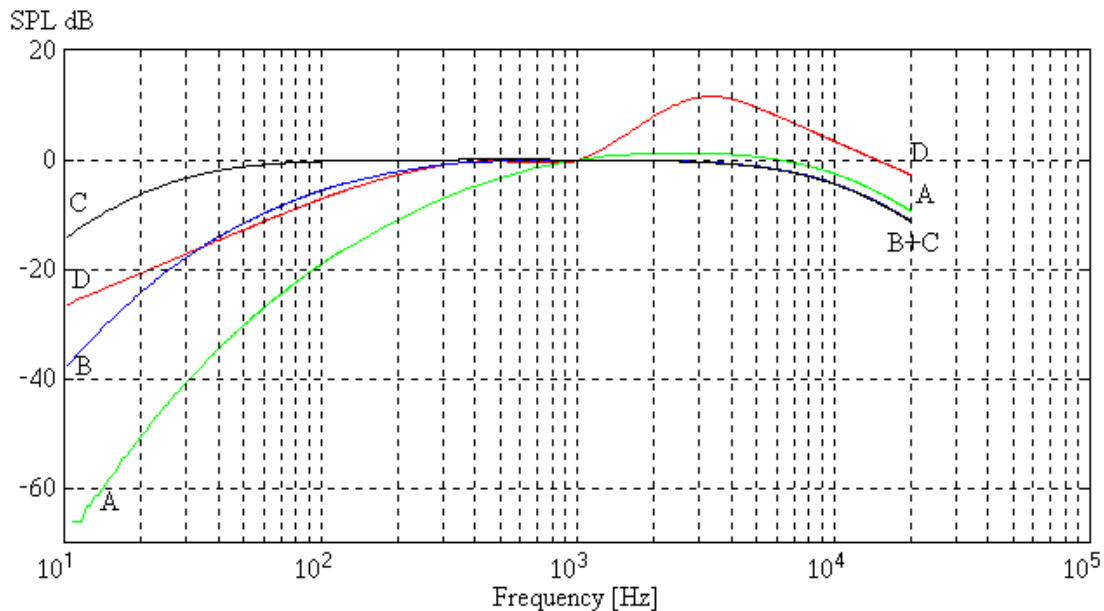
Figure A1-1: A, B, C and D Weighting of Sound.

Active Hearing Protector – An earmuff or earplug that employs active electronic components to achieve the desired performance.

Active Noise Reduction (ANR) Hearing Protector – An earmuff or earplug employing technique/s for actively cancelling acoustic noise using wave interference.

Acoustically Transparent – Sound-restoring, Level-dependent, passive or active hearing protectors that are specifically designed to preserve binaural localization cues and/or restore the ambient soundscape and as a design feature produce a change in sound attenuation as a function of the external sound level.

A-Duration Impulse Noise – The duration of an impulsive sound from its initial sharp increase in positive sound pressure to the point where the sound pressure becomes negative.

Assumed Protection Value (APV) (EU) – The Assumed Protection Value (APV) of a hearing protection device is calculated using mean and standard deviation attenuation performance figures to provide a selected protection performance (i.e. the attenuation likely to be achieved by a certain percentage of the population of wearers) ISO 4869-2:1994(E). An USA analogous values (NRR, NRSA, and NRSG are defined in ANSI S12.68.

Attenuation – The reduction of sound pressure level provided by a hearing protector by structural elements, acoustic pathways, electronic or mechanical means.

Bone Conduction (including Tissue Conduction) – Transmission of acoustic energy to the cochlea or inner ear via pathways other than the ear canal.

Comfort – Absence of discomfort.

Communication Headset (Hearing Protector) – A voice communication device (earplug, earmuff, semi-insert device or helmet) that is also designed to reduce the level noise at the users' ears through passive and/or active attenuation.

Continuous Noise – Noise with a duration exceeding 1 second normally with a constant or consistent spectrum.

