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Noise is one of the most common occupational hazards faced by military servicemembers in both operation and support of Department of Defense (DoD) systems. It is also the only known occupational hazard with exposures exceeding protection (mitigation) capability of available protective equipment. In ultra-high noise environments, double hearing protection (earplugs with earmuffs) alone cannot reduce the noise to a safe level thereby potentially impacting mission readiness. Due to these factors, interest in noise control during the acquisition process has reached flag/Senior Executive Service level attention. This report presents evolving improvements in control technologies and the permanence of engineering control through design versus administrative control measures. The objective is to further improve the acquisition and system design process for noisy systems by identifying potential control approaches – including acoustic and non-acoustic impacts of specific treatment types. The recommendations, as presented herein, are not explicit for any particular system. A detailed acoustic design analysis would be required to optimally select treatments and determine the impact on all systems' parameters, including mission and operating environment.

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Acoustical Engineering Controls and Estimated Return on Investment for DoD Selected High Noise Sources: A Roadmap for Future Noise Control in Acquisition

Ray Fischer
Christopher Page

April 25, 2013

NCE JOB No.	11-088
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0.0 EXECUTIVE SUMMARY[1]

Noise is one of the most common occupational hazards faced by military servicemembers[2] in both operation and support of Department of Defense (DoD) systems. It is also the only known occupational hazard with exposures exceeding protection (mitigation) capability of available protective equipment. In ultra-high noise environments, double hearing protection (earplugs with earmuffs) alone cannot reduce the noise to a safe level thereby potentially impacting mission readiness. Due to these factors, interest in noise control during the acquisition process has reached flag/Senior Executive Service level attention. This report presents evolving improvements in control technologies and the permanence of engineering control through design versus administrative control measures. The objective is to further improve the acquisition and system design process for noisy systems by identifying potential control approaches – including acoustic and non-acoustic impacts of specific treatment types.

The recommendations, as presented herein, are not explicit for any particular system. A detailed acoustic design analysis would be required to optimally select treatments and determine the impact on all systems' parameters, including mission and operating environment. The recommendations contained herein point the way to considering noise early in the acquisition process and selecting treatments based both on their acoustic and non-acoustic impacts – this is a cost effective way to protect and enhance the warfighter and reduce hearing loss.

This project, sponsored by the Defense Safety Oversight Council with support of the Office of the Secretary of Defense (OSD) offices for Acquisition Technology and Logistics (AT&L) and Manpower, Personnel and Readiness (MPR) sought to: (1) Identify nine significant DoD high noise (steady-state) sources and one promising control technology; (2) Develop noise reduction concept and design plans based on the best available engineering control methods and (3) Evaluate the projected return on investment for treatment versus hearing loss compensation.

The cost of noise related hearing impairment claims among veterans has been increasing every year for the past decade, with the Veterans Affairs (VA) spending over a billion dollars a year on hearing loss disability compensation. According to the 2011 U.S. Department of Veterans Affairs (VA) Annual Benefits Report, tinnitus and hearing loss are the two most prevalent service-connected disabilities for veterans receiving compensation at the end of fiscal year 2011. Besides VA disability compensation, tinnitus and hearing loss impose additional human costs due to lost communication ability and social isolation endured by those with permanent hearing loss. In the DoD civilian sector, noise related hearing impairment ranks number 5 for workers' compensation payouts ($32M in Chargeback Year 2012). Numerous studies have identified

[1] A presentation summarizing this report is provided in Appendix C
[2] GAO, Report GAO-11-114, *Hearing Loss Prevention, Improvements to DoD Hearing Conservation Programs Could Lead to Better Outcomes* p.3.

noise problems within DoD, such as the 2005 National Academy of Sciences report, "Noise and Military Service-Implications for Hearing Loss and Tinnitus," but none have provided specific engineering solutions.

Stakeholders, noise control experts and acoustical engineers, collected and established a noise database (including physical parameters controlling the noise, operation conditions, and utilization) for the nine steady-state high noise sources selected for review as part of this project. Commercial off the shelf (COTS) and novel or advanced (non-COTS) noise control approaches were evaluated for each noise source. In selecting treatment approaches, the efficacy of the treatment and non-acoustic impacts on space/weight/cost were considered as part of the feasibility and return on investment studies discussed herein. A projected return on investment was estimated for each source using a Microsoft Excel based program, which included the following parameters:

- Time-weighted average noise level
- Number of systems
- Number of crew
- Service life of crew and system(s)/equipment being evaluated
- Effectiveness of hearing protection
- Cost of audiograms, hearing aids and veterans' disability
- Estimated effectiveness and cost of treatments (materials and installation)

The treatment approaches for all sources showed a positive return on investment with the implementation of engineering controls. Due to the unavailability of data, this study excluded several potentially non-acoustic benefits. Examples of non-acoustic benefits include improved communications, operational safety, lower vibration and associated equipment wear, reduced life-cycle maintenance costs reduced signature (hostile detectability). Likewise, potentially adverse effects of noise controls such as increased weight and reduced space were discussed but not quantified monetarily.

The modular cabin/capsule/pod concept is a promising technology that is standard for much of the commercial cruise industry. There are two distinct applications on military ships-for berthing areas to allow the ears to 'recover' and as isolation booths in high noise areas to physically separate the worker from hazardous noise. The modular cabin has been tested on a Navy aircraft carrier and was found to reduce noise attributed to multiple sources by 10 dB. Future consideration of isolation booths, modular work stations, staterooms or prefabricated berthing, offers promising potential with regards to noise and vibration control.

This report illustrates that noise control, even for some of the highest noise sources within DoD, may be feasible and cost effective as summarized in the table below. In general, the applicability of noise control treatments can significantly reduce noise and have a positive return on investment. Specific systems and sources need to be investigated on their own merits in order to determine whether these findings apply. Other factors such as survivability, replacement cost and overriding system objectives were not directly considered as this report is intended to identify the tools available to redress noise issues on high noise sources.

DoD Source	Return on Investment	Potential Noise Induced Hearing Loss (NIHL) Cost Reduction	Untreated Time-Weighted Average (TWA) in decibels, A-scale (dB(A))	dB(A) Reduction	Service Years
Shipboard Diesel Driven Systems	0.2:1 – 4:1	$774,708,120	110	33	40
Shipboard Gas Turbines	0.2:1 - 2:1	$38,509,074	90	8	35
Ships and High Speed Craft	1:1 – 3:1	$49,218,444	97	17	22
Aircraft Carrier Operations-On Deck	203:1 – 509:1	$1,121,310,000	143	13	50
Aircraft Carrier Operations-Internal Compartments	37:1 – 44:1	$565,873,000	100	21	50
Tracked Vehicles	0.1:1 – 1:1	$8,125,110,030	113	16	50
Wheeled Vehicles	2:1 – 5:1	$7,958,058,768	90	7	30
Cockpit Noise	0.8:1 – 4:1	$246,473,773	98	12	35
Shipboard Equipment	11:1 – 40:1	$3,889,987,680	95	7	40

The report is available for use by the Defense Department and their contractors as a roadmap for future noise control in acquisition. Although none of the engineering solutions presented for the nine noise sources should be construed as a DoD requirement, the process and approaches provided in this report can be applied to any noise source issue. Reducing noise will improve mission readiness, add to quality of work life, support sustainability efforts, and reduce long term costs to the Defense Department and the taxpayer.

Noise Source Reduction Concept and Design Plan summaries for each project noise source and the promising technology, as well as, the Final Brief are provided as Appendices to this report.

