Improved Hearing Protection for Aviation Personnel

Richard L. McKinley[1], Valerie S. Bjorn[2], and John Allen Hall[3]
Air Force Research Laboratory[1,3]
AFRL/HECB, Bldg 441
2610 Seventh Street
Wright-Patterson AFB, OH 45433-7901, USA
Naval Air Systems Command[2]
AEDC/DOF
740 Fourth Street
Arnold AFB, TN 38389-6000, USA

richard.mckinley@wpafb.af.mil

ABSTRACT

Hearing loss has long been associated with the operation of aircraft. Some of the first hearing protectors were developed for use around military aircraft. Today's high performance military aircraft generate noises which typically range from 110 dB to 150 dB. Normally, the source of the noise cannot be quieted without loss in performance. Therefore hearing protection is the primary tool to mitigate aviation personnel noise exposures during operations of aircraft. This paper describes a joint U.S. Air Force and U.S. Navy approach to improve hearing protection and reduce hearing loss risk. The approach included research and development to improve hearing protection as well as technologies to allow personnel to be moved from high noise work areas; recommendations for administrative controls; and investigation of hearing protective pharmaceuticals. The development of improved passive and active hearing protection technologies employed a three phased approach with attenuation performance goals for near-term (35-40 dB), mid-term (40-45 dB), and long-term (45-50+ dB) solutions. The technologies which have been developed to achieve the first two hearing protection goals will be described along with their attenuation performance characteristics. Ongoing research to achieve the long term (45-50+ dB) goal will be described with considerations of bone conducted noise pathways.

1.0 INTRODUCTION

For over 100 years, aircraft have generated levels of noise sufficient to cause hearing loss in personnel operating and maintaining those aircraft. Pilots, aircraft mechanics, and flight line personnel have long understood the risk of hearing damage when flying and working around aircraft. Early attempts at hearing protection included stuffing cotton or chewing gum into the external ear canal. The first earmuffs were basically jelly jars dipped in rubber and put on a headband. The introduction of jet aircraft brought broadband noise spectra and higher overall noise levels into the personnel noise environment. High performance military aircraft frequently generate levels of noise not normally experienced in the general civilian or industrial workplace. These levels typically range from 140 dB to over 150 dB at the worst case maintenance personnel locations (see Figure 1) and from 110 dB to 120 dB in the cockpit (9) at the pilot location.

McKinley, R.L.; Bjorn, V.S.; Hall, J.A. (2005) Improved Hearing Protection for Aviation Personnel. In *New Directions for Improving Audio Effectiveness* (pp. 13-1 – 13-12). Meeting Proceedings RTO-MP-HFM-123, Paper 13. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.aps.

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **01 APR 2005**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Improved Hearing Protection for Aviation Personnel**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory1,3 AFRL/HECB, Bldg 441 2610 Seventh Street Wright-Patterson AFB, OH 45433-7901, USA**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

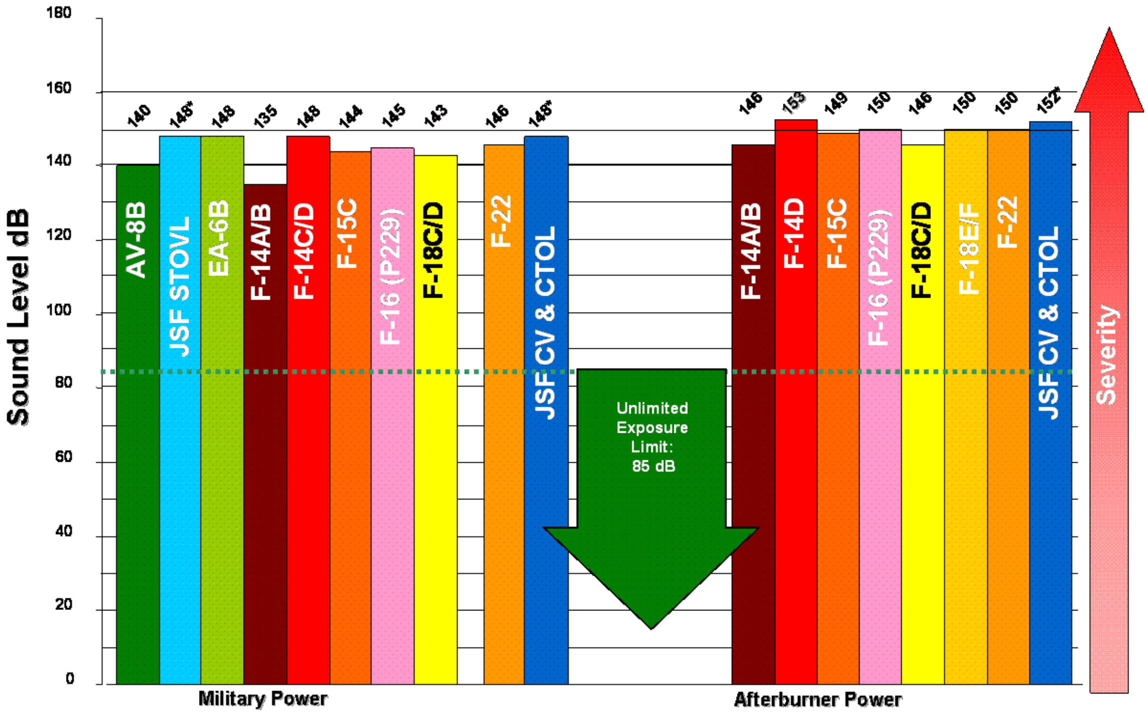
See also ADM001856, New Directions for Improving Audio Effectiveness (Nouvelles orientations pour l'amelioration des techniques audio)., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18



* SDD F-35 Estimate

Figure 1: Worst case noise levels at personnel locations of legacy high performance military aircraft

Double hearing protection consisting of earmuffs and earplugs is required to work in these higher near-field personnel noise levels. However, passive hearing protectors available today, even when worn as double hearing protection, do not reduce the highest jet noise enough to prevent noise induced hearing loss. The concept of Active Noise Reduction (ANR), or electronically sensing and transmitting anti-noise to reduce noise in headset earcups, was demonstrated in the late 1950's by Meeker *et al* (12) working for the Radio Corporation of America (RCA) at Wright-Patterson Air Force Base. By the 1980s, the first practical ANR headsets (5) were available. Typically, ANR headsets improve attenuation 10-15 dB in the noise frequencies below 800 Hz and in sound pressure levels below 135 dB. While providing a significant gain in hearing protection, ANR headsets fall short for protecting the hearing of personnel working in noise above 135 dB.