Exchange Rate – The time-intensity trading relationship associated with an exposure criteria – the number of dB allowing a doubling or halving of exposure time, i.e. 3 dB per doubling – 85 dBA for 8 hours or 88 dBA for 4 hours or 5 dB per doubling – 90 dBA for 8 hours or 95 dBA for 4 hours.

Exposure Criteria – The level and duration of noise which allows an acceptable (policy decision) amount of permanent threshold shift (hearing loss) in the population for long term (20 – 40 year) exposures, i.e. 85 dBA for 8 hours with 3 dB/doubling.

Field Attenuation – The degree to which the ambient noise reaching the ear is reduced, as measured under simulated or real-life operational conditions. Attenuation can be calculated from real-ear attenuation at threshold, transmission loss, and insertion loss data.

Field Performance – Combination of the acoustic performance of a device and user acceptability under simulated or real-life operational conditions. Acoustic performance includes noise attenuation, speech intelligibility, localization and detection. User acceptability includes comfort, ease of use, and situational awareness.

Hearing Protector – A device, also called a hearing protection device, worn to reduce the sound level in the ear canal.

Helmet – A device that provides impact protection to the head or skull and that is designed also to reduce noise through either passive and/or active attenuation.

HML (High, medium, and low) Rating for Hearing Protectors – The HML method uses the octave-band sound attenuation data provided by the manufacturer for a hearing protection device and the measured C and A-weighted sound pressure levels of the noise to predict the effective A-weighted sound pressure level at the ear when hearing protection is worn [ISO 4869-2:1994(E)]. A USA analogous value NRSG is defined in ANSI S12.68.

Impulse Noise – An acoustic event/s that are characterized by a very short rise time and having a duration of less than one second.

Insertion Loss – The algebraic difference in decibels between the sound pressure levels measured at a reference point with and without the hearing protection device in place.

Laboratory Attenuation – Attenuation measured in a laboratory setting.

Level Dependent – Devices that are designed to provide less attenuation at low sound intensities and increased attenuation at high sound intensities.

Level Equivalent (L_{Aeq}) – The L_{Aeq}(8 hr) is the notional sound level which would, in the course of an 8-hour period, cause the same A-weighted energy to be received by the ear as that due to the actual fluctuating sound over the actual working period.

Therefore, the equivalent continuous A-weighted sound pressure level, L_{Aeq},T.

Given by the equation:

$$L_{Aeq,T} = 10 \lg \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{p_A^2(t)}{p_0^2} dt \right]$$

where $t_2 - t_1$ is the period T over which the average is taken starting at t_1 and ending at t_2.

Notes:

1) The period, $t_2 - t_1$, used for direct measurement or calculation of L_{Aeq} ,T, should be chosen to give results representative of the whole period.

2) For continuous noise, unvarying in level, L_{Aeq} is numerically equal to L_{pA}.

Linear Attenuation – Attenuation in dB which is invariant independent of the noise level.

Localization – The ability to locate a sound source in a sound field.

Noise – Unwanted or undesired sound.

Noise Dose – Percentage of the allowable noise exposure relative to an exposure criterion, i.e. an exposure of 88 dBA for 2 hours relative to a 85 dBA, 8-hour, 3 dB/doubling criterion gives a 50% noise dose.

$$Dose = 100 \times \sum_{i=1}^{n} \left(\frac{t_i \times 2^{\left(\frac{l_i - L}{E} \right)}}{T} \right)$$

where:

Dose = Percentage dose
t_i = Exposure time in minutes for the ith time period
l_i = A weighted level in dBA for the ith time period
L = Exposure criterion A weighted level in dBA (for example 85 dBA)
E = Exposure criterion exchange rate in dB per doubling of exposure time (for example 3 dB/ doubling)
T = Exposure criterion Time in minutes (for example 8 hours would be 480 minutes)
n = Total number of exposure time periods (for example if you had 17 separate noise levels and time periods, then n = 17)

Noise Reduction – The algebraic difference in decibels between two microphones simultaneously measuring the sound pressure levels external to the hearing protector and under the hearing protector – the same as transmission loss.

Noise Reduction Rating – The US Environmental Protection Agency (EPA) required single number rating value for labelling the performance of all hearing protectors sold in the USA.