1.0 INTRODUCTION

The objective, via the application of proper management, predictive tools, and engineering solutions, is to reduce steady-state noise levels for some significant high sources within the DoD. The project is intended to support noise control in design through:

(1) Describing the limitation of noise “control” approaches primarily reliant on use of protective equipment;
(2) Identifying feasible, cost effective control approaches for common categories of systems and equipment;
(3) Describing some of the potential challenges and limitations of applying Commercial Off-the Shelf (COTS) technologies for defense systems on the basis of competing performance requirements; legacy design considerations and cost, schedule and performance parameters;
(4) Illustrating potential approaches to cost-benefit analysis and risk-evaluation/management acceptance applicable to defense systems

While hearing protection devices (HPDs) are an important component of any hearing conservation program, they should not replace an effort to control noise and limit exposure. In practice, HPD’s provide substantially less effective attenuation then the ideal Noise Reduction Rating (NRR) (as measured on manikins and highly trained subjects). De-rating schemes are included in the Occupational Safety and Health Administration (OSHA) occupational noise exposure standard (29 CFR 1910.95). The effective NRR is typically in the range of half the “ideal” NRR.

The DoD Instruction (DoDI) 6055.12, “Hearing Conservation Program,” mandates that, “Engineering controls shall be the primary means of eliminating personnel exposure to potentially hazardous noise. All practical design approaches to reduce noise levels to below hazardous levels by engineering principles shall be explored.” DoD Acquisition policy[3] requires a system engineering approach; application of Military Standard (MIL-STD- 882) which includes a hierarchy of controls, and application of human systems integration to design the system(s) and equipment to support user effectiveness, safety and habitability.

The DoD requires a hearing conservation program be implemented when personnel are occupationally exposed to:

[3] See DODI 5000.02 and the Defense Acquisition Guidebook

(1) Continuous and intermittent noise (20 to 16,000 hertz) that has an 8-hour time-weighted average (TWA) noise level of 85 decibels A-weighted (dBA) or greater.
(2) Impulse noise sound pressure of 140 decibels peak (dBP) or greater.
(3) Ultrasonic exposures, which occur under special circumstances that require specific measurement and hazard assessment calculations.

Acquisition programs shall include implementation of noise assessment and engineering control measures through the systems engineering and systems safety process as directed by DoDI 5000.02 when:

(1) Legacy systems have recognized noise exposure concerns as indicated by personnel exposures at or above 85 dBA or 140 dBP.
(2) New systems are considered likely to create noise exposures at or above 85 dBA or 140 dBP.
(3) Communication is anticipated to be potentially impaired by background noise caused by new equipment.

Due to funding constraints, the specific sources selected by DoD stakeholders for evaluation as part of this project are listed in Table 1A and include only steady noise sources (e.g., continuous and intermittent noise). Discussions of the source levels used in this document are provided in the section pertaining to each source.

Table 1A presents the lower and upper A-weighted noise levels measured for the noise sources of concern and one promising technology. The representative levels listed in the table are based on measurements and published levels of the sources operating within various platforms. The authors acknowledge that the values listed are by no means exhaustive nor characteristic of all sources in all DoD platforms. The fourth column presents the estimated allowed exposure time in seconds for unprotected exposure time. The last column presents an estimated allowed exposure time with the use of double hearing protection (e.g., earplugs and earmuffs). These times are based on the DoD exposure standard of 85 dB (A) for eight hours, with a three dB exchange rate (illustrated in Table 1B).

Table 1A - Sound Level Ranges for DoD Noise Sources and Estimated Exposure Times With and Without Double Hearing Protection

Source	Low Level dB(A)	High Level dB(A)	Allowed Worst Case Unprotected Exposure Time	Estimated Exposure Duration With Double Hearing Protection*
Shipboard Diesel Driven Systems	98	120	9 seconds	2.5 hours
Shipboard Gas Turbines	85	101	12 minutes	Unlimited
Ships and High Speed Craft	85	126	2 seconds	40 minutes
Aircraft Operations – On-Deck Aircraft Operations – Interior Compartments	115 85	167 113	Less than 1 second 45 seconds	Less than 1 second 12 hours
Tracked Vehicles	90	118	14 seconds	4 hours
Wheeled Vehicles	85	112	57 seconds	16 hours
Cockpit Interior	85	121	7 seconds	2 hours[4]
Shipboard Equipment	84	114	36 seconds	6 hours
Abrasive Blasting[5]	85	145	Less than 1 second	28 seconds
Modular Cabin/Capsule/Pod	70	70	Promising Technology	Promising Technology

*Estimate using 30 decibel (dB) reduction for double hearing protection, realizing this may be a conservative best case scenario.

[4] With the exception of noise-cancelling headsets, most helmet and communication systems provide levels of noise attenuation comparable to single hearing protection. Use of double protection is impeded by the fact that earplugs dampen communications and would require increasing the volume of COM systems to compensate, thus overcoming the desired protection provided by earplugs.

[5] With two exceptions, available abrasive blasting air supply respirators do not accommodate earmuff or provide high levels of noise attenuation. The only exception for a hard helmet is the RPB (respiratory abrasive blast respirator).

Table 1B - Noise Level Exposure Standard based on duration per day*:

Allowable Unprotected Sound Level (dBA)	Duration Per Day	Unit of Time Per Day
80	24	Hours
82	16	Hours
85	8	Hours
88	4	Hours
91	2	Hours
94	1	Hour
97	30	Minutes
100	15	Minutes
103	7.5	Minutes
106	3.75	Minutes
109	1.88	Minutes
112	0.94	Minute
115	28.12	Seconds
118	14.06	Seconds
121	7.03	Seconds
124	3.52	Seconds
127	1.76	Seconds

*This is the DoD Standard which is based on the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values for Noise

To illustrate how the 3 dB exchange rate affects exposure time, the following examples are provided. If the noise source level is reduced by 3 dB, the allowed exposure time would effectively double; a reduction by 6 dB would quadruple the exposure time and a reduction by 12 dB would allow 16 times the exposure time.

How existing noise levels, the controlling factors creating these levels, existing and potential controls and their impact on both acoustic and non-acoustic parameters are discussed in the subsequent sections of this report. Non-acoustic parameters include cost, weight, space, and regulatory compliance with fire, smoke, toxicity, etc. Bear in mind that low noise and low source level equipment are in general more energy efficient and may provide fuel and operational savings via reduced weight of treatments.

Although a critical step, this project does not address the ‘management’ approach and mindset necessary to implement an engineering based approach to acquire ‘quiet’ systems designed to achieve acceptable or at least minimize noise levels (Bearden, 2011), (Hughes, 2011), (Ohlin, 2009),(Geiger, 2007). Hughes suggests that in the acquisition and weapons system design process “there is no overall corporate approach to manage efforts to mitigate exposure to hazardous noise and the resulting noise induced hearing loss” (Hughes, 2011). National Aeronautics and Space Administration (NASA) (The Many Benefits of Noise Control, n.d.), Office of Mine Safety (Yantek, 2012), and the Centers for Disease Control (CDC) (Buy Quiet Workshop, 2012) have implemented successful management approaches and may provide a blueprint for DoD programs. These management approaches may also benefit from the DoD's Green Procurement Program (GPP) which includes requirements for developers and contracting officers.

Prevention through design or "safety through design - the integration of hazard analysis and risk assessment methods early in the design and engineering stages, and taking the actions necessary so that risks of injury or damage are at an acceptable level "(Manuele, 2008) is a viable approach to reducing noise from DoD sources. This is consistent with the DoD-mandated approach of describing system capabilities or important systems' attributes through the Joint Capabilities (Requirements) Systems and derivative documents (guidance for noise control requirements and contracting documents are outlined in a related Defense Safety Oversight Council (DSOC) project (http://www.public.navy.mil/navsafecen/Pages/acquisition/noise_control.aspx).

Another programmatic approach discussed in several sections of this report is the "Buy-Quiet" program. As stated by " Dr. Smith, "The Buy Quiet campaign is based on the fact that changes can and should be made to equip factories with quieter machinery, the intention being that pressure from purchasers will encourage suppliers to respond with improved designs. Increasing the importance of noise as a factor in the design of a machine does not mean sacrificing other criteria such as operating efficiency or other safety aspects. Indeed the earlier that noise is taken into consideration, the lower the likelihood that costly and difficult remedial noise control measures will be needed" (Smith, 2011).

