

Cost Benefit Analysis

Cost Benefit Analysis for Human Effectiveness Research: Bioacoustic Protection

A Report for:

**Air Force Research Laboratory
Human Effectiveness Directorate
Crew System Interface Division
2610 Seventh Street, Area B
Wright-Patterson Air Force Base, Ohio 45433-7901**

By:

Michael E. Rench
Consultant

Sharon Johnson
Associate

Thomas Sanders
Senior Associate

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11. SUPPLEMENTARY NOTES This report is one of several cost benefit efforts in the area of human effectiveness research sponsored by AFRL/HE. Other specific topics include the Air Combat Capability Enhancement Suite (ACCES), Distributed Mission Training (DMT) and a State of the Art Report (SOAR) outlining the generic steps required to conduct a CBA on human centered technologies.				
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13. ABSTRACT (Maximum 200 Words) Human Systems IAC was asked to assess the costs and benefits associated with providing improved hearing protection for Air Force flightline personnel. To ensure individuals with a direct stake in this area of study were included, input was obtained from subject matter experts as well as stakeholders such as Air Force fighter pilots and maintenance crew chiefs. A standard eight-step process was used to identify and evaluate the costs and benefits associated with the current bioacoustic protection system in use and two alternative systems. This study evaluates the costs and benefits associated with three hearing protection alternatives. Each alternative was estimated for cost and evaluated for relative benefits. By assigning a numerical value to the benefits, Human Systems IAC was able to develop a cost/benefit ratio (CBR) for each of the three alternatives. The lower the CBR, the more desirable the alternative. Human Systems IAC found that the most effective alternative with respect to the stated goals is alternative #3, ACCES with ANR (CBR = 9.0). The second most desirable alternative was ACCES (CBR = 10.9). Based on the evaluated cost and benefits the least cost effective solution in providing hearing protection was alternative #1, the fielded system (CBR = 11.6).				
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NOTICE

This report is one of several cost benefit analysis efforts in the area of human effectiveness research sponsored by AFRL/HE. Other topics include the Air Combat Capability Enhancement Suite (ACCES), Distributed Mission Training (DMT), and a state of the art report (SOAR) that outlines the generic methodology needed to conduct effective cost benefit analyses on human centered technologies.

EXECUTIVE SUMMARY

A. Overview

At the request of the Air Force Research Laboratory, Human Systems IAC assessed the costs and relative benefits of three select alternatives for providing hearing protection for Air Force ground crew personnel. The three alternatives examined in our analysis are:

- Status Quo: Passive earplugs combined with passive earmuffs that provide approximately 30 decibels (dB) attenuation.
- Near-term solution: Attenuating Custom Communication Earpiece System (ACCES) combined with earmuffs. When ACCES is worn alone, it is estimated to provide 35-40 dB attenuation.
- Mid-term solution: ACCES enhanced with Active Noise Reduction (ANR) technology combined with passive earmuffs; Estimated to provide 40-50 dB attenuation.

Military personnel are exposed to occupational noise intensities far exceeding their counterparts in commercial industry. Specifically, ground crew are subjected to noise levels up to 400-600 times the maximum noise energy recommended by the National Institute for Occupational Safety and Health (NIOSH). The overall goal of this analysis is to examine alternatives that can provide improved hearing protection to Air Force ground crew personnel. Two of the alternatives promise to provide an enhanced level of noise attenuation, which may help reduce the incidence of noise induced hearing loss.

B. Study Methodology

1. Costs Costs for the alternatives analyzed in this CBA were estimated using a variety of methodologies and sources. Methodologies used include actual costs, expert opinion, analogous systems and Air Force cost factors. A summary of each alternative's groundrules and assumptions can be found in Section 2.4. The detailed methodology, data sources and cost worksheets are in Appendix C. Table 1 below summarizes the total cost, in both FY01 dollars and then year dollars, by appropriation for each of the alternatives:

Table 1. Summary of Alternative Costs

FY01 \$000	Alternative #1	Alternative #2	Alternative #3
EMD (Appn 3600)	0	93	615
O&M (Appn 3400)	0	531	531
Procurement (Appn 3080)	788	2,326	4,814
Total	788	2,950	5,960
Then Year \$000	Alternative #1	Alternative #2	Alternative #3
EMD (Appn 3600)	0	95	635
O&M (Appn 3400)	0	564	564
Procurement (Appn 3080)	836	2,469	5,084
Total	836	3,128	6,283

2. Benefits Benefits were assessed in several ways as well. Many benefits were clear from information gathered in the literature search. Additional benefits were identified through an exhaustive coordination with subject matter experts and users who possess real world experience with the noise environment being analyzed. Table 2 summarizes the benefits.

Table 2. Benefits Definitions

Benefit Name	Benefit Definition
Communication	System impact on user's ability to give and receive auditory commands or instructions.
Hearing Protection	System impact on level of hearing protection provided.
Morale	Impact on user acceptance and willingness to perform duties.
Safety	System impact on flightline safety and injury prevention.
Usability	System impact on ease of use and fit of hearing protection equipment.

The assessment of these benefits was documented using a decision support software tool, Expert Choice. The tool was used to document the detailed assessment process and numerically rank the three alternatives. Expert Choice leads the decision maker through a series of judgments between the alternatives and then between the benefits. The tool then combines all the priorities to arrive at an overall ranking of the alternatives. The resulting benefits analysis showed that, with respect to the prescribed goal, alternative #3, with a score of 662, best satisfies the requirements. Alternative #2 is the next best alternative, scoring 270. The least beneficial alternative, alternative #1, scored a 68. These benefit scores reflect the fact that a lower score results in a reduced degree of noise protection. As a result, the alternative with the lowest benefits score will also have the highest likelihood of resulting in hearing loss for the operator.

3. Cost/Benefit Ratio The cost/benefit ratio (CBR) was used as a method of combining the costs with the benefits to establish an overall conclusion regarding the investment alternatives. Combining costs and benefits determines the true value of each alternative. The CBR represents the cost per unit of benefit. Thus, the lower cost/benefit ratio is preferred.

Table 3. Alternative Cost Benefit Ratios and Rankings

Alternative	Cost (FY01\$000)	Benefit Score	Cost/Benefit Ratio	Ranking
#1 Status Quo	788	68	11.6	3
#2 ACCES	2,950	270	10.9	2
#3 ACCES with ANR	5,960	662	9.0	1

Based on this data alone, alternative #3 is the most cost-effective. The analysis indicates it provides the greatest benefit for the money, with respect to the stated goal. Alternative #1 ranked the least cost-effective and alternative #2 fell in the middle.

C. Sensitivity Analysis

Since the cost estimates for alternatives #1 and #2 were largely based on actual costs or proven prototype program data, excursions from the baseline concentrated on alternative #3. The excursion illustrated the impact on the cost estimate when a key variable or assumption used in the baseline analysis was changed. Because the prime mission product (hardware in the central material item) cost element comprised over 60 percent of the total cost of this alternative, it was the focus of the sensitivity analysis. Specifically, the sensitivity of ANR headset portion of the

estimate was evaluated. Assuming all other elements remain constant, the ANR headset cost would have to increase by 75% in order to have an effect on the ranking of alternatives.

D. Risk Analysis

The focus of the risk analysis centered on developmental subsystems that represent the highest level of technological complexity, and therefore, the greatest level of risk with respect to cost and benefits. One of the areas investigated was the technological maturity of ANR for use in an operational military environment. Also addressed were general issues associated with the use of an analogous system as source data for the cost estimate and the relatively subjective nature of assessing the benefits of human-centered technologies using Expert Choice with subject matter experts.

E. Conclusions

This study evaluated the costs and benefits associated with three hearing protection alternatives. Each alternative was estimated for cost and evaluated for relative benefits. By assigning a numerical value to the benefits, Human Systems IAC was able to develop a cost/benefit ratio for each of the three alternatives.

The most effective alternative with respect to the stated goals was alternative #3, ACCES with ANR (CBR = 9.0). Even though it provides a reduced level of hearing protection, the second most desirable alternative was the ACCES system (CBR = 10.9). Based on the evaluated cost and benefits the least cost-effective solution for providing hearing protection was the fielded system (CBR = 11.6).

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1. INTRODUCTION

1.1 BACKGROUND

Hearing damage and loss is the number one disability among retired U.S. military personnel (29 Sep 00 SAF/AQR memo). Based on the increasing incidence of hearing loss and hearing loss claims, the current hearing protection technology used by ground personnel is inadequate for combating the noise levels of the newest generation fighters. Recent data indicates that 54% of personnel using current hearing protection will experience a significant hearing loss. As a result, the Veteran's Affairs statistics show an annual cost of \$300M in compensation for primary hearing loss claims (Veteran's Affairs Office, 1999). The number of impaired individuals and the associated costs will continue to climb unless an effective solution is provided.

Hearing damage is directly related to the intensity of the sound in dB and the length of exposure time. As the sound increases in intensity, the length of time it takes to cause hearing damage decreases. For instance, a crew chief can safely operate in a noise environment of 135 dB for four minutes with current protection. With enhanced protection, that operator could safely work in the same environment for 480 minutes.

Military personnel are currently exposed to occupational noise intensities far exceeding their counterparts in commercial industry. According to NIOSH statistics, 90 percent of private industry noise is 90 dB or below. In contrast, military fighter aircraft noise level exposure reaches ranges of 130-150 decibels (JSF Noise Issue Review, August 2000). With no technology in existence to reduce fighter aircraft engine noise without a dramatic loss of performance, and a significant annual expenditures on hearing loss compensation this issue must be addressed via improvement of the currently fielded bioacoustic protection technology. In June 2000, a two-day workshop on hearing loss caused by exposure to aircraft engine noise was held. This workshop resulted in a formal recommendation by the Under Secretary of Defense that an additional \$11.5M be invested in basic research to develop improved hearing protection for our military personnel.