Non-Linear Attenuation – Attenuation in dB which varies depending on the level of the noise.

Octave Band – A range of frequencies where the highest frequency of the band is double the lowest frequency of the band.

Passive Hearing Protector – A hearing protector with attenuation based solely on the use of materials and/or structural elements.

Peak Sound Pressure – The maximum instantaneous sound pressure for an impulsive sound.

SNR – The Single Number Rating (SNR) method determines a single attenuation value calculated from the octave-band sound attenuation data provided by the manufacturer for a hearing protection device which is then subtracted from the measured C-weighted sound pressure level of the noise to provide a prediction of the effective A-weighted sound pressure level at the ear when hearing protection is worn [ISO 4869-2:1994(E)]. USA analogous values (NRR, NRSA, and NRSG are defined in ANSI S12.68.

Spectrum – The frequency amplitude energy distribution – typically of the noise.

Tactical Hearing Protector – Normally active hearing protectors designed to attenuate both impulse noise and continuous noise, level dependent, while providing some ambient listening capability while enhancing communication capability with interfaces to radio communication devices.

Time Weighted Average (TWA) – Equivalent to Leq, T for a fixed value of T.

Transmission Loss – The algebraic difference in decibels between two microphones simultaneously measuring the sound pressure levels external to the hearing protector and under the hearing protector – the same as noise reduction.

Appendix 2 – IMPULSE NOISE MEASUREMENT

A2.1   TRANSDUCERS

A2.1.1   Diameter of the Pressure Transducer

The rise time measured with a pressure transducer, when a shock wave is passing over the membrane is dependent on the diameter of the sensitive surface (membrane). The diagram on the right of Figure A2-1 shows this influence on the measurement of an idealized weapon noise (Friedlander impulse) with an A-duration of 0.5 ms. It can be observed, that the systematic error on the measurement of the peak pressure is 17% if a pressure transducer with an active diameter of 1" is used. When reducing the diameter to a ¼" the error is reduced to less than 1%. Moreover, the error is dependent on the A-duration of the impulse which becomes more important the shorter the A-duration is. As a rule, the ITOP proposes a maximum transducer membrane diameter of 5 mm for weapon noise measurement.
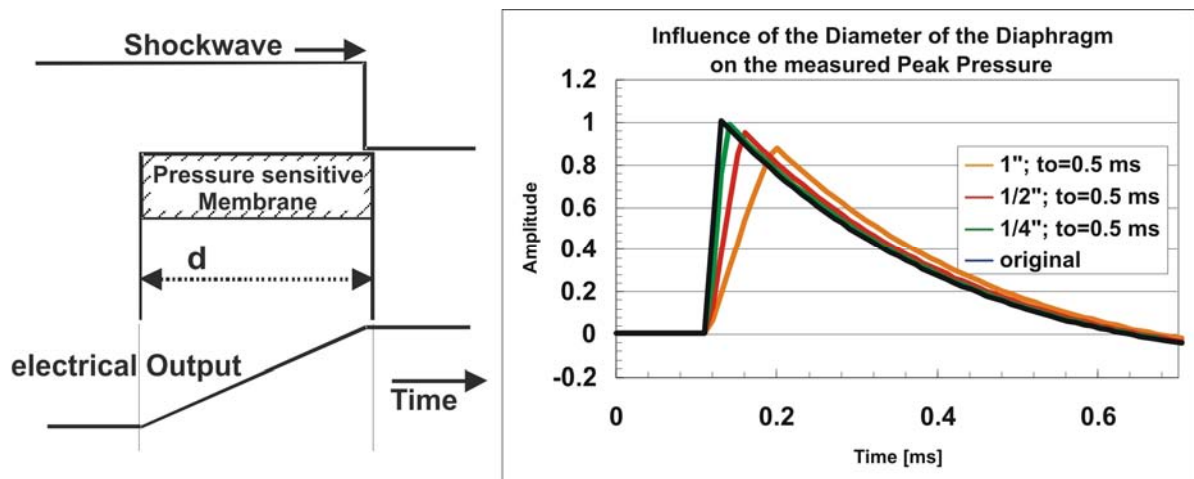
Figure A2-1: Influence of the Diameter of the Pressure Transducer on the Measured Peak Pressure of a Friedlander Wave (t0 = 500 µs).