The design of a next generation high performance aircraft usually begins with a new engine. These engines are generally more powerful, more efficient, and unfortunately, frequently produce high noise levels. Concerns over the increasing prevalence of military personnel hearing loss and related disability compensation (see Figure 2) prompted the U.S. Navy and U.S. Air Force to jointly pursue improved hearing protection for aviation personnel – pilots and maintainers – with a focus on the highest noise level environments associated with military aircraft and engine maintenance operations.

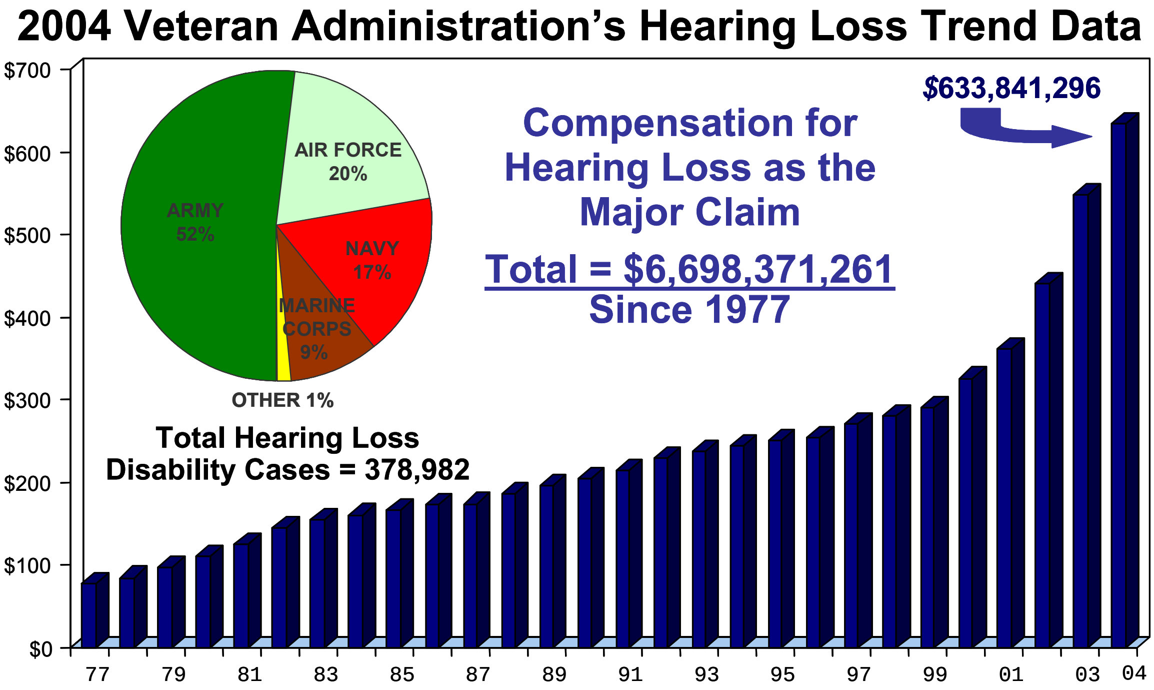


Figure 2: United States Veterans Affairs Compensation Payments for Hearing Loss Disability

2.0 RATIONALE

In 2001, the U.S. Air Force and U.S. Navy developed a joint service 7 year plan to reduce hearing loss in military aviation personnel. In addition to the U.S. Navy and U.S. Air Force, the total effort involved researchers and developers from universities and commercial technology developers as well. Figure 3 provides a schematic of the three-part plan implemented. The first part, improved hearing protection, is the focus of this paper. The goal was to develop a hearing protection system that would protect personnel working in 150 dB environments for up to 15 minutes per day, i.e. a nominal 50 dB hearing protector. Figure 4 shows how 50 dB hearing protection increases safe allowable exposure times. To meet the 50 dB hearing protection goal, near-, mid-, and long-term noise attenuation goals were set: 2004 goal was 35-40 dB; 2006 goal is 40-45 dB; 2008 goal is 45-50+ dB. The second part of the plan, administrative controls, focused on stiffening rules and regulations concerning personnel noise exposure and hearing protector use. The third part, enabling technologies, broadened the approach to include aircraft and ship technologies that could allow personnel to be moved out of noise hazards and to include pharmaceuticals that had a potential to protect against permanent hearing loss. In summary, the 50 dB hearing protector concept would protect most personnel, and the remaining hearing hazards could be addressed by administrative controls and enabling technologies.