Military Standard 1474D provides regulations regarding hearing protection associated with aircraft noise. It states that "flight members shall not be exposed to continuous noise that exceeds 115 dBA" (MIL-STD-1474D, page 66). Exposure up to 115 dBA is allowable, but only for safety-adjusted lengths of time (e.g., 30 seconds at 115 dBA). Noise over 115 dBA is forbidden for any amount of time. The intent of this requirement is the protection of flight members' hearing (MIL-STD-1474D, page 82). Sound levels that exceed 115 dBA can cause rapid severe damage to human hearing. This requirement should be invoked for all aircraft systems in establishing upper boundaries for protection of personnel from overexposure. Furthermore, Military Standard 1472F states that, "Personnel shall be provided an acoustical environment which will not cause personal injury..." (MIL-STD-1472F, page 123). Clearly a protection solution is required by military standards.

In addition to military requirements, there are also civilian recommendations in place. For instance, Military Standard 1472F states that, "Design of non-military-unique workplaces and equal shall conform to OSHA standards unless military applications require more stringent limits" (MIL-STD-1472F, page 6). By order of the Occupational Safety and Health Act of 1970 (Public Law 91-596), the National Institute for Occupational Safety and Health (NIOSH) was given the responsibility of recommending occupational safety and health standards for every working man and woman. As a result, NIOSH (1972) published guidelines for recommended standards to reduce the risk of developing permanent hearing loss as a result of occupational noise exposure. Subsequent evaluation of scientific information has resulted in NIOSH going beyond attempting to conserve hearing. In a published 1998 report, NIOSH recommended

exposure limits of 85 dB in an effort to conserve hearing by focusing on *preventing* occupational noise-induced hearing loss.

1.2 PURPOSE OF CBA

A cost benefit analysis (CBA) is a systematic method of assessing the economic desirability of selected investment alternatives based on their costs and benefits. The objective of the assessment is to identify one alternative that is preferable to all of the others.

The specific objective of this CBA project was to evaluate the economic desirability of three proposed hearing protection systems for use by flightline ground crew. The alternative eventually implemented should provide adequate noise protection for ground crew working near high performance aircraft as well as improved voice communication capability in 140-150 dB noise environments.

1.3 OVERVIEW OF APPROACH

As stated above, a CBA is a systematic method employed to make rational decisions on alternative systems by comparing them based on their estimated costs and evaluated benefits. Conducting a CBA assists in the allocation of scarce resources by probing each investment alternative so that all questions relevant to an appropriate decision are answered. The overall objective and alternatives are clearly defined; costs and benefits are presented; and important assumptions, factors and judgments are highlighted. Outlined in the following sections, are the eight steps used by Human Systems IAC in conducting this CBA. They are:

- Assess Current Environment,
- Perform Gap Analysis,
- Identify Investment Alternatives,
- Estimate Cost,
- Perform Sensitivity Analysis,
- Characterize and Value Benefits,
- Determine Net Value of Each Alternative, and
- Perform Risk Analysis

Once programmatic, technical and schedule ground rules and assumptions are established, a cost estimate is prepared for each alternative. Each estimate is then normalized to a standard base year for cost comparison purposes. Analysis of the benefits is accomplished using a decision support software tool (Expert Choice) that enables leveraging the expertise of key stakeholders and experts in the field. The values derived for the cost and benefits of each alternative are then used to calculate a cost benefit ratio for each alternative. The analysis is documented and presented to decision makers for consideration and action, if appropriate.

2. COST BENEFIT ANALYSIS

2.1 CURRENT ENVIRONMENT

2.1.1 Process

In evaluating the current environment, Human Systems IAC investigated the types of technologies currently in use. The need for a material solution based on the objectives was also considered. Finally, the need for the man-in-the-system and the consequences of removing him/her from the system were investigated.

The current technology in bioacoustic protection was surveyed and thoroughly examined to establish a baseline for the analysis. In addition, the scope of the system was established through collaboration with the customer. For example, the costs associated with hearing protection hardware will be included, but the costs of hearing compensation claims will not.

Assessing the current environment began with an in-house literature search to ascertain the general nature of the topic. Based on this search, a comprehensive list of keywords, catch phrases, subject matter experts (SME), and example articles was developed. This list was refined and combined with a short background description of the topic, the problem, and the expected outcome. As is often the case, the customer is a SME in the field and knew a great deal about the specific topic of hearing protection. The literature search strategy was developed with customer review and feedback, see Appendix E. The search resulted in the identification of literally hundreds of citations. These citations were surveyed for the most relevant and insightful resources. The emerging sources became the backbone literature source of information used throughout this CBA.

Once the background work was completed, selected documents were acquired and SMEs were contacted. The information was then combined to provide an accurate perspective of the current system. In the case of bioacoustic protection, it was established that the current technology provides only about 30 dB of protection to operators on a flightline (McKinley, 2000). Further results of this assessment are described in the following section.

2.1.2 Evaluation

Hearing protection technology has not changed significantly in over 30 years. However, the noise environment it was designed to protect against has changed dramatically. With each new generation of aircraft, the engines have become increasingly more powerful and the noise produced has increased with that power. To decrease the noise produced to safe levels would result in an unacceptable loss of performance. This disparity has led to an increase in hearing loss.

Potential solutions to the increasing problem of hearing loss fall within two categories; doctrine changes or material solutions. One solution to hearing loss would be to change existing doctrine regarding exposure time. Each worker could simply work in the high noise environment for his/her maximum exposure time for that noise level for that day and then leave the flightline. Using the crew chief example, the operator could work in the noise for four minutes and then leave for the day. This solution would require a significant increase in the number of individuals assigned to the appropriate Air Force Specialty Codes (AFSC). The required increase in manpower and training make the overall cost of this solution unfeasible.

Another doctrine change that could potentially solve the problem would be removal of the man from the dangerous part of the system. For example, the work being done could be conducted remotely via teleoperation technology. This solution was considered not viable for

several reasons. First, the work performed by the individual requires complex actions and decision-making skills. Real men and women are crucial contributors to the system performance. They carry out command and control tasks that would be impossible to perform remotely. Second, teleoperation would require the development of numerous new technologies, cost significantly more than the current problem, and would eliminate thousands of military jobs.

An alternative to doctrine change was to pursue improving the material protection available to operators. Within the Air Force two primary hearing protection technologies are currently being used. These are generic "foamy" earplugs that are rolled up and inserted into the user's ears (Figure 1), and protective circumaural earmuffs that cover the ears (Figure 2). Depending on the intensity of the noise environment, these two protections are also used simultaneously with the plugs inserted under the muffs for a level of protection up to 30 dB. Even with this protection in place, 54 percent of personnel continue to experience a primary hearing loss.



Figure 1. "Foamy" Ear Plugs



Figure 2. Earmuffs

2.2 GAP ANALYSIS

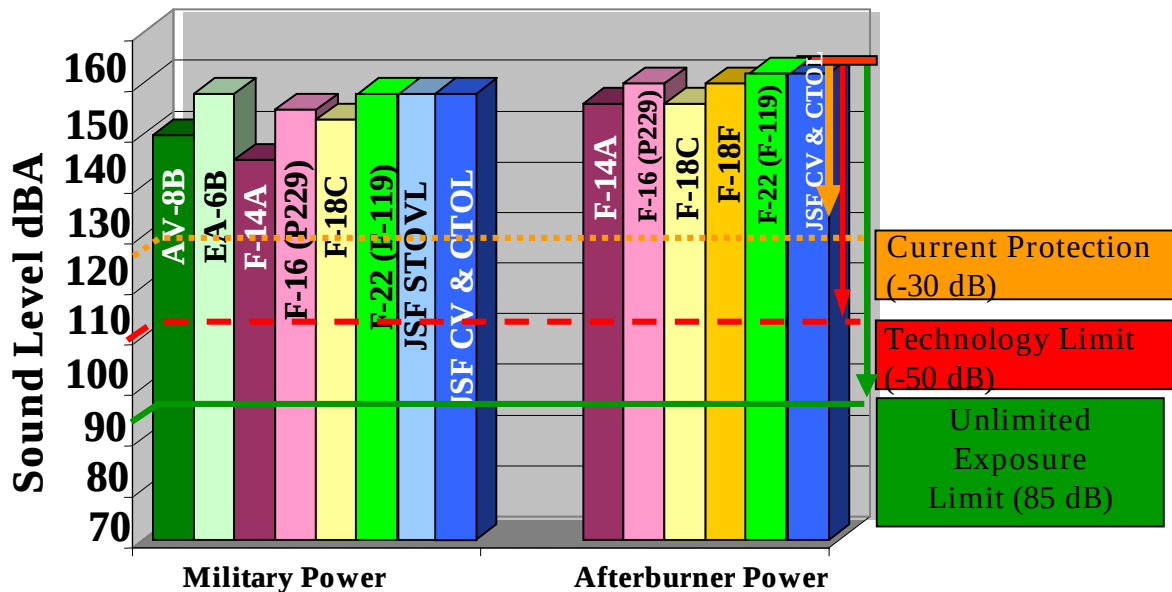
2.2.1 Process

This step of the CBA investigates the gap between the current technology in use and what the desired state is. By understanding the desired system's requirements and the effectiveness of the current technology (baseline) in meeting those requirements, it is determined where mission needs are not being met.