Noise levels can be "managed" to a successful conclusion if considered early in the design process. This also requires coordination from specification development through compliance testing which are the components of any successful Noise Control Program Plan (Fischer & Yankaskas, 2011), (Fischer et al. 2011), (Yankaskas, 2006), (Fischer, 2006).

While not evaluated in this project secondary effects of reducing hearing exposure levels can provide other benefits such as increased comfort, communications and situational awareness (Yankaskas, 2008), (Casali & Talcott, 2011). Furthermore, studies have shown a high return on investment when engineering controls is considered vice hearing loss compensation payment (Bowes, Shaw, Trost & Ye, 2006), (Tufts, Weathersby & Rodriguez, 2010).

2.0 APPROACH

The objectives for this project were to: (1) Identify nine significant DoD high noise (steady-state) sources and one promising technology; (2) Develop noise source reduction concept and design plan (NSRCDP) for each steady-state source, based upon the best available engineering control methods and (3) Evaluate the project return on investment (ROI) for treatment versus hearing loss compensation. The overall approach for each noise source reduction control plan involved:

- Identifying current noise ranges of the significant noise sources with allowable exposure times, both with and without hearing protection,
- Describing commercial off-the-shelf (COTS) noise controls and advanced noise control treatments
- Estimating projected noise reductions with various treatments
- Recommending optimal noise reductions from those described
- Calculating projected return on investments

In collaboration with Noise Control Engineering, Inc. (NCE), DoD stakeholders identified the nine high steady state noise sources and one promising technology to be evaluated. For nearly all DoD platforms, the noise generated by the significant noise sources is dependent on the specifics of each platform in which it operates. Furthermore, the source levels are a function of platform operating conditions which can change continuously during normal operations.

The impact of service member exposure to each source was estimated using a Microsoft Excel based program developed by NCE. The tool estimates noise induced hearing loss (NIHL) according to American National Standards Institute (ANSI) Standard S3.44-1996 and International Standards Organization (ISO) 1999:1990. Lifecycle costs were estimated using the model published by the Naval Submarine Medical Research Lab (NSMRL) (Sachs 2007). This study modified the model published by NSMRL to account for the cost of tinnitus empirically as there are no quantitative algorithms for predicting tinnitus. Tinnitus cannot be ignored since it is the most prevalent service connected disability granted followed by noise induced hearing loss as the second most prevalent service connected disability (U.S. Department of Veterans Affairs, 2005, 2006, 2007, 2008, 2009, 2010, 2011). According to the 2011 Veteran's Benefits Administration Annual Benefit Report, 840,865 veterans had a service connected disability for tinnitus, compared to 701,760 veterans who were service connected for NIHL (US Department of Veterans Affairs, 2011). In 2011, tinnitus made up 6.4% and NIHL 5.4% of all individual service connected disabilities. Therefore, Veterans Affairs (VA) disability compensation estimates which ignore tinnitus disability compensation severely understate the cost of noise exposure to the VA. VA data of Navy veterans was used to establish a ratio of tinnitus service connected disabilities to NIHL service connected disabilities. This ratio was used to estimate the occurrence of tinnitus based on the number service members predicted to have NIHL from the ANSI S3.44-1996 algorithm. Initially, the Noise Evaluation Acquisition Tool (NEAT) was used to assess NIHL costs and engineering control return on investment (ROI); however, the NEAT algorithm was shown to be inaccurate when calculating ROI so a new tool was developed by NCE. The issues with NEAT are outlined later in the report.

Using the NCE developed tool, a set of engineering controls representing current best design practices were proposed for each source. Military Department audiogram costs, hearing aid costs and Veterans' Affairs (VA) disability compensation costs were calculated before and after the application of engineering controls. An estimated noise control ROI was calculated for each source. Significant parameters impacting the ROI calculation such as mission readiness, the cost to replace soldiers who test out of their rating due to hearing loss and adverse social impacts were not considered. Non-acoustic paybacks (e.g., Buy Quiet programs, longer equipment life, lower maintenance, increased efficiency, etc.) were not considered as the data were not available.

2.1 General Noise Abatement Approaches

The physics of noise is classified by three mechanisms: the source, path and receiver. Controlling any of these three mechanisms can lead to noise reduction. Controls implemented early in the design stage can be used to avoid the applications of costly engineering treatments later in the design cycle. However, engineering treatments are often unavoidable and when chosen correctly are capable of successfully reducing noise. Regardless of the approach taken it is necessary to understand the nature of the noise problem, specifically, the noise level of concern, its spectral content (frequency) and operating conditions (temporal exposure). In addition, the noise producing mechanism (source) must be understood (i.e. mechanical, aero-dynamic, hydro-dynamic and thermo-dynamic). Lastly, the path, or how the source couples to its environment to reach the receiver's ear, must be known. In this report, these parameters are identified to the extent possible for each of the specific sources in the following sections and common design and treatment approaches are expanded upon. In general terms these sections outline noise control approaches following the steps outlined by (Yankaskas n.d.).

2.1.1 General Noise Abatement Approaches – Design

The most efficient method of reducing noise is to address it early in the design stage and attack it directly at the source. Source levels can be reduced using a multitude of ways during the design stage. For example, the selection of rotary over reciprocating equipment can have a significant impact on source noise levels. Reciprocating equipment include piston pumps which require additional isolation mounting, enclosures and other treatments to achieve structure and airborne noise levels equivalent to rotating equipment. The selection of higher quality machinery early on can result in noise reductions greater than those obtained through acoustic treatments. Quiet machinery is built with tighter tolerances, improved balance and better materials than conventional machinery. As a result, quiet machinery generally has higher upfront costs but also has improved maintenance life. Additionally, the implementation of noise source level purchase specifications can ensure the selection of quiet machinery and equipment. Implementation of 'Buy Quiet' programs have been undertaken at both NASA and Bureau of Mines and are gaining popularity in industry (Smith 2011). Other design approaches to reduce the noise at the source include: the addition of add-on technologies such as gear tooth coating and magnetic bearings, the use of multiple smaller or hybrid systems over larger systems, high efficiency design techniques such as computational fluid dynamics (CFD), fan speed control and the use of smart materials such as Quiet Steel ® or Quiet Aluminum ®[6].

Furthermore, the noise transmission path can be addressed in the design. By separating noise sources and compartments containing noise sources with rarely or intermittently occupied spaces such as lockers or store rooms the impact of the source on the receiver can be mitigated.

2.1.2 General Noise Abatement Approaches - Treatment

Accurate noise prediction algorithms are essential to the successful implementation of acoustic treatments. Stated simply, you cannot control what you do not understand. Accurate noise prediction algorithms help designers better understand the frequency dependency of the noise source, structure and airborne paths. Furthermore, predictive algorithms provide insight into how the source couples to the structure and airborne paths and the general characteristics of the receiver space (i.e. free space or reverberant). Armed with an understanding of the noise phenomenon, designers can specify the appropriate treatments to address the offending frequency, source or transmission paths. Common acoustic treatments include isolation mounts for machinery, baffles for Heating, Ventilation and Air-conditioning (HVAC) systems, mufflers for intake/exhaust systems, source enclosures, insulation and active control. In selecting treatments, the designer must simultaneously consider non-acoustic impacts such as regulatory limits on fire, smoke and toxicity and system impacts like weight, cost, space and maintenance.

A generalized matrix of cost, space and weight for the more common treatments and an estimate of their effectiveness are contained in Tables A8 through A15 in Appendix A. Specific discussions of non-acoustic impacts are contained within the discussion for each source.

2.2 Analysis Approach

Cost benefit analysis for each of the selected high noise sources was conducted using a Microsoft Excel based tool developed by NCE. This section outlines the algorithm and cost metrics employed in the tool.