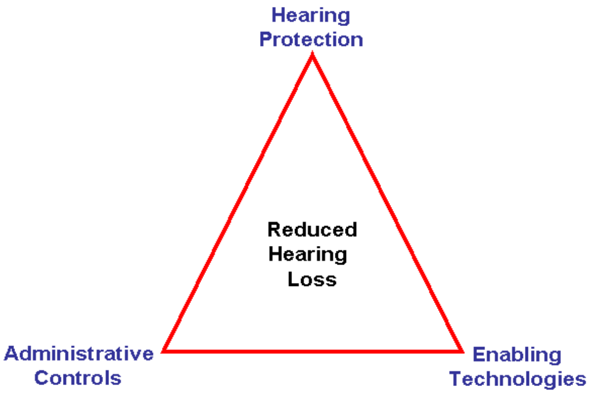


Figure 3: Three Part Plan to Reduce Hearing Loss

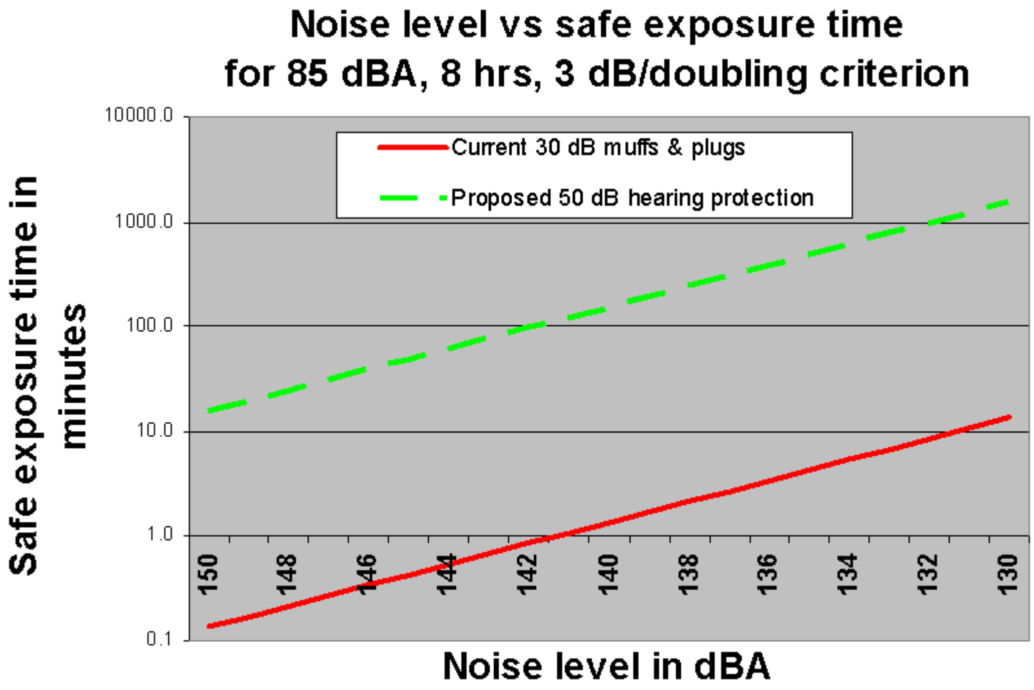


Figure 4: allowable exposure vs noise level with 30 dB and 50 dB hearing protection

Figure 5 shows the hearing protection performance goals, technologies, and time lines for improved aviation personnel hearing protection.

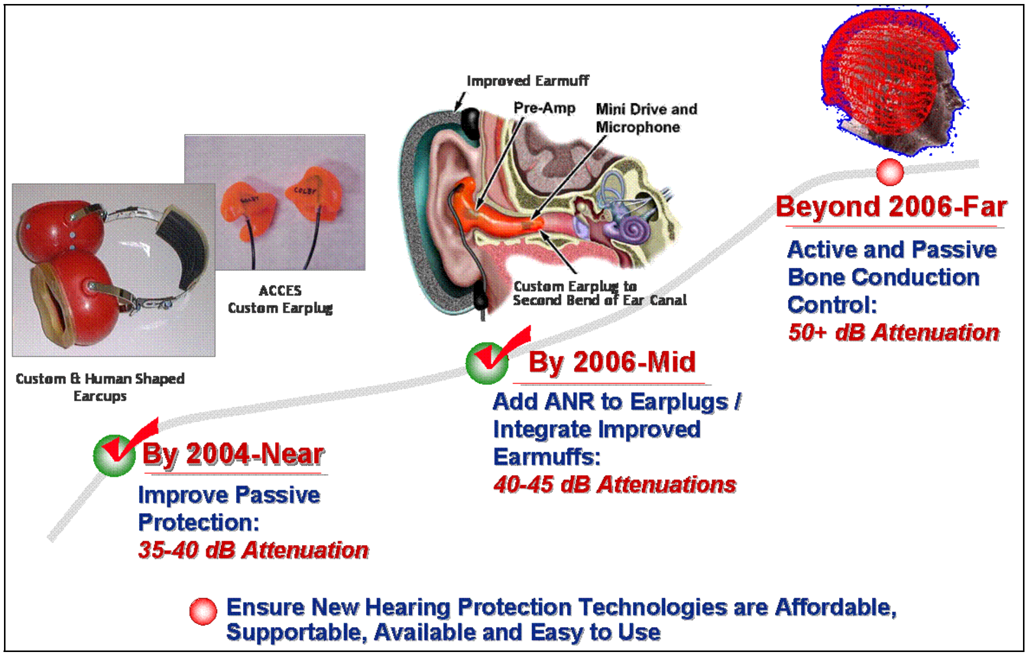


Figure 5: Hearing protection attenuation performance goals

3.0 METHODS

The joint U.S. Air Force – U.S. Navy plan included developing a combination of passive attenuation and active attenuation systems and testing to verify their attenuation performance. They included passive and active noise reduction custom fit earplugs, custom fit earmuffs, custom fit earcushions, cranial helmets, new materials, and new fabrication methods. The technologies were initially applied to existing designs (4, 6, 8, 11, 14, 15, 16, 19, 20, 21) to look at the potential advantages of the new technologies. Then the new technologies were combined in attempt to make more significant attenuation improvements. In all cases, the goal was to minimize the total A-weighted noise exposure of the personnel.

The noise fields at personnel locations were measured and analyzed along with the operational times at each condition. These individual exposures were summed, as shown in equation 1, to arrive at a total daily noise exposure, or TDE, for personnel across a flight line/deck. Typically, it was the highest level noise conditions which were the primary factors in the TDE calculation. Noise contours around an aircraft were plotted, then exposure time computed, and the resulting TDEs were mapped as seen in Figure 6. The black line is the TDE = 1 condition. Therefore, locations outside the black line are TDE < 1 and locations inside the black line are TDE > 1, indicating a daily over-exposure to noise. Personnel locations and TDE calculations were used to determine the amount of hearing protection attenuation needed to protect an individual at a particular location and to meet the allowable noise exposure criterion.