2.2.2 Evaluation

Hearing protection currently in use provides 30 dB of attenuation. Modern Air Force aircraft produce noise from 130 to 150 dB. NIOSH has established safe hearing levels of no greater than 85 dB over an eight-hour period, assuming 16 hours of quiet rest. Therefore, even

with the best hearing protection available, individuals working on the flightline are exposed to noise that exceeds safe limits by 15 or more decibels. Illustrated in Figure 3, even with 50 dB of added protection the gap between the technology limit (red line at 100 dB) and recommended exposure (green line at 85 dB) is about 15 dB. It was this gap that was addressed by the alternative systems.



These measurements are for named aircraft field noise at about 30 feet.
Gold dotted line indicates current level of protection available (-30 dB).
Red dashed line shows technological limit of protection of protection (-50 dB).
Solid green line indicates level of noise acceptable for unlimited exposure (85 dB).

Figure 3. Gap Between Protection and Exposure

A better fitting earplug, such as one custom molded for each user, provides better hearing protection than a generic protector. The custom-fit earplug can more effectively fill the ear canal, safely going deeper into the canal and eliminating the air that would otherwise conduct sound. In addition, it is nearly impossible to insert a custom earplug incorrectly. In comparison, a generic "foamy" earplug is typically rolled-up and inserted into the ear canal. When the foamy expands, it also fills the ear canal and protects against noise. When used appropriately, "foamies" can be effective. However, it is easy to insert these types of earplugs incorrectly, and it is difficult to determine if they are being used to their full effectiveness.

Technologies that work well in protecting hearing are those that effectively protect the user from intense sound energy. Passive protection (provided by earmuffs and earplugs) is effective at blocking the sounds at shorter wavelengths (higher pitched). These passive protections are not as effective at the longer wavelengths (lower pitched). However, a more recent technology, active noise reduction (ANR), is particularly good at attenuating lower pitch noise. The inherent combination of these two technologies appears to be the most effective protection available.

ANR works by detecting noise wavelengths within a given space (i.e., inside an earmuff) and then cancels out the "noise" by producing sound wavelengths out of phase with the noise. This can be illustrated with a pool of water. If one produces waves at one end of a pool, the

waves will travel evenly to the other side. If one then produces waves of the same amplitude (height) but out of phase with the original waves (peaks meet troughs and troughs meet peaks) at the opposite end of the pool, then the center of the pool will be smooth and without waves. This is because the waves interfere with each other, effectively canceling each other out. Seen in Figure 4, the black noise waves are canceled by the green (gray if in black and white) anti-noise waves. This is the principal behind ANR.

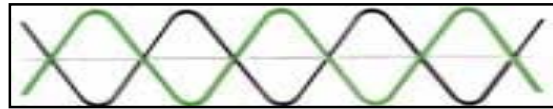


Figure 4. Sound Waves

The less space that ANR has to protect, the less energy and electronics are required. By installing ANR inside the ear, as opposed to inside an earmuff cup, the effectiveness of the protection provided by that earplug could be enhanced significantly. This would also supplement the passive nature of the earplug.

As can be seen in Figure 3, there is a significant gap between the protection required and the protection available. Even if one of the proposed investment alternatives reaches today's technology limit in protection, aircrews will still be at risk for excessive noise exposure.

2.3 INVESTMENT ALTERNATIVES

2.3.1 Process

Utilizing the information from the current environment and the gap analysis, customer input and opinions of technical experts are used to identify potential investment alternatives. Alternatives can be identified in several ways. Generally the status quo (currently fielded system) is one of the alternatives examined as it establishes a baseline for comparison. Additional alternatives are often the next generation of technology identified in the literature. The final alternative list is arrived at considering SME and user input as well as customer feedback.

2.3.2 Evaluation

The primary goal of the technologies being evaluated is to improve hearing protection for flightline crew in an effort to reduce personnel noise exposures. The protection should also improve communication systems for enhanced flightline safety. A net result of the technology should be a reduction in Air Force noise-induced hearing loss.

It was established during the assessment of the current environment that a material solution was necessary. Key attributes of a material solution include effective hearing protection that is compatible with existing equipment and technology. It must also fit well, provide improved communication ability and be simple and easy to use. Based on the results of the environmental assessment and the gap analysis, the solution should have these described features.

Three alternatives were identified to analyze with respect to these features. The first was the status quo protection. This system was under scrutiny because it provided a baseline to compare the solution systems. The second investment alternative was the Attenuating Custom Communication Earpiece System (ACCES). This was the first step in improving protection for the operator. The third alternative addressed in this CBA was ACCES with ANR capability. This final alternative incorporated all of the requirements and used technology identified as the

most effective to date. Each of these alternatives is described in further detail in the following sections.

2.3.2.1 Alternative #1, Status Quo

This alternative is the protection currently in use by flightline ground crew personnel. It consists of disposable passive earplugs combined with passive earmuffs (see Figures 1 and 2). The measured dB attenuation provided by this alternative is 30 dB. Of that, approximately half of the protection is a result of the earplugs. The remainder of the protection is provided by the earmuffs. The protection provided, while reducing the noise exposure of crew, still does not meet the needs of the mission. This limited effectiveness is further reflected in the benefits analysis score (see Section 2.6.2).

2.3.2.2 Alternative #2, Near-Term Solution

The Attenuating Custom Communication Earpiece System (ACCES) is a customized silicon earpiece poured from individual impressions of the wearer's ear. The earpiece contains a miniature transmitter embedded deep within the earpiece and may be attached via its shielded coaxial cable to communication headsets or aircrew helmets. For purposes of this comparison and cost estimate, ACCES will be evaluated as being worn under conventional passive earmuffs. The estimated dB attenuation provided by this alternative is 35-40 dB. While this alternative does have some protection advantages over the first alternative, the level of protection this alternative provides still does not protect the user to the degree required by the mission (see Section 2.6.2).



Figure 5. ACCES Earplugs with Ear Muffs

2.3.2.3 Alternative #3, Midterm Solution

The third alternative consists of ACCES enhanced with active noise reduction (ANR). See the description of ACCES in section 2.3.2.2. The actual ANR components will reside within an external headset with noise cancellation taking place within the ear canal. The small space protected (versus an entire headset cup) results in a reduced requirement for power and speaker size.

ANR technology is a means of reducing noise levels in a personal hearing protector by measuring noise present inside the area being protected and reinserting a processed (and out of phase) noise signal back into the area. The reinserted signal combines with the noise that was originally measured, causing it to be cancelled (see Figure 6). The estimated dB attenuation provided by this alternative is projected to be 45-50 dB. Again, this alternative provides an increase in hearing protection and comes close to meeting the needs of the mission (see Section 2.6.2).

Red arrows are noise, Yellow arrow is information signal

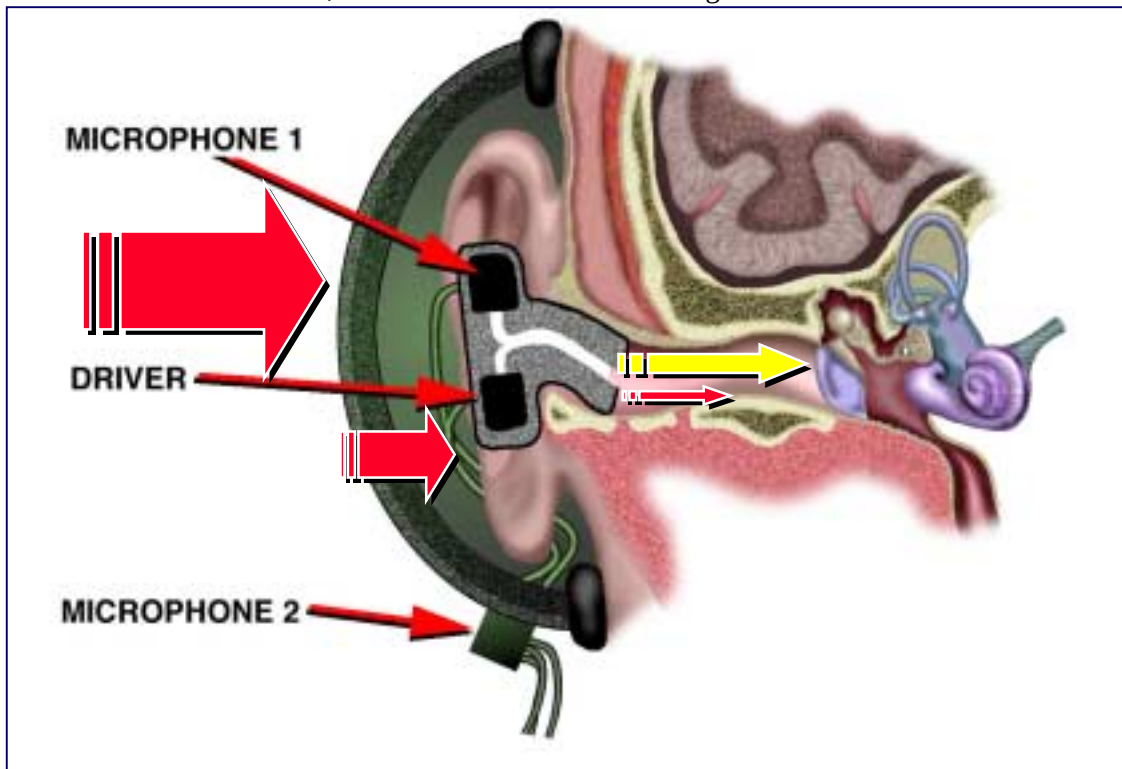


Figure 6. Graphic of ACCES with ANR

2.3.2.4 Global Ground Rules and Assumptions

The following ground rules and assumptions were used in estimating the costs and evaluating the benefits of each alternative:

- Three hearing protection alternatives were examined.
- Each alternative was estimated with the baseline goal of providing hearing protection for 5,000 ground crew personnel for a 3-year period.
- All detailed costs were presented in both constant FY01 dollars and then year dollars (adjusted for inflation) using standard DoD inflation rates.
- Average burdened labor rates were used for all civilian and military labor.
- Scenario for application of the technology was equivalent to the F-22 ground crew.
- Groundrules and assumptions specific to a particular alternative were summarized with the documentation for that alternative.