[6] MSC Quiet Steel® is a unique Noise, Vibration, and Harshness (NVH) damping material that uses an engineered viscoelastic layer laminated between two sheets of steel to meet application-specific damping, temperature, stiffness and operating environment needs. See http://www.matsci.com/acoustic-materials/quiet-steel/

2.2.1 Analysis Approach – NIHL Calculation

NCE's tool uses ANSI S3.44-1996 and ISO 1990:1999 to determine the NIHL of an exposed population. ANSI S3.44-1996 and ISO 1990:1999 are identical with the following exception, ANSI S3.44-1996 allows modification to a exposure time/intensity trade-off other than 3-dB for halving or doubling exposure time. For this analysis, the 3-dB time/intensity trade-off was used and the difference between standards is irrelevant in this analysis. A summary of the ANSI S3.44-1996 NIHL calculation procedure is provided here. For more detailed information please consult the standard.

The hearing threshold associated with age and noise exposure (HTLAN) is defined by

$$H' = H + N - \frac{HN}{120} \quad (1)$$

where, H is the hearing threshold with age (HTLA) and N is the noise induced permanent threshold shift (NIPTS). HTLA is a function of age, gender and frequency. For the 0.5 fractile the HTLA is expressed as

$$H_{0.50} = a\left(Y - 18\right)^2 + H_{0.50;18} \quad (2)$$

where a is a gender and audiometric frequency varying coefficient, Y is the age in years and $H_{0.5;18}$ is the HTLA for otologically normal persons aged 18. In accordance with ISO 389, $H_{0.5;18}$ is assumed to be 0 dB. For fractiles less than 0.50 and greater than 0.05, HTLA is defined by

$$H_{0.05<Q<0.50} = H_{0.50} + kS_u \quad (3)$$

where, k is a fractile (Q) dependent multiplier and S_u is a parameter which can be written as

$$S_u = b_u + 0.445H_{0.50}$$
(4)

For fractiles greater than 0.50 and less than 0.95, HTLA is defined by

$$H_{0.50<Q<0.95} = H_{0.50} - kS_l \quad (5)$$

where, k is a fractile (Q) dependent multiplier and S_l is a parameter which can be written as

$$S_l = b_l + 0.356H_{0.50} \quad (6)$$

In equation (4) and (6) respectively, b_u and b_l are dependent on audiometric frequency and

gender. Within the NCE tool, male values were used for all gender dependent parameters.
The NIPTS for the 0.5 fractile is defined by

$$N_{0,50} = \left[u + v \log_{10}\left(\frac{\Theta}{\Theta_o}\right) \right] \left(L_{A8h5} - L_0\right)^2 \tag{7}$$

Where u and v are frequency dependent coefficients, Θ is the exposure time in years, Θ_0 is one year, L_{A8h5} is the equivalent continuous A-weighted sound level normalized to an 8-hour work day and 5 day work week and L_0 is a frequency dependent source level threshold. For sources with overall levels less than L_0, the 0.50 fractile NIPTS is zero. When the exposure time in years is less than ten years, as is the case with many DoD systems, ANSI requires the median NIPTS value be calculated according to

$$N_{0,50,\Theta<10} = \frac{\log_{10}\left(\Theta + 1\right)}{\log_{10}\left(11\right)} N_{0,50,\Theta=10} \tag{8}$$

For fractiles between 0.05 and 0.50 the NIPTS can be written as

$$N_{0.05<Q<0.50} = N_{0.50} + kd_u \tag{9}$$

The NIPTS for fractile greater than 0.50 and less than 0.95 is

$$N_{0.50<Q<0.95} = N_{0.50} - kd_l \tag{10}$$

The multiplier k in (9) and (10) is the same fractile dependent multiplier in (3) and (5).
Parameters d_u and d_l are according to

$$d_u = \left[X_u + Y_u \log_{10}\left(\frac{\Theta}{\Theta_0}\right) \right] \left(L_{A8hn} - L_0\right)^2 \tag{11}$$

$$d_l = \left[X_l + Y_l \log_{10}\left(\frac{\Theta}{\Theta_0}\right) \right] \left(L_{A8hn} - L_0\right)^2 \tag{12}$$

where X_u, Y_u, X_l, Y_l and L_0 are functions of frequency. Like Sachs, the ANSI algorithm was found to give spurious values of NIPTS at 2 kHz for low fractiles and low years of exposure. Based on the method used by Sachs, the 2 kHz NIPTS was always taken as the lesser of the 2 kHz and 3 kHz NIPTS (Sachs, 2007).

As stated in the introduction, the noise levels of a source varies according to the platform the source is in, the operating conditions of the source and the exposure time to the source at each operating condition. The data needed to accurately establish equivalent A-weighted levels is extensive and not readily available (if available at all). Therefore, representative levels for each source were established by averaging overall A-weighted sound pressure levels at various operating conditions and within various DoD platforms. These levels were normalized to an 8-hour work day and 5 day work week time-weighted (TWA) according to

$$L_{A8h5} = L_{Aeq} + 10\log_{10}\left(\frac{h}{8}\right) + 10\log_{10}\left(\frac{d}{5}\right) \tag{13}$$

Where h is the length of the typical work day and d is the length of typical work day around a specific source. Particulars of the work day for each source are described in their respective sections. The A-weighted sound pressure levels used to obtain the overall level were derived from measurement or published data. Specifics for each source are discussed in the sub-section devoted to each source

Personal hearing protection is accounted for by de-rating the continuous equivalent A-weighted sound level normalized to an 8 hour work day and 5 day work, L_{A8h5}, by 5 dB. Tufts, used to ANSI 3.44-1996 to compute the hearing levels of Nuclear-powered Aircraft Carrier, Fixed Wing (CVN) machinist's mates and found that de-rating the L_{A8h5} brought the ANSI predicted results in line with actual hearing levels obtained from Navy audiogram data (Tufts 2007). This approach is replicated here. For aircraft carrier on deck flight operations a worst case noise reduction rating (NRR) of 21 dB from cranial protection was assumed and for tank crews ear muffs with a worst case NRR of 15 dB was used (Bjorn 2005).

ANSI S3.44-1996 is applicable to 8 hour work day, 5 day work week levels between 75 and 100 dB(A). Extrapolations to levels above 100 dB(A) are not supported by the standard. However, this analysis applies the ANSI standard to source levels above 100 dB(A). Furthermore, the ANSI standard is applicable to regular occupational noise exposures. Military noise exposures do not follow the typical occupational exposures of 8 hours a day, 40 hours a week and 52 weeks per year. For each source a service profile is described with an equivalent number of years of 'occupational' noise exposure for each year of military service.

2.2.2 Analysis Approach – Cost Calculation

The hearing loss due to age and noise (HTLAN) was calculated for each fractile from 0.05 to 0.95 in 0.05 increments on a yearly basis. Every year from entrance into the service until estimated date of death, costs were assessed based on the "should cost" model proposed by Sachs (Sachs 2007). The "should cost" model is based on 100% compliance with DoD Hearing Conservation Program (HCP) and VA policies. The "should cost" model is more expensive than the “actual cost” expense. The costs associated with the Navy HCP were used for all platforms regardless of the Military Department of the primary operator. The effect of tinnitus was considered empirically. A summary of the NIHL cost accounting is provided below.

1. Every service member (soldier, sailor, marine or airman) is enrolled in their respective service’s Hearing Conservation Program (HCP). HCP costs were based on the model proposed by Sachs and are summarized below
    a. Annual HCP overhead cost of $12.21 for every soldier based on 2004 numbers
    b. Annual audiogram cost $91.25 for all service members based on the CHAMPUS[7] maximum allowable charge (CMAC) from April 1, 2005
    c. For service members displaying an average significant threshold shift (STS), defined as an average change of hearing threshold change +/- 10 dB across 2000, 3000 and 4000 Hz when compared to the baseline audiogram, a follow-up audiogram costing $141.94 is ordered in addition of the annual audiogram
    d. If the average hearing threshold of any two adjacent audiometric frequencies between 1 and 4 kHz is 30 dB, hearing aid costs of $440.30 per year are incurred by 15% of the population. For every 10 dB increase in the average, the percentage of the population requiring hearing aid costs doubles.