A2.1.2   Type of Transducer

The choice of transducer is mainly governed by the peak pressure value that has to be measured and its bandwidth. The three major types of pressure transducers used for impulse noise measurements are shown in Figure A2-2.
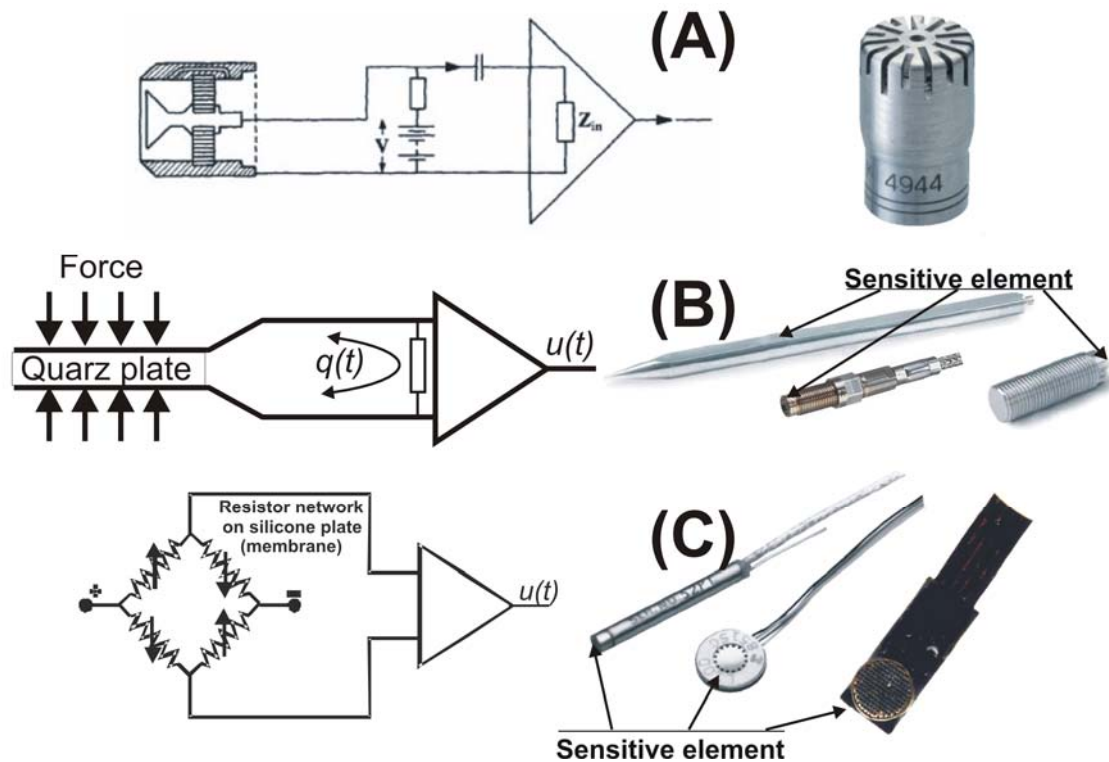
Figure A2-2: Different Types of Pressure Transducers.

Condenser Microphones (Figure A2-2A):

This type of microphone may be used for peak pressure levels lower than about 185 dB (35 kPa) depending on the manufacturer and the polarization voltage. These devices are relatively unaffected by temperature, the typical bandwidth is 4 Hz to 70 kHz, and the resonances are well damped.

Piezoelectric-Electric Transducers (Figure A2-2B):

This type of transducer is well suited for high peak pressure levels (>170 dB). They have a large bandwidth (>150 kHz) and can be used in all rough environments. However they are quite sensitive to temperature changes which should be taken into account when measuring weapon noise. Another problem associated with this type of device is the fact that the resonances have little damping.