- Technology or hearing protection peripheral to the agreed-upon alternatives was not addressed.
- Benefit assessment values were based on the opinions of the experts present in the Expert Choice session.
- The Expert Choice session was guided by the agreed upon alternatives and benefits established with customer coordination prior to the session.

2.4 COST ESTIMATE

2.4.1 Process

For each alternative, technical, schedule and programmatic ground rules and assumptions were established. Based on this information an estimating methodology was selected and data was gathered. A cost estimate was prepared for each alternative and the estimates were normalized to a constant fiscal year (impact of inflation eliminated) for cost comparison purposes.

2.4.2 Evaluation

2.4.2.1 Alternative #1, Status Quo

This alternative was the current system used for hearing protection by flightline ground crew personnel. It consisted of disposable passive earplugs combined with passive earmuffs. The measured dB attenuation provided by this alternative was 30 dB.

In addition to the global groundrules and assumptions outlined in Section 2.3.2.4, the following assumptions were made in preparing the cost estimate for this alternative:

- No engineering manufacturing & development (EMD) effort, supplemental production costs, training, maintenance or disposal costs were required.
- Both the plugs and muffs were available through normal GSA channels using a national stock number (NSN).
- The earplugs were one time use and disposable; assume ground crew use an average of 40 pairs per month in the performance of their jobs.
- The passive earmuffs were estimated to have a 3-year useful life; foam padding must be replaced annually.

Table 1 summarizes the costs of alternative #1.

Table 1. Alternative #1 Costs (FY 01 \$ in 000)

Costs *	FY02	FY03	FY04	FY05	Total
Production					
Ear Plugs	0	237	237	237	712
Ear Muffs	0	51	0	0	51
Spares/Repair Parts					
Foam Cushion Repl	0	0	13	13	25
Alternative #1 Total	0	288	250	250	788

* Detailed methodology, source data, cost element descriptions, and worksheets can be found in Appendix C. Numbers may not add due to rounding.

2.4.2.2 Alternative #2, Near-Term Solution

This alternative consisted of ACCES combined with passive earmuffs (see complete description in Section 2.3.2.2 above). The attenuation provided by this alternative was estimated to be up to 40 dB.

In addition to the global groundrules and assumptions outlined in Section 2.3.2.1, the following assumptions were made in preparing the cost estimate for this alternative:

- A viable, tested ACCES prototype currently exists; documented costs were \$150 per unit which include all material and labor to produce the unit.
- Additional EMD costs of \$100K for Government support were required during the first year (travel and civilian labor).
- The passive earmuffs were available through normal GSA channels using a NSN.
- The costs associated with integrating ACCES with headsets were inconsequential and therefore not considered in this estimate.
- There were no sustainment, training or disposal costs associated with this alternative.
- Maintenance costs for ACCES were limited to normal cleaning by the wearer.
- ACCES was estimated to have a 1-year useful life.
- Conventional earmuffs were estimated to have a 3-year useful life; foam padding must be replaced annually.

Table 2 summarizes the costs for alternative #2.

Table 2. Alternative #2 Costs (FY 01 \$ in 000)

Costs *	FY02	FY03	FY04	FY05	Total
EMD					
Labor	66	0	0	0	66
Travel	26	0	0	0	26
Production					
ACCES	0	750	750	750	2,250
Ear Muffs	0	51	0	0	51
Govt Labor		177	177	177	531
Spares/Repair Parts					
Foam Cushion Repl.	0	0	13	13	25
Alternative #2 Total	93	978	940	940	2,950

* Detailed methodology, source data, cost element descriptions, and worksheets can be found in Appendix C. Numbers may not add due to rounding.

2.4.2.3 Alternative #3, Midterm Solution

This alternative consisted of ACCES enhanced with ANR technology (see complete description in Section 2.3.2.3 above). The measured attenuation provided by this alternative was estimated to be in excess of 40 dB

In addition to the global groundrules and assumptions outlined in Section 2.3.2.4 above, the following assumptions were made in preparing the cost estimate for this alternative:

- A viable, tested ACCES prototype currently exists; documented costs were \$150 per unit which include all material and labor to produce the unit.
- The complexity, circuitry and components of the incorporated ANR technology were assumed to be analogous to currently available analog ANR headsets (\$300 per set).

- Integration costs of combining the two existing technologies is assumed to be inconsequential, and are therefore not addressed in this estimate.
- Additional EMD effort was required to enhance the existing ACCES unit with ANR technology.
- Current approved funding for the EMD program is \$.911M for FY02. This funding may be expended over a 2-year period.
- Development program will produce 25 prototype units.
- Based on proven application of ANR technology (ANR headsets), it was assumed that this alternative will operate effectively in a military operational environment.
- ACCES was estimated to have a useful life of 1 year.
- There were no sustainment, training, or disposal costs associated with this alternative.
- There was a requirement for battery power to be attached in-line to the communications cable for the ANR unit. The estimate includes two rechargeable AAA nickel hydride batteries for each unit.
- ANR headsets were estimated to have a 3-year useful life; foam padding must be replaced annually.

Table 3 summarizes the costs for alternative #3.

Table 3. Alternative #3 Costs (FY 01\$ in 000)

Costs *	FY02	FY03	FY04	FY05	FY06	Total
EMD						
Prototype	11	11	0	0	0	22
Test & Evaluation	2	2	0	0	0	3
SE/PM	2	2	0	0	0	3
Govt Labor	266	266	0	0	0	531
Govt Travel	26	26	0	0	0	53
ECO	1	1	0	0	0	2
EMD Subtotal	307	307	0	0	0	615
Production						
Prime Mission Product						
ACCES	0	750	750	750	0	2,250
ANR Headset	0	1,500	0	0	0	1,500
Rechargeable Batteries	0	7	0	0	0	7
Battery Chargers	0	5	0	0	0	5
Test & Evaluation	0	45	15	15	0	75
SE/PM	0	225	75	75	0	375
Data	0	90	30	30	0	150
Govt Labor	0	177	177	177	0	531
Production Sub total	0	2,799	1,047	1,047	0	4,893
Spare/Repair Parts						
ANR Headset Foam Cushion	0	0	150	150	150	450
Battery Repl	0	0	1	1	1	3
Spare/Repair Parts Subtotal	0	0	151	151	151	452
Alternative #3 Total	307	3,106	1,198	1,197	151	5,960

* Detailed methodology, source data, cost element descriptions, and worksheets can be found in Appendix C. Numbers may not add due to rounding.

2.5 SENSITIVITY ANALYSIS

2.5.1 Process

Sensitivity analysis in a CBA illustrates how changes in key assumptions and variables (excursions) within the cost estimate may have an impact on the overall evaluation of the alternatives. It answers the question, "What costs, if changed, would influence the net value of each alternative?" The result of each excursion is an assessment of the magnitude of change required within the key cost elements sufficient to influence the outcome of the analysis.

2.5.2 Evaluation

Two of the investment alternatives evaluated contained cost elements largely based on published price listings or proven prototype programs. Therefore, variation in the costs for these alternatives was unlikely.

Alternative #3, ACCES with ANR, contained cost elements partially based on assumptions. The Prime Mission Product (PMP) element was derived using analogous system information and SME opinion. It comprised over 60 percent of the total cost of the alternative. The excursion from the baseline assumptions concentrated on this alternative. While this was only one of many that could have been evaluated, it was the one most likely to be of interest to the customer.

The analogous system cost used in the estimate was based on information gathered from experts who stated that the components and circuitry of currently available analog ANR headsets were comparable to the desired ACCES with ANR unit. Therefore, a reasonably comparable ANR headset was selected with the assistance of marketing representatives. Since expert opinion was solicited to determine the analogous system costs used for the ANR portion of this estimate and there are uncertainties associated with applying a new version of ANR technology in an operational military environment, it is possible that those costs could be understated. Assuming all other elements remain constant, the ANR headset cost would have to increase by 75% in order to influence the ranking of alternatives. However, a cost increase of this magnitude is unlikely.

2.6 BENEFITS CHARACTERIZATION AND VALIDATION

2.6.1 Process

Analysis of benefits was accomplished using a decision support software tool, Expert Choice, which enabled leveraging the expertise of key stakeholders and subject matter experts in evaluating the benefits offered by each alternative.

Benefits were identified using a combination of bottom-up and top-down analyses. First, Human Systems IAC identified any and all terms or phrases that could be associated with an improvement or decrement in any of the three identified investment alternatives. In the case of bioacoustic protection, a list of over 40 possible benefits was developed. This bottom-up approach was intended to tease out any and all benefits of the three alternative systems. The resulting list was then broken down into categories of benefits. For instance, any benefit that influenced the ease of use or comfort of the hearing protection was included in the "usability" group.

Next, we took a top-down approach. Using the overall goal of "improving hearing protection for flightline crew in an effort to reduce personnel noise exposures", the primary attributes of each material solution were analyzed. For example, it must fit well, provide

increased communication ability, and be simple and easy to use. The list of attributes was categorized based on the global areas of improvement or decrement that would result in a difference between the alternatives.