Equation 1.

$$TDE = \sum_{i=1}^{n} (t_{li} \div 480) \times 2^{(L_{Ali} - 85)/3}$$

where i ≡ exposure segment
where n ≡ total number exposure segments
where t_{li} ≡ the duration in minutes of the i^{th} exposure segment
and L_{Ali} ≡ A-weighted sound pressure level (dBA) at the ear of the i^{th} exposure segment

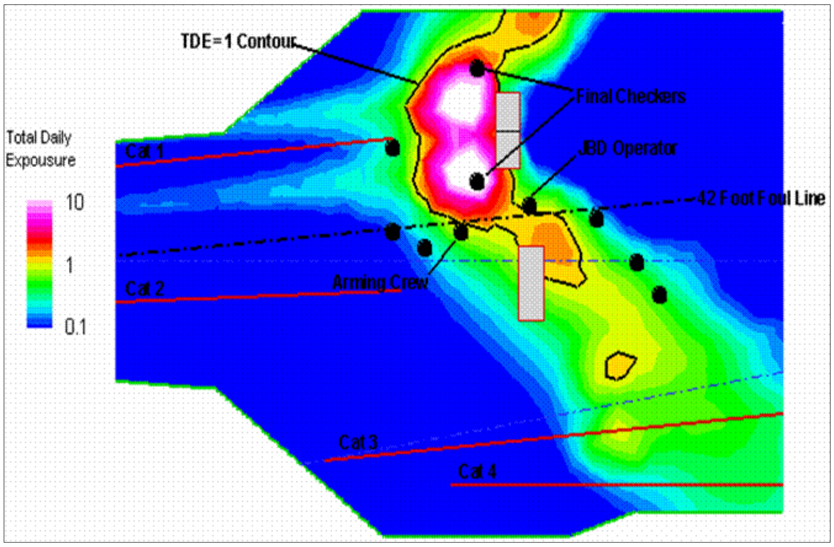


Figure 6: Notional Total Daily noise Exposure (TDE) contours for an aircraft carrier flight deck

Additionally, consideration was given to the statistical distribution of hearing protector performance. The mean or average attenuation adequately protects 50% of the personnel. If hearing protector attenuation performance was normally distributed (which it sometimes is) then subtracting 2 times the standard deviation of the attenuation would protect approximately 98% of the population. However, hearing protector performance can be a bimodal distribution, or some other non-normal distribution. To increase the accuracy of an attenuation rating of a hearing protector for a given population (like U.S. military flight line/deck personnel) attenuation performance was measured on either an actual sample from that population or a subject population selected to represent that population for age, gender, and head size.

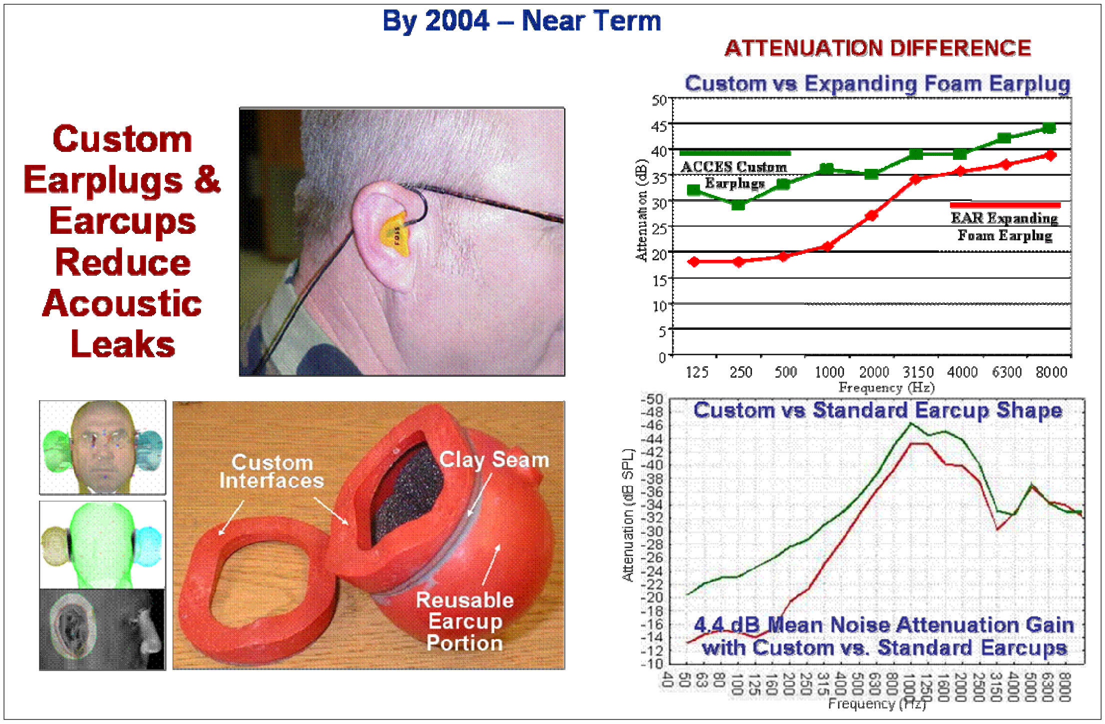
Hearing protector attenuation testing (1, 2, 10, 17, 18) followed national ANSI and/or international ISO consensus standards. Passive attenuation hearing protectors were tested on subjects using subjective and objective test methods in a 115 dB pink sound field, i.e., 115 dB at all frequencies. The subjective attenuation test method was the Real Ear Attenuation at Threshold, or ANSI S12.6 REAT method. In this method, the subject determined his threshold of hearing at several frequencies with and without the hearing protector. The difference in the two thresholds was the attenuation of the device. This method was used to test passive attenuating earplugs and earmuffs (REAT is not recommended for active noise reduction devices). The objective attenuation test method used was the Miniature Microphone in Real Ear, or ANSI S12.42 MIRE method. In this method, the subject was configured with two microphones, one at the entrance of each ear canal. The subject was placed in the sound field. MIRE data were collected with the subject wearing and then not wearing the hearing protector over the microphones. The difference between the two data sets was the attenuation of the device. The MIRE method was used to test earmuff attenuation. MIRE can not be used to test passive attenuating earplugs but is used to characterize the active attenuation performance of ANR headsets. ANR earplug attenuation test methods are evolving to use the microphone that is integral to the ANR earplug system, since it is not practical to add an independent microphone alongside an ANR earplug, deep inside the ear canal.