2. If a service member experiences a STS during their career all subsequent NIHL costs during retirement are incurred by the VA (i.e. NIHL is service connected)
    a. Benefits are limited to hearing aid costs, which remain at $440.40 but include an additional $172.19 for VA overhead.
    b. VA criterion for hearing disability is hearing loss at any audiometric frequency of 40 dB or greater or an average HL at any combination of three audiometric frequencies greater than 26 dB
    c. For Navy sailors VA data show that 3.98 sailors have a compensable tinnitus disability for every sailor with a compensable noise induced hearing loss disability. Tinnitus compensation is provided at a rate corresponding to a 10% disability. Unlike NIHL disability compensation, tinnitus compensation is not predicated on having a STS during the service members career
    d. Disability compensation is assigned according to Table 2

[7] Cost data from (Sachs 2007) used information from CHAMPUS. NCE’s tool is based on (Sachs 2007)

Table 2 - Simplified Costs of Veterans' Disability Compensation[8]

% Disability	0	10	20	30	40	50	60	80	100
Average HL (in dB) at 1,2,3,4 kilohertz (kHz)	< 56	56-62	63-69	70-77	78-83	84-90	91-97	98-104	105+
Cost per Month	$0	$108	$210	$389	$553	$772	$970	$1,402	$2,407
% Not Offset	15%	15%	15%	15%	15%	100%	100%	100%	100%
4.1% Overhead	$0	$0.61	$1.29	$2.39	$3.40	$31.65	$39.77	$57.48	$98.69
Net VA Cost per Month	$0	$16.86	$32.79	$60.74	$86.35	$803.65	$1009.77	$1459.48	$2505.69

The return on investment (ROI) for engineering treatments was computed according to

$$ROI = \frac{(\text{Cost Savings} - \text{Treatment Implementation Cost})}{\text{Treatment Implementation Cost}} \tag{14}$$

2.2.3 Issues with NEAT

The NEAT tool was evaluated against two baselines and was unable to replicate published results. In the first test, NEAT was used to calculate the median NIPTS value for a single person exposed to a constant noise source of 90 dB for 30 years. The median NIPTS values obtained from NEAT were compared to tabulated results in ANSI S3.44-1996. The results are shown in Table 3. This test showed the NEAT program unable to compute the NIPTS of an exposed person.

Table 3 – Comparison of NIPTS Values from NEAT to ANSI S3.44-1996

Frequency Range (Hz)	**500**	**1000**	**2000**	**4000**
Predicted NIPTS (dB) NEAT	8.29	2.08	0.21	1.55
Predicted NIPTS (dB) ANSI S3.44-1996	0	0	5	14
Difference (dB)	8.3	2.1	- 4.8	-12.4

In the second test case NEAT was used to calculate the lifetime NIHL costs of a CVN Machinist's Mate and the results were compared to the analysis done by Sachs Using the same

[8] From (Sachs 2007)

input parameters as Sachs, NEAT shows no Military Department or VA costs, where Sachs reported a per person, per career cost of $14,105.43. A summary of both the second test case is shown in Table 4. The per person per career costs computed by the NCE tool are also shown in Table 4

Table 4 - Comparison of NEAT Output to Sachs

Frequency Range (Hz)	Per person/ per career costs (Predicted VA Hearing Loss Costs, NIHL Only)
NEAT	$ 0.00
NCE Algorithm	$14,408
Sachs 2007	$14,105

NEAT showed appreciable deviation from published results.

3.0 ENGINEERING TREATMENT ANALYSIS FOR THE SELECTED DoD HIGH NOISE SOURCES (NOISE SOURCE REDUCTION CONCEPT AND DESIGN PLANS (NSRCDPS)

This section discusses the results obtained from NCE's cost analysis spreadsheet for each of the selected DoD noise sources. The estimated hearing loss compensation costs due to noise exposure *before* applying engineering controls are presented. Engineering noise controls pertinent to each source are discussed and results from noise exposure cost analyses incorporating sets of these controls are highlighted. Inputs to analysis and simplifying assumptions regarding the applicable system life cycle data are discussed on a per source basis. In general, public resources such as the Federation of American Scientists website, Army, Navy Air Force and Marine Corps fact files were consulted to estimate system life cycle, number of systems and crew sizes (Federation of Scientists nd), (United States Army Fact File nd), (The Official Site of the US Air Force nd), (Marine Corps Aircraft nd), (United States Navy Fact File, nd). For systems where complete lifecycle data could not be obtained; life cycle data from a similar platform was used. All source levels and noise reductions listed herein are in dB(A).

Note: NSRCDP summary slides for each selected DoD noise source and the promising technology are available in Appendix C.

3.1 Shipboard Diesel Driven Systems

Diesel systems are a significant source of vibration and structureborne noise on ships and vehicles. This section examines shipboard diesel driven systems. Noise controls for diesel driven vehicles are discussed in sections 3.6 and 3.7. In general, diesel systems produce high levels of broadband noise due to the combustion process and the lube/cooling subsystems. Diesel turbochargers contribute to high frequency noise. High levels of low frequency noise are generated by the low rotation and firing rate components. Furthermore, intake and exhaust systems can produce high noise levels topside and or along passageways near intake and exhaust ducting. Currently, few vendors are producing 'low' noise source level diesels. However, diesel vendors have responded to regulatory requirements on emissions suggesting that the implementation of requirements on low noise levels or Buy Quiet programs could be successful. In addition, the prevalence of low-noise electric generators used to support events such as outdoor concerns supports the potential for commercial enhancements of existing technology.

3.1.1 Noise Control Approaches for Shipboard Diesel Systems

A number of possibilities for reducing diesel source levels are identified here. Kim has identified the firing pressure are the main source of noise from a diesel engine block (Kim 2007). Force pulse tailoring can be achieved through modifications to the chamber shape and adjusting the injection timing or air-fuel ratio. Noise due to piston slap can be altered through component re-design and noise attributed to timing gear forces can be mitigated by altering the gear design. However, non-acoustic impacts on the efficiency of the diesel engine must also be considered. Structural modifications to the diesel such as isolating diesel components can favorably alter the transmission path. Incorporating damping treatments can reduce the levels of vibration and changing the shape and thickness of covers can reduce vibration levels and reduce radiation efficiency.

Other than separating source and receiver to the greatest extent possible, the primary control approach is use of noise control treatments. To address the airborne path, vendors are providing cladding composed of a limp mass layer on top of a compliant surface such as fiberglass. Diesel casing is the main radiator in terms of area and radiation efficiency. When cladding has been applied, 2 to 3 dB reductions in the A-weighted noise level have been demonstrated. The secondary market and diesel vendors are also supplying silencers and filters which reduce turbo noise. For diesel gen-sets, walk-in enclosures are particularly effective at reducing broadband airborne noise. Walk-in enclosures have been used on AOE-6, LPD class and other 'quiet' research vessels with broadband reductions greater than 10 dB and as high as 20 dB. In addition to noise reduction, these enclosures have served as fire boundaries and have successfully contained engine fires. However, non-acoustic impacts such as access for maintenance, and the need for additional cooling and firefighting systems must be considered. The use of a partial barrier can mitigate some of the access drawbacks associated with walk-in enclosures. Partial barriers can be used to reduce A-weighted noise in a typical engine room by 2 to 5 dB and when used at a watch-stander station can reduce noise on the order of 5 to 10 dB. High and mid frequency noise attributed to the intake and exhaust systems can be addressed with silencers and mufflers. Again non-acoustic impacts such as weight, space and back-pressure need to be considered before silencer or mufflers are implemented.