The final step in developing the benefit list was to compare the bottom-up with the top-down list. The top-down list described the global benefits and differences between investment alternatives. The bottom-up list described the specifics that should be represented by the global benefits. Any bottom-up benefits that were not represented in the global list were considered a unique benefit. Any top-down benefit that was not well represented by specific instances from the bottom-up list was reevaluated as a benefit. In the end, five global benefits were identified using this combination approach. They were communication, hearing protection, morale, safety, and usability.

The Expert Choice session began by reviewing the overall goal of the session and definitions for the three investment alternatives and the five associated benefits to be evaluated. The Expert Choice process used in this approach is illustrated in Figure 7.



Figure 7. Expert Choice Process

Once the definitions were clearly defined and understood by all participants, the Expert Choice group ranked all five of the benefits in order of importance. For instance, safety is more important than communication, and communication is more important than morale. Based on the group's responses, the Expert Choice tool calculated the benefit scores and attached a value to the benefits and alternatives. The end result was that the highest score determined the alternative with the most overall benefit value.

Then, the group ranked the three investment alternatives from highest to lowest importance for each benefit individually. As a result, the three alternatives were compared five times, once for each benefit. The alternative ranked with the highest importance meant that it realized the highest value for that benefit. That is, the best alternative provided the greatest payoff with respect to that benefit. For instance, if alternative #2 had the best safety features, according to the Expert Choice group, then it would have been rated highest on safety.

2.6.2 Evaluation

The three alternatives assessed, shown in Table 4, were Status Quo (described in Section 2.3.2.1), ACCES (described in Section 2.3.2.2), and ACCES with ANR (described in Section 2.3.2.3).

Table 4. Alternative Abbreviations

Expert Choice Abbreviation	Alternative Name
STATQUO	Status Quo System
ACCES	ACCES
ACCESANR	ACCES with ANR

Six benefits were identified through a thorough review of the requirements, the literature, and SME input. These were communication, fit, hearing protection, morale, safety, and usability. The group of user experts determined that fit and usability were not significantly different and for purposes of the Expert Choice session, they were treated as one benefit with a slightly greater scope, simply called "usability." Each of the three identified investment alternatives was evaluated across all five remaining benefits using Expert Choice. Stakeholders identified by Human Systems IAC conducted the evaluation. Among these stakeholders were an active duty Air Force fighter pilot and a retired aircraft maintenance officer.

Table 5 lists the abbreviations used in the Expert Choice model, with their respective benefit name and the definition used in this analysis.

Table 5. Benefits Abbreviations and Definitions

Expert Choice Abbreviation	Benefit Name	Benefit Definition
COMM	Communication	System impact on user's ability to give and receive auditory commands or instructions.
HR PROT	Hearing Protection	System impact on level of hearing protection provided.
MORALE	Morale	Impact on user acceptance and willingness to perform duties.
SAFETY	Safety	System impact on flightline safety and injury prevention.
USABLTY	Usability	System impact on ease of use and fit of hearing protection equipment.

Benefits were evaluated using pairwise comparisons to "prioritize" the importance of each with respect to the goal. The following table shows the results of each comparison:

Table 6 adds the rank order, individual score, and summarizes these comparisons into a single table. As can be seen in Table 6, the Expert Choice group determined that hearing protection was the most important benefit. Safety followed closely and was considered by the evaluators to have about the same importance as hearing protection. Communication fell into the middle, while usability and morale were ranked as the least important benefits, respectively.

Table 6. Rank Order of Benefits

Rank	Benefit	Benefit Rating Score Out of 1.0
1	Hearing Protection	.402
2	Safety	.379
3	Communication	.128
4	Usability	.061
5	Morale	.030

2.6.2.1 Evaluation of Alternatives for Benefits

Once the definitions of the alternatives and benefits were agreed upon, each alternative was evaluated based on the worst-case mission scenario for each benefit. In most cases, this meant that the operator was wearing hearing protection while working in a hot environment while in close proximity to very noisy aircraft (e.g., F-22, JSF). Supported by the information in Appendix D, the Expert Choice team discussed the positive and negative aspects of each alternative. Their inputs were distilled into a single ranking for each alternative across each benefit. These rankings were then used by Expert Choice to complete the benefits analysis. Based on the results from the benefits analysis, shown in Table 7, the most effective system was ACCES with ANR (662), with ACCES falling in the low-middle (270). The least effective alternative with respect to benefits was the Status Quo system (rated 68).

Table 7. Alternative Benefit Scores

Alternative	Benefit Score
Status Quo System	68
ACCES	270
ACCES with ANR	662

Although it is illustrated as the most important benefit and further indicated in the benefits scores, the level of hearing protection should be addressed separately. These benefit scores reflect the fact that alternative 1 and, to some degree, alternative 2 provide a reduced level of hearing protection when compared to alternative 3. As a result, the likelihood for hearing loss will be greater with those alternatives with less hearing protection. The implications of this lack of protection are further explored in section 3, Conclusions.

2.7 NET VALUE ANALYSIS

2.7.1 Process

The net value analysis is the consideration of life cycle costs developed in the cost assessment with the alternative benefits evaluated in the benefits assessment. The cost benefit ratio is simply a combination of the costs (numerator) and the benefits (denominator) into a ratio. For example, the CBR for the first alternative would be:

$$\text{CBR Alternative 1} = \frac{\text{Cost of Alternative 1}}{\text{Benefit Score of Alternative 1}}$$

2.7.2 Evaluation

As stated in Section 2.5, the Benefits Evaluation, the overall benefit ratings by subject matter experts and stakeholders rated alternative #1, the fielded system with a score of 68, alternative #2, ACCES scored 270, and alternative #3, ACCES with ANR scored 662. When combined with the costs, we see that alternative #1, with a CBR of 9.0, has the greatest value when costs and benefits were combined. Alternative #2 has less value (CBR = 10.9), and alternative #1 has the least value (CBR = 11.6) with respect to the cost/benefit ratio.

Table 8. Cost Benefit Ratio of Each Alternative

Alternative	Cost (FY01\$000)	Benefit Score	Cost/Benefit Ratio	Ranking
#1 Status Quo	788	68	11.6	3
#2 ACCES	2,950	270	10.9	2
#3 ACCES with ANR	5,960	662	9.0	1

2.8 RISK ANALYSIS

2.8.1 Process

In the final step of a cost benefit analysis, both costs and benefits of the alternatives are investigated from a risk perspective. The overall objective of this step is to isolate the areas of the alternative where there are uncertainties with the analyses, so that decision makers can focus their attention on those areas. In general, the more complex the alternative, the more likely it will be that problems or changes in schedule/cost, or benefit assumptions will change. For example, if certain cost assumptions or benefit assessments change dramatically, the overall findings will likely change as well. These areas are addressed in the evaluation below.

2.8.2 Evaluation

The focus of the bioacoustic protection risk analysis was on developmental subsystems that represented the highest level of technological complexity, and therefore, the greatest level of risk with respect to cost and benefits. As stated in the sensitivity analysis, two of the investment alternatives (fielded system and ACCES) were either operationally proven or based on published price listings. Variations in the actual costs or changes in the benefit evaluations were unlikely for those alternatives. The overall assessment of alternative #3, ACCES with ANR, has the greatest potential for risk due to several issues associated with both the cost and benefit assumptions. The cost issue will be discussed first, followed by the benefits issues.

The alternative #3 cost estimate was largely based on expert opinions. Therefore, the potential existed that, during the development program of such a complex, unproven system, unforeseen variations may develop that will inflate or deflate the cost estimate. These could be due to the application of a relatively unproven technology to meet the unique requirements of an operational military environment. As a result, the estimate could change dramatically, depending on technical issues that were beyond the scope of this report.

There were two areas of technical risk associated with the benefits assessment in this study. The first was the maturity level of ANR technology, and the second related to the potential variability of the opinions and analysis provided by the pool of experts. While the first risk was associated with alternative #3 only, the second risk identified had the potential to influence the results of the entire assessment.

Given that alternatives #1 and #2 have been operationally tested, there was little risk associated with the evaluation of benefits gained from their use. The risk emerged in the third alternative, ACCES with ANR. The potential variability was due to the maturity level of the technology employed. While ANR is used in operational military environments, it has never been employed in such a way. As a result, there was some risk that the technology may not work as expected when used in a rugged military application.

Based on published documents and verified reports, cost estimates are largely robust in their foundation. However, the assessment of benefits was performed using the subjective opinions of SMEs. Although the benefit rankings were the result of expert opinions, those

rankings could change if a different group of experts were used. For instance, if a new Expert Choice group was brought together, they may rank the alternatives in a different way, based on their own personal experiences and opinions.

Another consideration was the mathematical limits imposed by the Expert Choice program. The scores were a result of an internal algorithm employed by the program. This "artificial ceiling" may have imposed limits that would otherwise not have been present when using a different decision making tool. As a result of this program, no alternative could have a benefits score greater than 999 points greater than another alternative. For instance alternative #3 received a score of 662 versus alternative #1, which had a score of only 68. While significant, this difference could never get greater than 999 to 1. However, any alternative rankings would be likely to have the same scale of difference (e.g., two to one). These benefit considerations in no way negate the validity of the conducted assessment, but should be noted as a factor to consider when making programmatic decisions based on the conclusions contained in this report.

3. CONCLUSIONS

This study evaluates the costs and benefits associated with three hearing protection alternatives. Each alternative was estimated for cost and evaluated for relative benefits. By assigning a numerical value to the benefits, Human Systems IAC was able to develop a cost/benefit ratio for each of the three alternatives.