The data in this report include REAT data for earmuffs and earplugs, and both REAT and MIRE data for custom earmuff testing. The ANR earplug total attenuation was estimated using REAT data for the passive earmuff and earplug attenuation, and MIRE data from the ANR earplug microphone to estimate the active attenuation. ANR earplug MIRE data presented in this report were measured in the trapped volume between the tympanic membrane and inserted end of earplug tip. This trapped volume was always less than 1 cc and in most cases less than 0.5 cc; for this small volume, a phase shift from the ANR earplug microphone to the tympanic membrane was not considered to be an error factor. This conjecture was supported by subject reports of perceived decreases in the noise level when the ANR earplug system was powered.

4.0 RESULTS AND DISCUSSION

The near term and mid term goals to develop 40 dB and 45 dB overall attenuation devices were met and exceeded. Custom shaped earcups provided a 4.4 dB mean protective attenuation gain over standard, flat earcups (47 dB attenuation at approx. 1 kHz). Passive custom earplugs worn under standard earmuffs resulted in 42 dB mean overall attenuation. Active noise cancelling custom earplugs worn with standard earmuffs resulted in 47 dB mean overall attenuation.

The near term effort focused on improving passive attenuation both in earplugs and in earmuffs. Custom fitting procedures developed and advanced in this program resulted in improved fit and comfort. Custom earplugs and earcups minimized the size of acoustic leaks by improving fit. Figure 7 shows mean attenuation data that compares custom earplugs and earmuffs to expanding foam earplugs and standard flat earcups, both commonly used by U.S. Navy and U.S. Air Force aviation personnel.



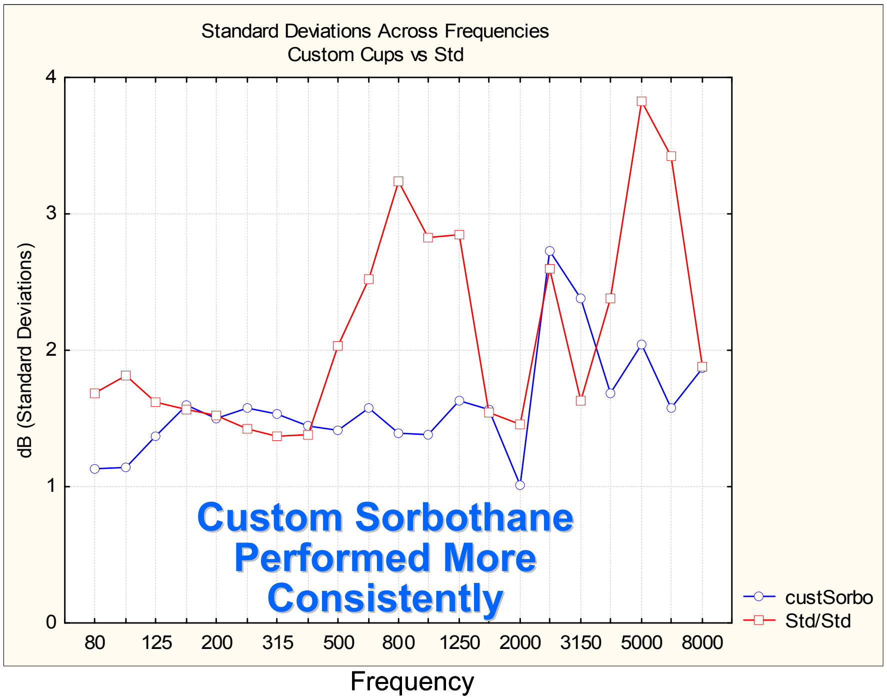
By 2004 – Near Term

Custom Earplugs & Earcups Reduce Acoustic Leaks

4.4 dB Mean Noise Attenuation Gain with Custom vs. Standard Earcups

Figure 7: Near term hearing protection attenuation performance and technologies

Customizing earplugs and earcups improved the reliability of fit as evidenced by a reduced standard deviation in attenuation scores compared to currently used earcups (see Figure 8).



Custom Sorbothane Performed More Consistently

Figure 8: Custom versus Standard Earcup Attenuation Standard Deviations

A hearing protector that was comfortable and provides consistent attenuation within and between subjects was desirable for ensuring field use and ensuring field attenuation performance. The current hearing protection consists of a combination of earplugs and earmuffs, typically foam earplugs and a large volume earmuff. The reliability and consistency of fit in the field was an issue(3).

In a recent survey of 301 aviation personnel, Bjorn *et al* (3) found that while 73% reported inspecting their cranial helmets at least daily, 41% of the earcup cushions and/or earcup foam inserts were in poor condition (deteriorated, flat, hard, or missing). Only 14% reported always wearing earplugs beneath their cranials (double hearing protection), while 47% percent reported never wearing earplugs. Of those who used earplugs, only 7% inserted earplugs deeply enough in both left and right ear canals to benefit fully (full attenuation). For subjects who reported wearing earplugs sometimes or always, Figure 9 shows earplug insertion depths and the percentage who achieved each depth. In total, 79% of the ears of flight deck personnel interviewed received an estimated 0-6 dB of noise attenuation from either shallow earplug insertion depths or never wearing earplugs.