Vibration isolation on low frequency mounts or distributed isolation materials can be used to reduce structureborne noise. These mounts serve to ‘disconnect’ the source’s vibration from the ship or vehicle and are capable of achieving mid to high frequency range reductions on the order of 10-20 dB for low frequency mounts and 5 to 10 dB of distributed isolation pads. Additionally, high impedance (stiff) foundation can be utilized to avoid resonant response and keep structureborne energy from coupling to the ship or vehicle. Stiff foundations are effective at addressing broadband vibrations but also impose a small added weight penalty to the ship or vehicle. These structureborne treatments are not effective at reducing noise in the engine room, rather they are effective at reducing noise in adjacent compartments.

Treatments not widely used today may become useful at reducing diesel noise in the future. Active noise control (ANC) is most effective at reducing low frequency noise in small spaces and could be used in gen-set enclosures. ANC requires the use of multiple sensors and actuators which can be difficult to maintain in an engine room environment. ANC is not limited to engine rooms and could be used to control diesel intake and exhaust noise. However, the drawbacks mentioned above also apply when ANC is used for diesel intake/exhaust noise.

Active isolation mounting systems are currently being installed on NOAA Fisheries Research Vessels and have demonstrated effective reductions in low frequency noise at rotation rates of the generator sets. Active isolation mounts have the benefit of low weight and space impact. They also work well with constant speed devices such as diesel gen-sets but have difficulty tracking variable speed machines such as propulsion diesels. Outside of purely active isolation systems, hydraulic mounts are non-linear devices that could be used to control spectrally varying and amplitude sensitive stiffness characteristics (Singh 2010). Lastly, tuned vibration absorbers represent a completely passive approach to control vibration. Vibration absorbers have been shown to reduce vibration on marine structures by as much as 5 dB (Harne 2009).

It should be noted that not all diesel noise treatments contribute to reducing noise in the immediate diesel receiver space. Vibration isolation treatments, high impedance foundations and active control of intake and exhaust noise are treatments which reduce the amount of diesel noise transmitted to spaces throughout the ship. These treatments have a negligible impact on noise levels in the vicinity of diesel sources. However, the treatments may provide quiet areas which are essential for reducing the negative effects of noise exposure. In fact the ANSI and ISO standards are based on the assumption that a period of relative quiet is experienced following exposure to hazardous occupational noise. It is therefore, recommended that these treatments also be included in a holistic noise control design approach.

3.1.2 Cost Analysis for Shipboard Diesel System Noise Exposure

The number surface ships, number of diesels per ship and ship service life were used to determine the total number of diesel systems in the Navy inventory and the number of exposed individuals. Ships operated by the Military Sealift Command and active ships operated by the US Army were also considered. All non-combatant ships were assumed to have at least one diesel generator regardless of ship propulsion system. The representative diesel service life was derived from the average life of the Navy, Military Sealift Command and Army ships considered. Table A1 in Appendix A lists the ships included in this analysis. It is acknowledged that this representative diesel life is longer than the lifecycle of an individual diesel engine, but it is considered reasonable because a diesel will always be present on a particular ship during its lifecycle. To determine the number of exposed individuals it was assumed that 25% of each ship's crew was exposed to diesel noise and the total number of affected individuals for each ship was based on the ship's service life and a 20-year career for each crew member. Furthermore, it was assumed that diesel noise exposed crew's career began at age 18 and lasted until age 38. The assumed career profile for diesel noise exposed populations is based off of the career paths for Enginemen (EN) and Machinists Mates (MM) as reported on the Navy Personnel Command website. Table 5 summarizes the career paths for EN and MM ratings.

Table 5 - Career Paths for Enginemen (EN) and Machinists (MM)

Rotation	Sea Tour Length	Shore Tour Length
Training - 2 years	N/A	N/A
1st Tour	5 years*	3 years
2nd Tour	5 years	3 years
All Tours after 2nd Tour	4 years	3 years

* - Machinists Mates first Sea Tour is only 54 months but assumed to be a full 60 months to be consistent with Enginemen career path

Consistent with prior analyses performed by Tufts and Sachs, it was assumed that noise exposure accrued at a rate of 0.5 years for every year spent at sea and the exposed individuals worked 12 hours a day and 7 days per week at sea. Again, in accordance with Tufts and Sachs it was assumed that time spent on shore and in training did not contribute to NIHL. A representative crew size for all diesels was chosen so that the total number of affected individuals matched the total number of individuals over the lifetime of each ship. NCE data for diesel engines was averaged to obtain a representative level of 107 dB. This database encompassed diesels with powers from 600 to 27,500 horsepower and speeds from 93 to 2100 RPM. Based on recommendations published by Tufts, this overall level was normalized and reduced by 5 dB to be in agreement with hearing loss levels observed in Navy audiometric data (i.e. account for personal hearing protection PHP). Table 6 lists the inputs into the analysis.

Table 6 - Input Summary for Shipboard Diesel Cost Analysis

Representative Service Life	40 years
Number of Systems	1095 diesels
Affected Individuals over Service Life	26,280
Representative Crew Size	12
Source Level	107 dB
TWA Source Level	110 dB
TWA Source Level, De-rated for PHP	105 dB

Table 7 lists the costs associated with noise exposure *before* engineering controls are implemented.

Table 7 - Costs Associated with Diesel Noise Exposure

	Per Person Per Career	Lifetime System Costs	Annual System Costs
Audiograms	$2,106	$55,345,680	$1,383,642
Hearing Aids	$21,313	$560,105,640	$14,002,641
VA Disability (NIHL)	$3,022	$79,418,160	$1,985,454
VA Disability (Tinnitus)	$5,799	$152,397,720	$3,809,943
Total	$32,240	$847,267,200	$21,181,680

Based on the assumed career profile, source levels, crew size and number of systems, the noise exposure cost algorithm shows a per person career cost of $32,240, an annual cost for all diesels of $21,181,680 and a lifetime cost over all diesel systems of $847,267,200.

3.1.3 Engineering Noise Control Costs and Return on Investment for Shipboard Diesel Systems

Cost estimates for treatments discussed in section 3.1.1 are listed in Table 8. The achievable noise reduction and rough order of magnitude (ROM) cost of each treatment is also listed. Not all treatments reduce noise in the immediate vicinity of diesel engines. However, implementation of these treatments is consistent with best quiet design practices and will reduce the contribution of diesel noise in other compartments of the ship. Appendix B lists examples of noise control treatments and their effectiveness. The reductions listed in Table 8 are general and noise reductions higher and lower than those listed may be realized.

Table 8 - Engineering Noise Controls for Shipboard Diesel Systems

Treatment	Immediate Receiver Space Noise Reduction	Lifetime Treatment Costs			
		Per Diesel		All Systems	
		Low	High	Low	High
Enclosure	15 dB	$10K	$15K	$11 M	$16M
Buy-Quiet	10 dB	$100K	$500K	$110M	$548M
Cladding	3 dB	$1K	$3K	$1M	$3M
Vibration Absorber	5 dB	$10K	$20K	$11M	$22M
High-Impedance Foundation	0 dB	$1K	$3K	$1M	$3M
Isolation Mounts	0 dB	$3K	$27K	$3M	$30M
Active Control – Intake/Exhaust	0 dB	$10K	$20K	$11M	$22M

Table 9 shows the reduction noise exposure costs and the ROI of incorporating the treatments listed in Table 8.

Table 9 - Costs Due to Shipboard Diesel Noise, Before and After Noise Controls

	Lifetime System Costs		NIHL Cost Reduction	
	Without Treatments	With Treatment		
Audiograms	$55,345,680	$52,428,600	$2,917,080	
Hearing Aids	$560,105,640	$0	$560,105,640	
VA Disability[9] (NIHL)	$79,418,160	$0	$79,418,160	
VA Disability (Tinnitus)	$152,397,720	$20,130,480	$132,267,240	
Total	$847,267,200	$72,559,080	**ROI**	
			Low	**High**
			0.2:1	4:1

Table 9 shows estimated ROIs ranging from 0.2:1 to 4:1 over the lifetime of diesel sources. All treatments listed in Table 8 were included in the analysis. High impedance foundations, isolation mounts and ANC of intake and exhaust noise do not reduce noise in the diesel receiver space but do reduce shipboard noise for other sailors. As a result, cost savings from these treatments would not be experienced by diesel exposed crews but would reduce the noise levels and costs experienced by crewmembers exposed to shipboard equipment noise (see section 3.10).