As stated in the net value analysis, the most effective alternative with respect to the stated goals was alternative #3, ACCES with ANR (CBR = 9.0). Even though it provides a reduced level of hearing protection, thus increasing the likelihood of hearing loss, the second most desirable alternative was the ACCES system (CBR = 10.9). Based on the evaluated cost and benefits the least cost-effective solution for providing hearing protection was the fielded system (CBR = 11.6).

Although outside the scope of this effort, several issues emerged that warrant future study and could further support the conclusions made in this study. Among these are the quantification of treatment costs and the influence of hearing protection devices on safety issues. Further areas of research could also include the operational costs associated with implementing programmatic and policy changes and the resulting training of personnel to observe hearing protection safety procedures.

The current annual cost of military hearing loss claims paid by the VA is estimated to be \$300 million and growing. Improved hearing protection has the potential to reduce the rate of increase and, eventually, cause a decrease in hearing loss compensation costs. Another, more important issue addressed by improved hearing protection, is the human costs. By improving the hearing protection available, the military will also be providing a better quality of life for those individuals after they retire from service.

APPENDIX A. ACRONYMS

ACCES	Attenuating Custom Communication Earpiece System
ACEIT	Automated Cost estimating Integrated Tools
AFSC	Air Force Specialty Code
ANR	Active Noise Reduction
ANSI	American National Standards Institute
ASC	Aeronautical Systems Center
CBA	Cost Benefit Analysis
CBR	Cost Benefit Ratio
CTF	Combined Task Force
Decibel (dB)	Exponential unit used to express differences in acoustic power
DoD	Department of Defense
DSP	Digital System Processor
DTIC	Defense Technical Information Center
EMD	Engineering Manufacturing and Development
GSA	General Services Administration
HPD	Hearing Protection Device
HSIAC	Human Systems Information Analysis Center
IAC	Information Analysis Center
JSF	Joint Strike Fighter
NHCA	National Hearing Conservation Association
NIHL	Noise Induced Hearing Loss
NIOSH	National Institute for Occupational Safety and Health.
NRR	Noise Reduction Rating
NSN	National Stock Number
NTIS	National Technical Information Service
O&M	Operation and Maintenance
OSHA	Occupational Safety and Health Administration
PMP	Prime Mission Product
SME	Subject Matter Expert
STOVL	Short Takeoff, Vertical Landing

APPENDIX B. REFERENCES

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APPENDIX C. COST ESTIMATING METHODOLOGY AND WORKSHEETS

Alternative #1 – Status Quo, Passive earplugs combined with passive earmuffs.

1.0 Production, Prime Mission Product – The PMP element refers to all hardware and software necessary to accomplish the prime mission of the material item

1.1 Ear Plugs - This cost element includes the passive, disposable earplug. The estimating methodology used was actual cost. The data source was the General Services Administration (GSA) price listing for National Stock Number (NSN) 6515-00-137-6345. The cost used in the estimate is \$19.77 per box; Each box contains 200 pair of plugs; Annual usage was estimated to be 40 pairs per month by each ground crew member (2 pair per day @ 20 workdays per month). This is a disposable item.

1.2 Ear Muffs - This cost element includes the passive earmuff to be used in combination with the passive earplugs. The estimating methodology used was actual cost. The data source was the GSA price listing for NSN 4240-00-759-3290. The cost used in the estimate is \$10.20 per set of muffs; Useful life is estimated at 3 years by SME's.

2.0 Spare/Repair Parts – This element refers to the spare components or assemblies used for replacement purposes in equipment end items.

2.1 Foam Cushion Replacement - This cost element includes the foam cushion replacements for the passive earmuffs. The earmuff unit has a useful life of 3 years, however, the foam cushions in the ear pieces require replacement annually. The estimating methodology used actual cost. A supplier of the passive earmuffs (Lightspeed Aviation) was contacted to determine the replacement cost of the foam cushions. The cost used in the estimate is \$2.50 per set of foam cushion replacements.

Alternative #2 Near –Term Solution, Attenuating Custom Communication Earpiece System (ACCES) combined with passive earmuffs.

1.0 Engineering Manufacturing & Development (EMD), Mission Support – This element refers to all costs associated with supporting the final development and test efforts of the prime material item.

1.1 Labor – This element includes the cost of government personnel compensation required to support the final development and testing efforts associated with fielding ACCES. The methodology used was expert opinion. AFRL/HEC estimated that three people would dedicate 25 percent of their time for one year to this effort (1560 Hours). The data source used for the pay rate was AFI 65-503, Attachment 26-2, Standard Composite Pay Rates (GS-13).

1.2 Travel – This element includes the cost of government personnel travel required to support the final development and test efforts associated with fielding ACCES. The methodology used was expert opinion. AFRL/HEC estimated that the three personnel assigned to this effort would average 5 trips per year; Each trip was estimated to cost an average of \$1,750.00.

2.0 Production, Prime Mission Product – The PMP element refers to all hardware and software necessary to accomplish the prime mission of the material item.

2.1 ACCES – This element includes the cost of the ACCES customized earpiece system. The estimating methodology used was actual cost. The data source was AFRL/HEC who provided program data from a prototype development effort with Westone Labs; \$150 per ACCES unit was used in the estimate. ACCES is estimated to have a useful life of 1 year.

2.2 Ear Muffs – This cost element includes the passive earmuff to be used in combination with the passive earplugs. The estimating methodology used was actual cost. The data source was the GSA price listing for NSN 4240-00-759-3290. The cost used in the estimate is \$10.20 per set of muffs; Useful life is estimated at 3 years by SME's.

2.3 Other Government Cost, Labor – This cost element includes the Government support required during the ACCES production program. The methodology used was expert opinion. AFRL/HEC estimated that two people would be dedicated to the program full time for the three year production phase (4,160 Hours annually). The data source used for the pay rate was AFI 65-503, Attachment 26-2, Standard Composite Pay Rates (GS-13).

3.0 Spare/Repair Parts – This element refers to the spare components or assemblies used for replacement purposes in equipment end items.

3.1 Foam Cushion Replacement – This cost element includes the foam cushion replacements for the passive earmuffs. The earmuff unit has a useful life of 3 years, however, the foam cushions in the ear pieces require replacement annually. The estimating methodology used actual cost. A supplier of the earmuffs was contacted to determine the replacement cost of the foam cushions. The cost used in the estimate is \$2.50 per set of foam cushion replacements.

Alternative #3 Midterm Solution, Attenuating Custom Communication Earpiece System (ACCES) enhanced with Active Noise Reduction (ANR) technology.

1.0 Engineering Manufacturing and Development - This element includes all costs associated with the design and development of 25 prototype units which satisfy the requirements specification(s)).

1.1 Prime Mission Product, Prototype - The PMP element includes all hardware and software costs necessary to accomplish the prime mission of the materiel item. The prototype unit includes the ACCES customized earpiece system combined with an ANR enhanced headset. The estimating methodologies used here combine actual cost, expert opinion and analogous system. The data source for the ACCES portion of the prototype was AFRL/HEC who provided program data from a prototype development effort with Westone Labs; \$150 per ACCES unit. ACCES is estimated to have a useful life of 1 year. The data source for the ANR headset portion of the prototype was AFRL/HEC subject matter experts; Currently available active noise reduction headsets with analog technology contain all the required components and circuitry for this alternative. Current price listings from hearing protection suppliers were referenced and crosschecked with the subject matter experts (Bose QuietComfort ANR Headset, \$300/unit). Because this specific form of ANR technology has not been applied in an operational military environment, a complexity factor of 2.0 was applied to account for uncertainties in the development program. The estimate prices 25 prototype units over a two-year development program.

1.2 System Test and Evaluation – This element refers to the use of the prototype to obtain and validate engineering data on performance of the system. It includes the system-level test, planning, conduct, support and reports as well as all hardware items that will be consumed in the conduct of the testing. The estimating methodology used here is analogy. The data source is the ASC Aeronautical Engineering Products Cost Factor Handbook which is documented in the ACEIT cost estimating tool developed by Tecolote, Inc. The factor used was 14 percent of PMP.

1.3 System Engineering/ Program Management (SE/PM) – This element refers to the technical and management efforts of the system's program engineering staff. It includes the planning, controlling and directing of the technical program efforts of design engineering and specialty engineering. It includes the engineering effort required to transform the operational need into a preferred system configuration that ensures the development of a supportable and cost effective system. The data source is the ASC Aeronautical Engineering Products Cost Factor Handbook which is documented in the ACEIT cost estimating tool developed by Tecolote, Inc. The factor used was 13.6 percent of PMP.

1.4 Other Government Costs – This element includes all costs incurred by the Government in support of the development efforts of the system

1.4.1 Labor – This element includes the cost of government personnel compensation required to support the development and test efforts associated with the prototype portion of the development program. The methodology used was expert opinion. AFRL/HEC estimated that three people would be assigned to support the program during the development stage of the program (2080*3 = 6,240 Hours). The data source used for the pay rate was AFI 65-503, Attachment 26-2, Standard Composite Pay Rates (GS-13).

1.4.2 Travel – This element includes the cost of government personnel travel required to support the development and test efforts associated with the prototype portion of the program. The methodology used was expert opinion. AFRL/HEC estimated that the three personnel assigned to this effort would average five trips per year; Each trip was estimated to cost an average of \$1,750.00.

1.4.3 Engineering Change Orders (ECO) – This element includes the cost associated with engineering changes requested by the Government during the development stage of the program. The methodology used was analogous system. The data source used was the ASC Aeronautical Engineering Products Cost Factor Handbook which is documented in the ACEIT cost estimating tool developed by Tecolote, Inc. The factor used was ten percent of PMP.