Piezo-Resistive Transducers (Figure A2-2C):

These types of transducers may be used for levels above 170 dB. They have a large bandwidth (>150 kHz) and may be used in rough environments. This type of transducer is available in a very flat casing and it is therefore possible to use them for measurements on surfaces. However, when used to measure weapon noise the sensitivity to temperature changes and to photo-flash has to be taken into account. As the transducers may show an almost un-damped resonance, a suitable signal conditioning has to be applied.

A2.2   MOUNTING AND POSITIONING OF TRANSDUCERS

As the steep pressure increase at the onset of a weapon noise event implies a high particle flow, diffraction effects may occur at the edges of the transducers if the pressure step reaches high amplitudes. Therefore

the mounting and the positioning of the transducers is important in respect to the precision of the measurement.

A2.2.1   Mounting

Basically two types of mounting of the transducers are possible:

- The mount as a "blunt cylinder probe" (Figure A2-3a) can be used for measurements where the peak pressure is below 30 kPa (184 dB); and

- The mount as a "tapered pencil gauge" (Figure A2-3b) can be used for all peak pressure levels, even higher than 184 dB. However, if pressure signatures have to be recorded in an environment where the direction of the primary un-reflected wave cannot be determined (e.g. reverberant conditions) this type of probe should not be used.
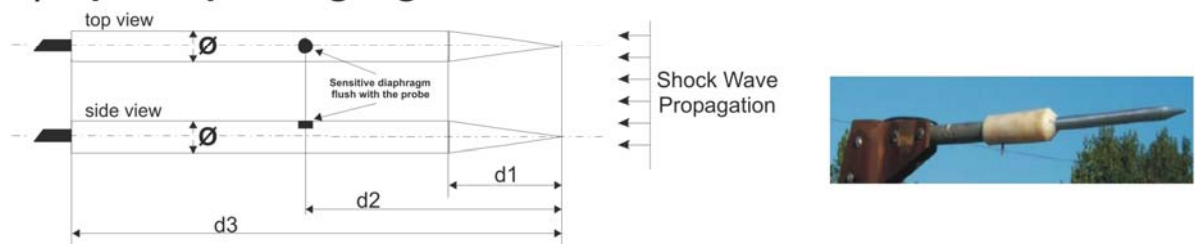
Figure A2-3: Different Types of Mounting of Pressure Transducers.

A2.2.2   Positioning

For optimal precision of the measurement the pressure transducers should be positioned in a way that the sensitive surface is perpendicular to the wave front.