9 The absence of computed/projected VA disability payments doesn't suggest the total control or avoidance of noise-induced hearing loss. Personnel with less than the 55 dB(A) threshold for VA compensation may still experience significant (but non-compensable) levels of hearing loss.

3.2 Shipboard Gas Turbines

Similar to diesel engines, gas turbines are significant contributors to structureborne noise on ships and vehicles. This section discusses shipboard gas turbine noise sources. Vehicle gas turbine noise sources are captured in section 3.6. Gas turbines induce higher mid- to high-frequency noise due to their higher rotation rate and large numbers of blades on the various compressor sections. In general, gas turbines have lower source vibration levels than diesels of the same power. The reductions are on the order of 10 to 15 dB and can be attributed to the gas turbine being a rotating piece of machinery as opposed to reciprocating like a diesel. Gas turbine vendors commonly supply total enclosures for the system which aids in reducing casing noise. While noise reductions due to the casing can be significant, casing noise reductions are not sufficient to reduce noise below hazardous levels for large gas turbines (15 kHp and greater). Noise transmitted along and through the intake/exhaust ducting becomes the critical path for noise. While noise induced by the enclosure cooling system can be critical in machinery spaces, noise from gas turbine intake/exhaust systems are oftentimes non-hazardous in other internal compartments.

3.2.1 Noise Control Approaches for Shipboard Gas Turbine Systems

Like diesel engine systems, reduction of gas turbine source levels by vendors is unlikely in the immediate future. With the exception of separating the source and receiver by the maximum extent possible, the primary control approach is the use of noise control treatments.

Commonly vendors provide total enclosures which are efficient at reducing gas turbine casing noise. However, these enclosures are not sufficient enough to lower airborne noise levels below non-hazardous levels for large turbines (15 kHp and above). Additional 5 to 10 dB of airborne noise reduction can be achieved if ‘hot’ spots in casing designs can be identified and altered. Airborne noise attributed to the intake and exhaust systems and cooling duct can be achieved by lining the ducting. These linings can reduce breakout noise and eliminate the need for a heavy silencer. However, non-acoustic factors such as space and lining resistance to corrosion need to be considered. The use of computer aided engineering (CAE) tools like computational fluid dynamics (CFD) can be employed in the design phase to help mitigate turbulence and flow induced noise. Proper design can limit flow noise by 10 to 15 dB and eliminate the need of a silencer or other treatments. Vibration isolation of the gas turbine on low frequency mounts or distributed isolation material remains one of the best ways to reduce the transmission of structureborne noise. Mid- to high-frequency structureborne noise can be reduced by as much as 15 to 25 dB with low frequency mounts and 10 to 15 dB with distributed isolation pads. However, mounts require replacement every 5 to 7 years and mount creep can cause alignment problems for propulsion systems. The use of high impedance or stiff foundations underneath the gas turbine can also reduce the amount of structureborne noise transmitted to the ship or vehicle. However, high impedance foundations come with an added weight penalty.

Though not commonly used today, ANC could be employed in the future to control noise within gas turbine enclosures. Active control is most effective at addressing low frequency noise. Again, the biggest drawback with ANC is the need for multiple sensors and actuators and the ability to maintain them in an engine room environment. The vibration absorber is a purely passive approach which has been shown to reduce structural vibration by 5 dB or greater.

As with diesel systems, not all gas turbine treatments reduce noise in the immediate receiver space. Vibration isolation, high impedance foundations, turbulence reduction and intake/exhaust noise treatments help to reduce the contribution of gas turbines to noise throughout the ship but do little to those directly exposed to gas turbine noise in an engine room. Regardless, these treatments are crucial to a robust noise control design philosophy and help to ensure a recovery period of relative quiet can be achieved in other ship compartments. Additional advantages include energy conservation and reduced fuel consumption due to improved duct and fan design that affect multiple spaces.

3.2.2 Cost Analysis for Shipboard Gas Turbine Noise Exposure

The number surface ships, number of gas turbines per ship and ship service life were used to determine the total number of gas turbine systems in the Navy inventory and the number of exposed individuals. Table A2 in Appendix A lists the ships considered as part of this analysis. It was assumed that 25% of the crew of each ship was exposed to gas turbine noise and the total number of affected individuals for each ship was based on the ship's service life and a 20-year career for each crew member. It is acknowledged that this representative gas turbine system life is longer than the lifecycle of an individual gas turbine, but it is considered reasonable because a gas turbine will always be present on a particular ship during its lifecycle. Furthermore, it was assumed that gas turbine noise exposed crew's career began at age 18 and lasted until age 38. The assumed career profile for gas turbine noise exposed populations is based off of conversations with Navy personnel and the career paths for Mechanical Gas Turbine Technicians (GSM) and Electrical Gas Turbine Technicians (GSE) as reported on the Navy Personnel Command website. Table 10 summarizes the career paths for GSM and GSE ratings.

Table 10 - Career Paths of Mechanical Gas Turbine Technicians (GSM) & Electrical Gas Turbine Technicians (GST)

Rotation	Sea Tour Length	Shore Tour Length
Training - 2 years	N/A	N/A
1st Tour	5 years	3 years
2nd Tour	5 years	3 years
All Tours after 2nd Tour	4 years	3 years

Specific information pertaining to the work hours of GSM and GSE ratings could not be obtained. It was assumed that the work profile used by Tufts and Sachs for MM ratings on CVN ships could reasonably be applied to GSM and GSE ratings. Again, this profile assumed a 12 hour work day, 7 days per week with 0.5 years of noise exposure accrued every year spent at sea. Noise exposure during training or while on shore duty was assumed to have no impact on NIHL. A representative level was obtained by averaging data from multiple gas turbine systems. Data used included overall levels from the LM2500 ship specification, average overall level measured over 180 LM2500 turbines and measurements on board the USS Conolly (DD 979). The average source level used in this analysis was 87 dB which was normalized according to GSM and GSE rating service profile and de-rated by 5 dB to account for hearing protection. Table 11 lists the system life cycle data and source levels used in the gas turbine noise exposure analysis.

Table 11 - Input Parameters for Shipboard Gas Turbine Cost Analysis

Representative Service Life	35 years
Number of Systems	510 Turbines
Affected Individuals over Service Life	15,173
Representative Crew Size	17
Source Level	87 dB
TWA Source Level	90 dB
TWA Source Level, De-rated for PHP	85 dB

Table 12 lists the Military Department and VA costs *before* engineering treatments are implemented.

Table 12 - Costs Associated with Shipboard Gas Turbine Noise Exposure

	Per Person Per Career	Lifetime System Costs	Annual System Costs
Audiograms	$2,001	$30,361,173	$867,462
Hearing Aids	$2,028	$30,770,844	$879,167
VA Disability (NIHL)	$344	$5,219,512	$149,129
VA Disability (Tinnitus)	$926	$14,050,198	$401,434
Total	$5,299	$66,351,529	$2,297,192

Based on the assumed career profile, source levels, crew size and number of systems, the noise exposure cost algorithm shows a per person career cost of $5,299, and a lifetime cost over all gas turbines systems of $80,401,727 and an annual cost of $1,895,758.