2.0 Production – This element includes all costs associated with the production phase of the program.

2.1 Prime Mission Product - The PMP element includes all hardware and software costs necessary to accomplish the prime mission of the materiel item. The unit includes the ACCES customized earpiece system combined with an ANR enhanced headset. The estimating methodologies used here combine actual cost, expert opinion and analogous system. The data source for the ACCES portion of the production unit was AFRL/HEC who provided program data from a prototype development effort with Westone Labs; \$150 per ACCES unit. ACCES is estimated to have a useful life of 1 year. Since the hearing protection device is custom fit for each wearer, no learning curve was applied to the production lot. The data source for the ANR headset portion of the production unit was AFRL/HEC subject matter experts; Currently available active noise reduction headsets with analog technology contain all the required components and circuitry for this alternative. Current price listings from hearing protection suppliers were referenced and crosschecked with the subject matter experts (Bose QuietComfort ANR Headset, \$300/unit). ANR headsets are estimated to have a useful life of 3 years; Foam cushion replacements are required annually.

2.2 Rechargeable Batteries – This cost element includes the batteries necessary to provide continual power to the system. The estimating methodology used was actual cost and expert opinion. AFRL/HEC personnel directed the use of nickel hydride rechargeable batteries. The data source was commercially available pricing information for bulk purchases of rechargeable batteries. The cost used in the estimate is \$1.44 for two AAA batteries. Each battery must be recharged daily and the estimated charges over the life of the battery is 1000. The estimate includes the production purchase of 10,000 batteries.

2.3 Battery Chargers – This cost element includes the battery chargers required for the rechargeable AAA batteries providing power to the unit. The estimating methodology used was actual cost and expert opinion. AFRL/HEC confirmed a maximum requirement of 1,000 chargers. The data source was commercially available pricing information for bulk purchases of chargers. The cost used in the estimate is \$4.75 per rapid charger.

2.4 Test and Evaluation – This element refers to the effort during production to continue to validate engineering data on performance of the system. It includes all required system-level test, planning, conduct, support and reports as well as all hardware items which are consumed in the conduct of the testing. The estimating methodology used here is analogy. The data source is the ASC Aeronautical Engineering Products Cost Factor Handbook which is documented in the ACEIT cost estimating tool (Tecolote, Inc.). The factor used was two percent of PMP.

2.5 SE/PM - System Engineering/ Program Management (SE/PM) – This cost element refers to the technical and management efforts during the production phase of the program. It includes the planning, controlling and directing of the technical program efforts of production engineering. It also includes the system engineering effort to ensure the production of a supportable and cost effective system. The methodology used is analogy. The data source is the ASC Aeronautical Engineering Product Cost Factor Handbook which is documented in the ACEIT cost estimating tool developed by Tecolote, Inc. The factor used was ten percent of PMP.

2.6 Data – This cost element includes the data reporting requirements necessary to document program status, cost and schedule of the production effort. The methodology used is analogy. The data source is the ASC Aeronautical Engineering Cost Factor Handbook which is documented in the ACEIT cost estimating tool developed by Tecolote, Inc. The factor used was four percent of PMP.

2.7 Other Government Cost, Labor – This cost element includes the Government support required during the ACCES with ANR production program. The methodology used was expert opinion. AFRL/HEC estimated that two people would be dedicated to the program full time for the two year production phase (4,160 Hours). The data source used for the pay rate was AFI 65-503, Attachment 26-2, Standard Composite Pay Rates (GS-13).

3.0 Spare/Repair Parts – This element refers to the spare components or assemblies used for replacement purposes in equipment end items.

3.1 ANR Headset Foam Cushion Replacement – This cost element includes the foam cushion replacements for the ANR headsets. The unit has a useful life of 3 years, however, the foam cushions require replacement annually. The estimating methodology used actual cost. A supplier of the headsets was contacted to determine the replacement cost of the foam cushions. The cost used in the estimate is \$30.00 per set of replacements.

3.2 Battery Replacement – This cost element includes the battery replacements necessary to provide continual power to the unit. The estimating methodology used was actual cost. The data source was commercially available pricing information for bulk purchases of rechargeable AAA batteries. The cost used in the estimate is \$1.44 per pair of replacement AAA batteries. The estimate includes replacing 500 batteries annually following the first year of production.

APPENDIX D. PAIR-WISE COMPARISON OF ALTERNATIVES

Table D-1 shows the all the benefit pairwise comparisons.

Table D-1. Global Table of Pairwise Comparisons

COMM	9	8	7	6	5	4	3	2	1	2	3	4	5	⑥	7	8	9	HR PROT
COMM	9	8	7	⑥	5	4	3	2	1	2	3	4	5	6	7	8	9	MORALE
COMM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	⑦	8	9	SAFETY
COMM	9	8	7	6	⑤	4	3	2	1	2	3	4	5	6	7	8	9	USABLTY
HR PROT	9	8	⑦	6	5	4	3	2	1	2	3	4	5	6	7	8	9	MORALE
HR PROT	9	8	7	6	5	4	3	2	①	2	3	4	5	6	7	8	9	SAFETY
HR PROT	9	8	⑦	6	5	4	3	2	1	2	3	4	5	6	7	8	9	USABLTY
MORALE	9	8	7	6	5	4	3	2	1	2	3	4	5	6	⑦	8	9	SAFETY
MORALE	9	8	7	6	5	4	3	2	1	2	3	4	⑤	6	7	8	9	USABLTY
SAFETY	9	8	⑦	6	5	4	3	2	1	2	3	4	5	6	7	8	9	USABLTY

Ratings: 1 = Equal; 3 = Moderate; 5 = Strong; 7 = Very Strong; 9 = Extreme

Example of interpretation: Communication (COMM) is strongly more important than usability (USABLTY).

While Table D-1 shows the global comparisons, the purpose of this evaluation was to assess potential benefits of fielding new bioacoustic protection systems compared to status quo. It was also to “quantify” the subjective qualities of both the existing and presented system benefits. When combined with cost estimate, this data will contribute to the cost benefit analysis (CBA) results.

Please note that this appendix is intended to support information found in the benefits analysis, Section 2.6, it may repeat information found in the body of this document. The repetition is intended to allow this appendix to stand alone as a separate entity.

The customer defined several goals for the three alternative hearing protection systems. These were:

- Improve hearing protection devices (HPD) to reduce personnel noise exposures.
- Improve communications systems for enhanced flightline safety.
- Reduce Air Force noise-induced hearing loss.

A table of global benefits can be found in Table D-2 below.

Table D-2. Benefits and Their Definitions

Benefit	Working Definition
Communication	System impact on user's ability to give and receive auditory commands or instructions.
Hearing Protection	System impact on level of hearing protection provided.
Morale	Impact on user acceptance and willingness to perform duties.
Safety	System impact on flightline safety and injury prevention.
Usability	System impact on ease of use and fit of hearing protection equipment.

To reiterate, the investment alternatives were:

- Alternative #1 Fielded System - The first alternative assessed by the Expert Choice Team was the fielded system, described in Section 2.1.2. This alternative consists of passive earplugs worn under passive earmuffs.
- Alternative #2 ACCES - The second alternative discussed by the Expert Choice Team was ACCES, described in Section 2.3.2. This alternative consists of ACCES earplugs worn under passive earmuffs.
- Alternative #3 ACCES with ANR - The final alternative assessed by the Expert Choice Team was the ACCES system combined with ANR capability, described in Section 2.3.2. This alternative consists of passive ACCES with ANR worn under passive earmuffs.

When ranking the three alternatives for each benefit, the Expert Choice team followed specific steps. These were:

- Review benefit definitions.
- Discuss examples of each benefit.
- Identify variations between alternatives, and .
- Rank All Benefits

The following sections outline the pairwise comparisons made with respect to the investment alternatives and the benefits.

D.1. COMMUNICATION

Table D-3 shows the pairwise comparisons associated with the communication benefit.

Table D-3. Communication Comparison

STATQUO	9	8	7	6	5	4	3	2	1	2	3	4	⑤	6	7	8	9	ACCES
STATQUO	9	8	7	6	5	4	3	2	1	2	3	4	5	6	⑦	8	9	ACCESANR
ACCES	9	8	7	6	5	4	3	2	1	2	3	4	⑤	6	7	8	9	ACCESANR

D.1.1. Definition

System impact on user's ability to give and receive auditory commands or instructions.

D.1.2. Example

By lowering the signal to noise ratio in the F-22, flightline personnel could hear instructions from aircrew. Before that, information exchange was impossible with engines ramped-up.

D.1.3. Background on Investment Alternatives

D.1.3.1. Alternative #1

Current military communication headsets can not generate sufficiently intelligible audio signals in a noise environment exceeding 100 dB. In fact, F-22 combined test force (CTF) filed a deficiency report on the inability to communicate with ground crew from cockpit during preflight engine run-ups above idle power.

D.1.3.2. Alternative #2

ACCES plugs into helmets or headsets for clear presentation of voice and audio communication. It also allows for a decrease in air trapped between plug and eardrum, resulting

in less vibration and a more robust speech signal. F-22 CTF indicated “outstanding” communication clarity even at afterburner power setting.

D.1.3.3. Alternative #3

Signal to noise ratio should increase as excess noise is reduced by the ANR. Using ANR headsets (no earplugs currently available), communication capability improved 10-15 percent.

D.2. HEARING PROTECTION

Table D-4 shows the pairwise comparisons associated with the hearing protection benefit.