Figure A2-4 shows the different possibilities for the positioning in respect to the front of the primary shock front of a blunt cylinder probe (upper) and for a tapered pencil probe (lower).
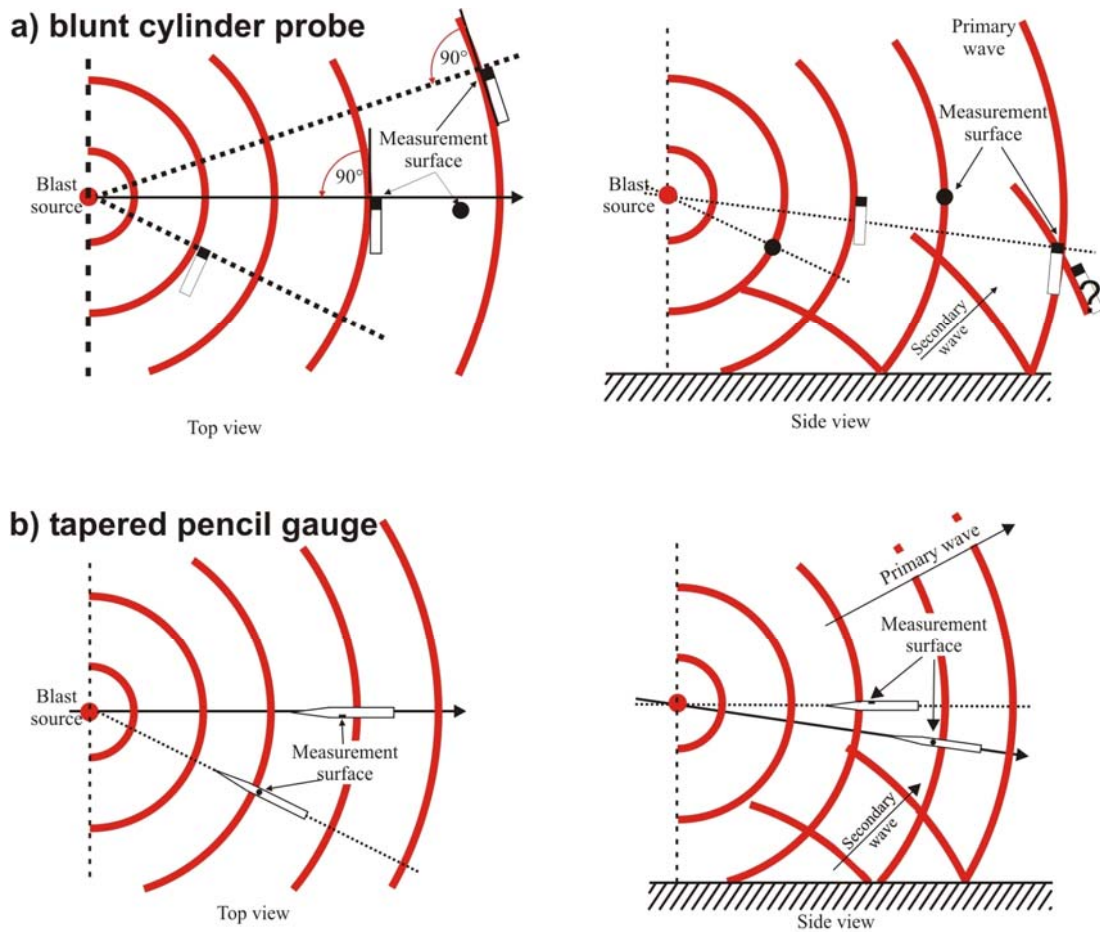
Figure A2-4: Preferred Positioning of the Pressure Transducers in the Acoustic Field.

In Figure A2-5 the effects of different angles of incidence of the shock wave are shown. It can be seen that the measurement error depends for a given size of transducer on the angle of incidence and on the peak pressure of the shock wave. The errors also depend on the size of the transducer, and become smaller with a decreasing size. If more than 1 main source is present (e.g. recoilless weapons, anti-tank weapons) or if strong reflections (e.g. close to structures) are present, the transducers should be positioned in respect to the strongest source. If possible, the membrane of the transducer should be placed on a plane passing through the strongest sources. More details are provided in the ITOP.
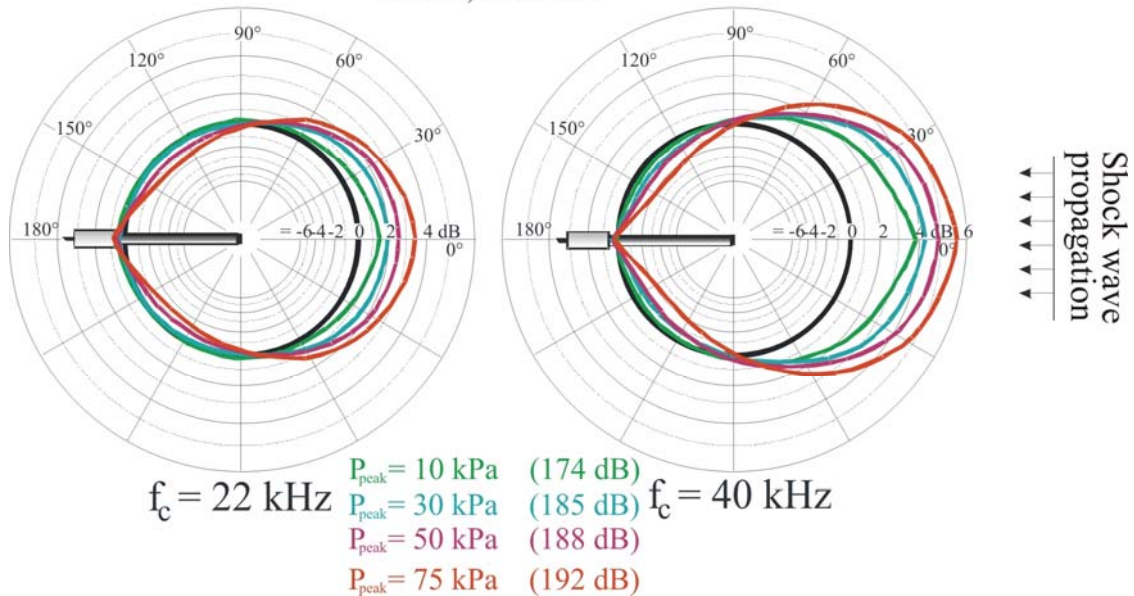
Figure A2-5: Influence of the Angle of Incidence of the Shock Wave Filtered at 22 or 40 kHz on the Measured Peak Pressure Level for Different Levels.