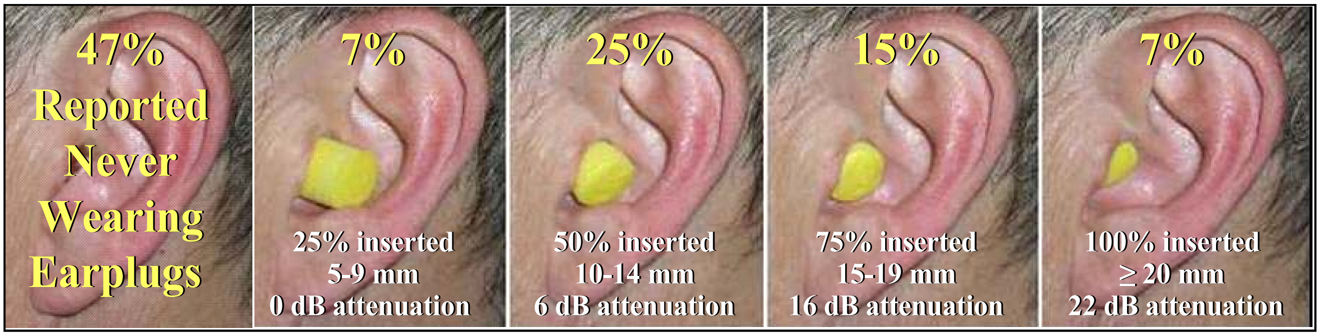
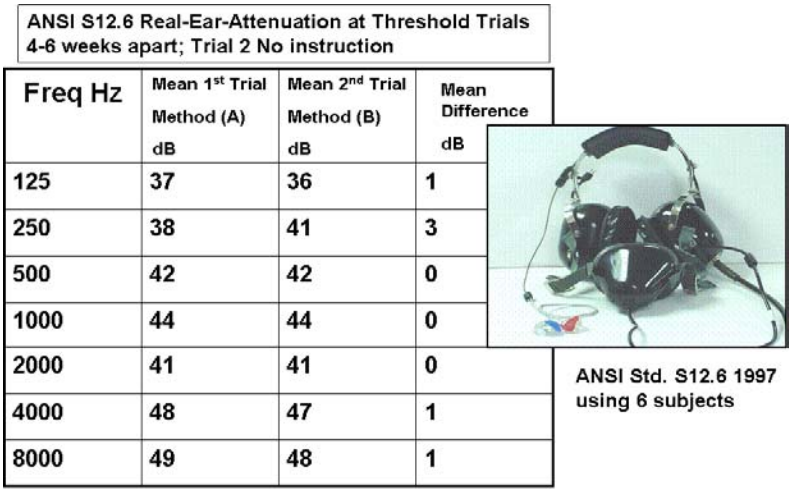


Figure 9: Left and right earplug insertion depths percentage of subjects at each depth

In comparison, Figure 10 shows the results of a limited study of custom earplug fit attenuation reliability and consistency of fit over a 4-6 week period. Once trained, subjects were able to reinsert the custom earplugs without assistance and achieve consistently high attenuation. One factor working in favor of deep insert custom earplugs was that incorrect earplug insertion was very uncomfortable. There was no viable partial insertion option for the custom earplugs; this is a significant difference when compared to almost every other available earplug. This factor, it is believed, will result in more consistent and higher overall attenuation when in actual use by personnel on flight lines and flight decks.



ANSI S12.6 Real-Ear-Attenuation at Threshold Trials
4-6 weeks apart; Trial 2 No instruction

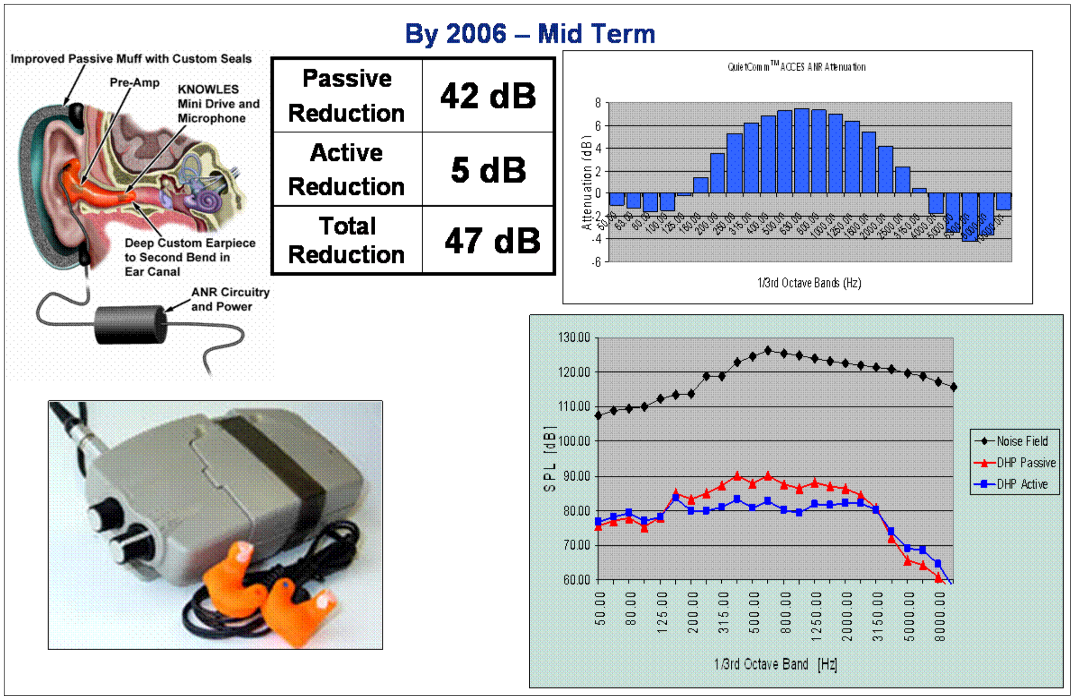
Freq Hz	Mean 1st Trial Method (A) dB	Mean 2nd Trial Method (B) dB	Mean Difference dB
125	37	36	1
250	38	41	3
500	42	42	0
1000	44	44	0
2000	41	41	0
4000	48	47	1
8000	49	48	1

ANSI Std. S12.6 1997
using 6 subjects

Figure 10: Custom deep insert earplug consistency and reliability of fit

With custom earplugs and earcups, double protection is still required. Either or both of these near-term technologies could be immediately fielded. The custom earmuff would result in an approximate 4-5 dB improvement in attenuation performance while the custom deep insert earplug would result in an approximate 10 dB improvement in attenuation performance.