Table D-4. Hearing Protection Comparison

STATQUO	9	8	7	6	5	4	3	2	1	2	3	4	5	6	⑦	8	9	ACCES
STATQUO	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	⑧	9	ACCESANR
ACCES	9	8	7	6	5	4	3	2	1	2	3	4	⑤	6	7	8	9	ACCESANR

D.2.1. Definition

System impact on level of hearing protection provided.

D.2.2. Example

30 dB of protection compared to 50 dB of protection. For example, in some "hot" areas, operators can safely work for only four minutes with less protection versus 480 minutes with improved protection.

D.2.3. Background on Investment Alternatives

D.2.3.1. Alternative #1

The status quo uses the same technology as 30 years ago. Current personnel exposures exceed AFOSH 48-19 requirements for hazardous noise exposure (cited in McKinley, 2000). USAF allowable exposure:

- 100 dB: 15 minutes/day
- 105 dB: 4.7 minutes/day
- 115 dB: 28 seconds/day

Currently, unlimited exposure limit without damage is 85 dB (8 hours, 3 dB/doubling) and the current protection is about 30 dB. The F-22 Crew Chief position has noise levels up to 139 dB. Even with 30 dB of protection, the noise is 109 dB, well above 85dB. The engine adjustment position for the F-22 has noise at 150 dB, which is 35 dB greater than the allowable noise, even with protection. It should be noted that 150 dB is 400-600 times more energy than 90 dB.

D.2.3.2. Alternative #2

ACCES combined with earmuffs provides about 40 dB of protection. This is a result of deeper insertion into ear, which improves protection about 10 dB over generic earplugs.

D.2.3.3. Alternative #3

This final alternative should provide about 50 dB of protection—the limit of current technology. ANR headsets improved hearing protection 12-15 dB.

D.3. MORALE

Table D-5 shows the pairwise comparisons associated with the morale benefit.

Table D-5. Morale Comparison

STATQUO	9	8	7	6	5	4	3	2	1	2	3	4	⑤	6	7	8	9	ACCES
STATQUO	9	8	7	6	5	4	3	2	1	2	3	4	5	⑥	7	8	9	ACCESANR
ACCES	9	8	7	6	5	4	3	2	1	②	3	4	5	6	7	8	9	ACCESANR

D.3.1. Definition

Impact on user acceptance and willingness to perform duties.

D.3.2. Example

Flightline crew are asked to face probable hearing loss in order to perform duties. Providing additional protection could have an impact on performance and overall job satisfaction and retention. This benefit should be more evident in senior personnel with greater experience.

D.3.3. Background on Investment Alternatives

D.3.3.1. Alternative #1

Using 1998 data, 109,226 records of 65 flightline AFSCs and workplace ID codes were surveyed for hearing loss. The results showed that:

- 54 percent had significant threshold shift at 2, 3, and 4 KHz (average 10+ dB).
- 73 percent had significant threshold shift at 1-4 KHz (average 15+ dB).

Experienced personnel know that they are or will lose some hearing.

D.3.3.2. Alternative #2

This alternative shows that Air Force leaders are making an effort to protect personnel should have a positive impact on performance, retention, and job satisfaction.

D.3.3.3. Alternative #3

Continuing improvements to hearing protection should further enhance morale. Cost of personalized units may have an impact on perceptions of decision makers.

D.4. SAFETY

Table D-6 shows the pairwise comparisons associated with the safety benefit.

Table D-6. Safety Comparison

STATQUO	9	8	7	6	5	4	3	2	1	2	3	4	⑤	6	7	8	9	ACCES
STATQUO	9	8	7	6	5	4	3	2	1	2	3	4	5	⑥	7	8	9	ACCESANR
ACCES	9	8	7	6	5	4	3	2	1	2	③	4	5	6	7	8	9	ACCESANR

D.4.1. Definition

System impact on flightline safety and injury prevention.

D.4.2. Example

Operators that can hear verbal or auditory warnings are more likely to hear, see, and avoid possible danger. Custom-fitted equipment is more likely to be used and well maintained, resulting in increased protection.

D.4.3. Background on Investment Alternatives

D.4.3.1. Alternative #1

“Foamies” may not be used properly, resulting in less protection and hearing loss. As a result, auditory warnings are difficult to discern with current protection.

D.4.3.2. Alternative #2

Personnel are more likely to consistently use custom-fitted protection, resulting in improved protection. In addition, improved communication will enhance safety through increased likelihood of effective auditory warnings.

D.4.3.3. Alternative #3

Safety should be improved through protection and enhanced communication.

D.5. USABILITY

Table D-7 shows the pairwise comparisons associated with the usability benefit.

Table D-7. Usability Comparison

STATQUO	9	8	7	6	5	4	3	2	1	2	3	4	5	⑥	7	8	9	ACCES
STATQUO	9	8	7	6	5	4	3	2	1	2	3	4	5	⑥	7	8	9	ACCESANR
ACCES	9	8	7	6	5	4	3	2	①	2	3	4	5	6	7	8	9	ACCESANR

D.5.1. Definition

System impact on ease of use and fit of hearing protection equipment.

D.5.2. Example

The system is easy to use and/or foolproof. Equipment is sized appropriately to conform to the user's body. Personalized earplugs will have a better fit than generic ones and are more difficult to misuse. Custom-fitted equipment is nearly impossible to use incorrectly as it would be uncomfortable to wear while generic devices are easily utilized in a poor manner.

D.5.3. Background on Investment Alternatives

D.5.3.1. Alternative #1

It is easy to insert “foamies” incorrectly. It is also difficult to determine if inserted properly.

D.5.3.2. Alternative #2

ACCES is individually poured from impressions for a customized fit. As a result, customized fit makes incorrect use of the earplugs very uncomfortable, if possible. This makes it practically impossible to insert ACCES incorrectly.

D.5.3.3. Alternative #3

This alternative should have the same fit and ease of use as ACCES.

APPENDIX E. LITERATURE SEARCH STRATEGY

For: Air Force Research Laboratory
Wright-Patterson Air Force Base, OH

Background:

Human Systems IAC has been asked to prepare a cost benefit analysis on the costs and benefits of the AFRL Bioacoustic Protection effort. The goal of the effort is to provide better hearing protection for fighter aircraft pilots and ground crew. Necessary research and development (R&D) in the area could result in huge payoffs for the DoD, which spends \$300M annually for hearing loss claims that could be avoided with adequate hearing protection.

The results of the literature search strategy will be used to derive cost and benefits as appropriate. The results are especially important in capturing the "value" of benefits in order to quantify them in our final analysis.

The specific goal of this literature search is to review recent literature on auditory protection to help Human Systems IAC identify and understand the current level of hearing protection technology and R&D, specifically in government aviation applications. This review should also help identify the available alternatives and what the potential payoffs are for continuing R&D in the bioacoustic protection effort. This information will then be evaluated with the cost data to determine the alternative technology with the greatest return on investment.

Search Terms:

See attached table of terms.

Key Authors:

Casali, John G.
Bazan, Nicholas

Possible Databases: (Final list to be determined based on client and expert searcher recommendations)

Aerospace Database

DTIC

ISI Science Citation Index

NASA Recon

NTIS

PsychINFO

Example Articles:

Casali, J. & Berger, E. (1996). Technology advancements in hearing protection circa 1995: Active noise reduction frequency/amplitude-sensitivity, and uniform attenuation. *American Industrial Hygiene Association Journal*, 57(2), 175-185.

Fitzpatrick, D. T. (1988). An analysis of noise-induced hearing loss in Army helicopter pilots. *Aviation, Space, & Environmental Medicine*, 59(10), 937-941.

Loeb, M. Luz, G., Sheidler, D., & Vandrehei, S. (1973). Assessment of auditory acuity, ear protection, and prediction of hearing loss in military personnel (DTIC No. AD-0776940). Fort Knox, KY: Army Medical Research Lab.

Pike, M. J. (1983). Hearing Protection. *Occupational Health in Ontario*, 4(3), 127-142.

Rawlinson, R., Wheeler, P., & Custard, G. (1987). The acoustical attenuation of some combinations of earplugs and earmuffs. *Annals of Occupational Hygiene*, 31(3), 299-309.

Table E-1. Literature Search Strategy Table

BIOACOUSTIC PROTECTION CBA SEARCH STRATEGY						
Main Ideas			Secondary Terms		Search Focus	Additional Items of Interest
1	Noise Noise Levels Intermittent Noise Continuous Noise Impulsive Noise	A N D	Noise Exposure Continuous Noise Exposure (CNE) Non-Continuous Noise Exposure (NNE) Audiometrics Auditory Processes Auditory Sensory System	A N D	Impact of CNE/NNE Threshold Shift Permanent Threshold Shift (PTS) Noise-Induced Permanent Threshold Shift (NIPTS) Effects on the auditory system Hearing Loss	A N D Military Personnel/Operators Aviator Crew Chief Aircraft Flight Line
Goal: To acquire information on the impact of noise on the operator.						
2	Protection Attenuation Reduction Elimination	A N D	Hearing Auditory System Auditory Processes Audiometrics	A N D	Auditory Equipment Auditory Protection Head Gear Bioacoustic Protection Ear Plugs Hearing Loss Prevention Hearing Loss Protection	A N D Military Personnel/Operators Aviator Crew Chief Aircraft Flight Line
Goal: To acquire information on the technology and R&D in noise reduction/protection.						
3	1 embedded on/in 2					
Goal: to acquire information on the impact of auditory protection on the operator.						

C-2

C-4

C-5

C-8

C-9

C-10

C-11

C-12

E-4