A2.3 DATA ACQUISITION AND FILTERING

As weapon noise is typically characterized by a very steep onset (<1 µs) and a slower decay (>200 µs) of the pressure wave (Friedlander type), the sampling frequency of data acquisition should be 100 kHz or higher. Some types of filters (e.g. Tchebyshev) lead to overshooting when a step function is input. This behaviour may lead to errors in the measurement of the peak pressure. It is therefore better to use Bessel filters for the conditioning of the signal before sampling (anti-aliasing, bandwidth reducing …) which do not show this type of behaviour. Figure A2-6 shows the response to a step function for different types of filters when the same cut-off frequency and order is used.
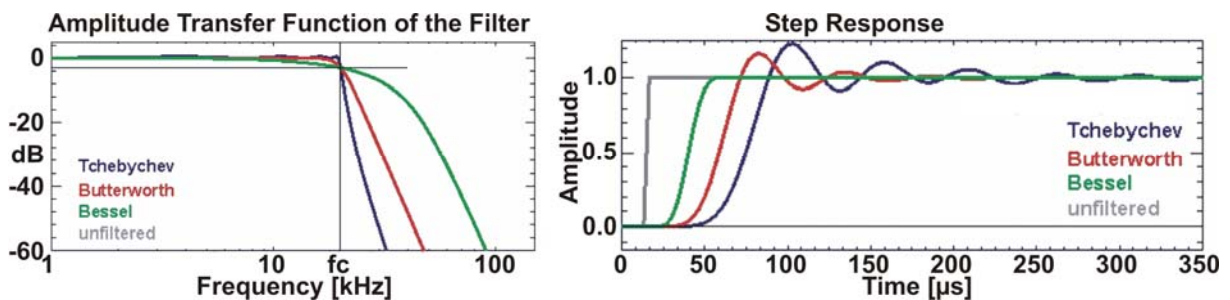
Figure A2-6: Influence of the Filter Type on the Unity Step Response.

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14. Abstract

Noise and the associated hearing loss and degradation of communication capability have been a common and significant problem in the military among the NATO member nations. Noise related issues have continued to grow in consequence and costs. This report details the requirements of the member nations for noise exposure and the associated hearing protection needs. A presentation of the wide range of military continuous and impulse noise environments and methods for their measurement is also presented. The combination of noise exposure criteria, noise levels, and exposure times can be used to calculate noise dose and determine the amount of noise attenuation required. Each type of currently available and emerging hearing protection technology including active and passive earmuffs and earplugs, level dependent earmuffs and earplugs, and communication earplugs, headsets, and helmets along with their attenuation performance is presented in the report. Additionally, new technology areas including techniques to reduce bone conducted noise and tactical hearing protectors for ground soldiers are presented, and the issue of laboratory versus field attenuation of hearing protectors and standardized methods for measurement of attenuation are addressed. Finally, guidance is given on hearing protection selection factors and criteria along with a summary and recommendations for future work.

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