Active noise reduction (ANR), i.e. active noise cancellation in a small volume, has been available in headsets and earmuffs since the mid 1980s. In this current U.S. Air Force and U.S. Navy program, the mid-term effort to improve hearing protection for aviation personnel was to add ANR to deep insert custom earplugs. The best available ANR headsets were able to actively cancel noises up to approximately 135 dB depending on the noise spectrum. With any ANR system, a limit is determined by the maximum excursion of the driver generating the canceling noise. The amplitude of the canceling noise needs to be equal and nearly 180 degrees out-of-phase to the insulting noise. Simply, there were no drivers available to generate the necessary 135 dB or greater canceling noise in a large volume earcup. However, the earplug approach offered a number of advantages. First, the driver in the earplug had to move a much smaller volume of air, typically less than 0.5cc. Second, the amplitude of the insulting noise to be cancelled had been reduced by the passive attenuation of both the earmuff and earplug, again reducing the excursion requirements on the driver. Finally, due to the small volume and associated small time delay, the maximum frequency of active attenuation would increase from the typical 800 Hz for an ANR headset to almost 3 kHz in the system shown in Figure 11.



By 2006 – Mid Term

Passive Reduction	42 dB
Active Reduction	5 dB
Total Reduction	47 dB

Figure 11: Active noise reduction earplug passive and active attenuation performance

An important point should be considered when designing any ANR system. The overall goal should be to reduce the A-weighted noise level at the tympanic membrane in the noise spectra in which the device is expected to be used. This may mean giving up large, low frequency active attenuation performance to gain modest mid-frequency active attenuation performance that more directly translates to reductions of the overall A-weighted sound pressure level at the ear and correlates to more accurate speech communications.

Once noise has been sufficiently attenuated via the ear canal, other noise pathways that flank the ear canal to arrive at the cochlea become the next technology challenge for hearing protection developers. The bone conduction limits have been described by many authors including Nixon, von Gierke, and Berger (7, 13). The consensus of these articles was that once 43-45 dB attenuation is achieved, bone and tissue noise pathways predominate at 2 kHz. Bone and tissue conduction were a factor at other frequencies but at greater attenuations.

Clearly in 150 dB noise environments, where 50 dB or more attenuation is required, bone conduction becomes an important issue. Two concepts have been conceived in an attempt to deal with the flanking paths provided by bone/tissue conduction. The first approach was a brute force approach with multiple sensors and drivers as depicted in Figure 12, left insert. The goal was to minimize the bone/tissue vibrations mechanically. The second approach (Figure 12, right insert) was to use an air conducted signal to cancel the bone/tissue conducted noise. This assumed the cochlea could not discriminate the source of vibrations reaching it; therefore, the cancellation signal for the bone/tissue conducted noise could be presented via an earphone. Some initial progress toward this goal of actively cancelling bone conducted noise has been made.

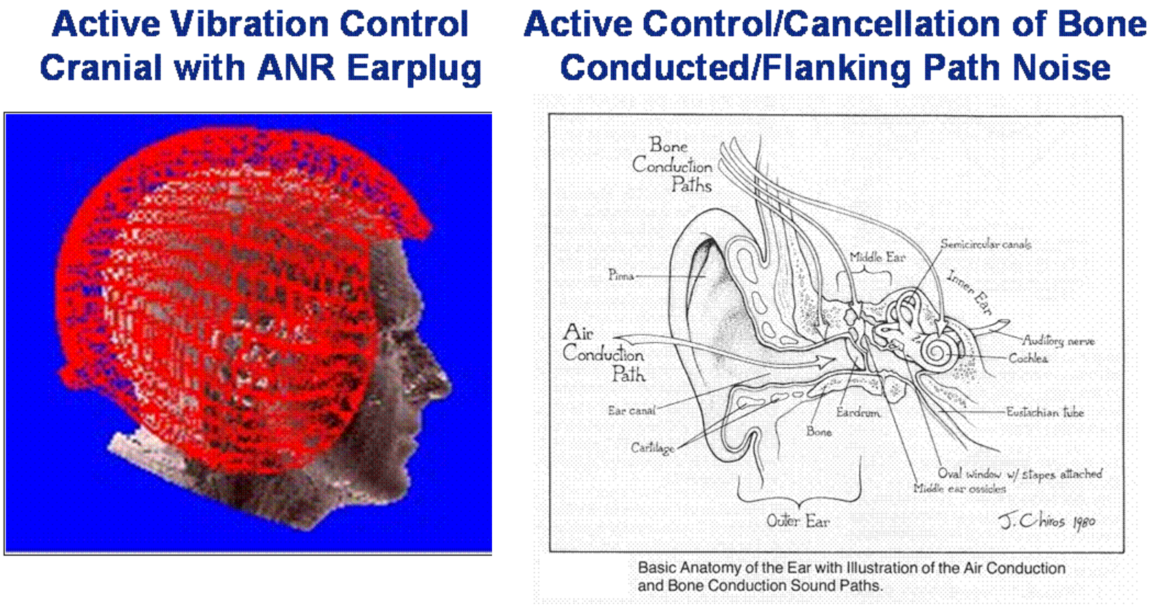


Figure 12: Active reduction of bone conducted noise concept

Measurements of noise levels present in the ear canal were made in high (>130 dB) noise fields. Also, noise measurements were made in the ear canal of noise reradiated in the ear canal from a bone conduction driver on the head of the subject. In both cases the noise levels present in the ear canal were sufficient to be potentially useful in an active noise reduction/cancellation system. Preliminary studies have shown that pure tone noise generated by a bone conduction driver can be actively cancelled by an air conducted cancellation signal. In this study, the phase and amplitude of the cancellation signal was controlled by the subject and the frequency was constant.

In theory, active cancellation of bone conducted noise would allow development of hearing protectors delivering virtually as much attenuation as required. To achieve this goal, an improved understanding of physical acoustics of the head and of the psychoacoustics of bone/tissue conducted noise is required.

5.0 CONCLUSIONS

Hearing loss has been and will continue to be a major disability associated with the operation of high performance aircraft. The joint U.S. Air Force – U.S. Navy program to reduce aviation personnel hearing loss has fostered new research and development in both passive and active noise attenuation resulting in significant improvements in attenuation performance with a 47 dB attenuation demonstration. The first two goals of the joint U.S. Navy – U.S. Air Force program have been met and work continues toward the development of a 50+ dB hearing protector. At 50+ dB, bone conduction is the predominant noise pathway at some frequencies. However, significant research and development in mitigating the bone conducted noise is being accomplished. The near-term technologies developed under this research and development effort are moving to operational use and should have a significant impact on reducing the incidence and severity of noise-induced hearing loss in aviation personnel.

Figure 12: Part of the joint U.S. Air Force – U.S. Navy improved hearing protection team

6.0 BIBLIOGRAPHY

1. Berger, E. H., Review and Tutorial - *Methods of Measuring the Attenuation of Hearing Protection Devices*, J. Acoust. Soc. Am. 79(6), pages 1655-1687, 1986

2. Berger, E. H., *International Activities in the Use, Standardization, and Regulation of Hearing Protection*, J. Acoust. Soc. Am. 99(4), Pt.2, page 2463, 1996

3. Bjorn, V. S., Albery, C. B., Shilling, R. D., *U.S. Navy Flight Deck Hearing Protection Use Trends: Survey Results*, NATO RTO HFM-123 Symposium Proceedings, “Directions for Improving Audio Effectiveness”, Amersfoort, The Netherlands, April 2005.

4. Blackstock, D.T. and von Gierke, H.E., *Development of an Extra Small and Extra Large Size for the V-51 R Earplug*, Wright Air Development Center Technical Report, WADC 56-142, Wright-Patterson Air Force Base, Ohio, April 1956

5. Carter, J, *Active noise reduction*, AFAMRL-TR-84-008, 1984

6. Dancer, A., Buck, K., Hamery, P., and Parmentier, G., *Hearing Protection in the Military Environment*, Noise & Health 5, 1-15, 1999

7. Franke, E.K., von Gierke, H.E., and von Wittern, W.W., *The Jaw Motions Relative to the Skull and Their Influence on Hearing by Bone Conduction*, Aero Medical Laboratory Technical Report number 6466, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, May 1951

8. Guild, E., Nixon, C.W., and Baker, D.J., *User Test of Flents Anti-Noise Ear Stopples*, Internal Memo, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, May 1959
9. James, S., Hancock, M., Hazel, A., and Rood, G. M., *Primary Contributors to Hearing Damage Risk in the Military Aircraft Cockpit*, Intl. Military Noise Conf., Baltimore, MD, 2001
10. Johnson, D.L., and Nixon, C.W., *Simplified Methods for Estimating Hearing Protector Performance*, Journal of Sound and Vibration, June 1974
11. Johnson, D. L., Nixon, C. W., and Skelton, M., *The Effect of Reduced Headband Force on the Attenuation of Muff-Type Protectors*, J. Acoust. Soc. Am. Suppl. 1, 74, S94, 1983

12. Meeker, W., *Active ear defender systems: component considerations and theory*, WADC TR 57-368, 1958

13. Nixon, C. W. and von Gierke, H. E., *Experiments on the Bone-Conduction Threshold in a Free Sound Field*, J. Acoust. Soc. Am. 31(8), pages 1121-1125, 1959

14. Nixon, C. W. and Knoblach, W. C., *Hearing Protection of Earmuffs Worn Over Eyeglasses*, Aerospace Medical Research Laboratory, Report No. AMRL-TR-74-61, Wright-Patterson AFB, OH, 1974
15. Nixon, C.W., Chapter 5 *Hearing Protector Standards, in Personal Hearing Protection In Industry*, edited by Alberti, P.W., Raven Press, New York, 1982

16. Nixon, C.W., Chapter 12 *Hearing Protective Devices: Ear Protectors*, in Handbook of Noise Control, edited by Harris, C., McGraw-Hill, 1979

17. Parmentier, G.; Buck, K.; Kronenberger, G., and Beck, C., *Artificial Head (ATF) for Evaluation of Hearing Protectors*, Institut Franco-Allemand De Recherches De St. Louis, St Louis, France, 1999
18. Rood, G. M., *The In-Situ Measurement of the Attenuation of Hearing Protectors by the Use of Miniature Microphones*, in Personal Hearing Protection in Industry, edited by P. W. Alberti, Raven Press, New York, NY, pages 175-197, 1982
19. Shaw, E.A.G. and Thiessen, G.J., *Improved Cushion for Ear Defenders*, J. Acoust. Soc. Am., Vol 30, Num 1, pages 24-36, Jan 1958

20. Shaw, E.A.G., *Hearing Protector Design Concepts and Performance Limitations*, International Symposium on Personal Hearing Protection, University of Toronto, Canada, May 1980

21. von Gierke, H. E., *Protection of the Ear from Noise: Limiting Factors*, J. Acoust. Soc. Am. 95(5), Pt. 2, page 2914, 1994