3.2.3 Engineering Noise Control Costs and Return on Investment for Shipboard Gas Turbines

Engineering treatments discussed in section 3.2.1 were incorporated into the NIHL cost analysis presented in section 3.2.2 and engineering treatment ROIs were computed. Input parameters such as system life, number of systems, crew size and career profile were unchanged from section 3.2.2. Table 13 summarizes all engineering treatments discussed, estimated noise reductions, and engineering treatment costs. Appendix B lists examples of noise control treatments and their effectiveness. The reductions listed in Table 13 are general and noise reductions higher and lower than those listed may be realized.

Table 13 - Engineering Noise Controls for Shipboard Gas Turbine Systems

Treatment	Immediate Receiver Space Noise Reduction	Lifetime Treatment Costs			
		Per GT		All Systems	
		Low	High	Low	High
Enclosure	8 dB	$5K	$8K	$2.6M	$4M
Buy-Quiet	7 dB	$200K	$1M	$102M	$510M
Vibration Absorbers	5 dB	$10K	$20K	$5.1M	$10.2M
Hi-Impedance Foundation	0 dB	$1K	$3K	$0.5M	$1.5M
Isolation Mounts	0 dB	$3K	$23K	$1.5M	$11.7M
Active Control – Intake/Exhaust	0 dB	$10K	$20K	$5.1M	$10.2M
CFD to Reduce Turbulence	0 dB	$5K	$10K	$2.6M	$5.1M
Intake/Exhaust Silencer	0 dB	$5K	$10K	$2.6M	$5.1M

Examining Table 12 and 13, both the low and high estimates for engineering treatments exceed the estimated lifecycle noise exposure costs. Gas turbine noise levels are relatively close to the DoD 8-hour time weighted average of 85 dB(A) and therefore require less extensive noise treatment. The ROI analysis included enclosure improvement, high impedance foundations, isolation mounts, active intake and exhaust control and CFD to reduce turbulence. This subset of treatments is consistent with best quiet design practices while being conscious of the comparatively low costs imposed by gas turbine noise exposure. The overall level was reduced by 8 dB in the ROI analysis.

Table 14 - Costs Due to Shipboard Gas Turbine Noise, Before and After Noise Controls

	Lifetime System Costs		Lifetime NIHL Cost Reduction	
	Without Treatments	With Treatment		
Audiograms	$30,361,173	$30,270,135	$91,038	
Hearing Aids	$30,770,844	$0	$30,770,844	
VA Disability[10] (NIHL)	$5,219,512	$0	$5,219,512	
VA Disability (Tinnitus)	$14,050,198	$11,622,518	$2,427,680	
Total	$80,401,727	$41,892,653	**Lifetime ROI**	
			Low	**High**
			0.2:1	2:1

Table 14 shows an estimated ROI between 0.2:1 and 2:1. This ROI is due to an estimated overall noise reduction of 8 dB. As with diesel engines, high impedance foundations, isolation mounts, turbulence reduction and intake and exhaust noise treatments have no impact in the immediate receiver space yet; their implementation is consistent with best quiet design practices. The effects of these treatments will be felt by sailors throughout the ship and help to provide a quiet recovery period needed to lessen the effects of high noise exposure during work hours.

3.3 Ships and High Speed Craft

Ships and high speed craft have numerous high noise and vibration sources in close proximity to affected receivers. The diesel and gas turbines employed in the multiple drive systems, common to ships and high speed craft, are large contributors to noise. Furthermore, aero and hydro-acoustic sources are found throughout high speed ships and crafts. Specifically, lift fans and propellers on air cushion crafts like the Landing Craft Air Cushion (LCAC) or Ship-to-Shore connector, cavitation propellers, water jets, super cavitating propellers and other advanced propulsors impart high levels of noise into the high speed craft's receiver space. These ships and craft have high power-to-weight ratios, implying the use of aluminum or composite hulls. Hulls

[10] The absence of computed/projected VA disability payments doesn't suggest the total control or avoidance of noise-induced hearing loss. Personnel with less than the 55 dBA threshold for VA compensation may still experience significant (but non-compensable) levels of hearing loss.

of this type have significantly different damping and acoustic coupling factors, which generally contribute to higher noise environments than found on typical steel hulled vessel.

3.3.1 Noise Control Approaches for Ships and High Speed Craft

Reduction of acoustic source levels, especially for fans and water jets, can be obtained with today's technology. Any higher design cost is more than offset by the elimination of add-on control treatments with their weight, space and cost impacts on craft with little margin for these impacts. This approach requires careful attention to crafting an acquisition specification identifying allowable noise and vibration levels at specific operation conditions. The allowable source level should be determined by the location of the nearest noise critical receiver. Most commercially available fans and water jets are not designed with respect to their acoustic properties. An appropriately designed fan or water jet should be able to reduce broadband and tonal noise by 10 to 20 dB over a system designed without any acoustic consideration. As discussed earlier, separating source and receiver to the maximum extent possible should always be a design approach. Reduction of diesel and gas turbine noise has been discussed in sections 3.1.1 and 3.2.1. The following addresses systems and sources unique to high speed craft.

The use of aero-acoustic best design practices, which include the use of CFD, to ensure the lift and propulsion systems are operating at the expected environment (wake) can help reduce airborne noise. Reductions greater than 10 dB can be achieved both at blade rate and broadband with a more efficient fan or propulsor. However, the non-acoustic impact of cost associated with the higher production cost of blades needs to be considered as well. Implementing best hydro-acoustic design practices, which also includes the use of CFD, can be used to increase the cavitation inception speed of the propeller and reduce the cavitation induced noise. When employed, best hydro-acoustic design practice can also be used to design quieter water jet impellers and to ensure propulsion systems are operating at the expected environment. Noise radiated from ship structures can also be reduced if materials with low radiation efficiencies, such as corrugated panels, are used. Similar to diesel and gas turbine systems, the water jets and lift fans on high speed craft can be isolation mounted to reduce their contribution to structureborne noise. Incorporating damping materials into the ship's construction also reduces structureborne noise (Yigang 2004).

Future noise reduction approaches should focus on developing lighter-weight, high transmission loss (TL) materials and combining the functionality of thermal/fire/acoustic and anti-sweat insulation into a single piece of insulation.

3.3.2 Cost Analysis for Ships and High Speed Craft Noise Exposure

The total number of high speed ships and craft in the DoD inventory was estimated from publically available sources. Ships included in this analysis were selected for their unique propulsion systems (i.e. water jets, thrusters and fans). Table A3 in Appendix A lists the ships and craft used in this analysis. Due to the smaller vessel size typical of high speed ships and craft, it was assumed that the entire crew of a given high speed vessel was exposed to noise. The crew profile used was based off the Sea/Shore Flow for LCAC operators. It was assumed that high ship and craft crews begin their military service at age 18 and complete 2 years of training before joining the LCAC community. Table 15 summarizes the career path for high speed ship and craft operators.

Table 15 - Assumed Career Paths for High Speed Ship and Craft Crew

Rotation	Sea Tour Length	Shore Tour Length
Training - 2 years	N/A	N/A
1st Tour	5 years	3 years
2nd Tour	5 years	3 years
3rd Tour	4 years	3 years
4th Tour	4 years	3 years

The work day for high speed operators is assumed to be 7-hours per day and 7-days per week with a 0.5 a year noise exposure accrued for each year at sea. The system life was assumed to be the average of all high speed ships and craft considered. NCE data for high speed ships and craft was averaged to obtain a representative level of 96 dB. The average value was taken from measurements of an LCAC, X-Craft, LCS, MK-5 and the Cyclone class patrol boat. Measurements encompassed a variety of operating conditions and positions. Based on recommendations published by Tufts the overall level was reduced by 5 dB to be in agreement with hearing loss levels observed in Navy audiometric data (Tufts, 2007). Table 16 lists the system life cycle data and source levels used in the ship and high speed craft noise exposure analysis.

Table 16 - Input Parameters for High Speed Craft Cost Analysis

Representative Service Life	22 years
Number of Systems	165 Ships and Craft
Affected Individuals over Service Life	4356
Representative Crew Size	24
Source Level (L_{A8h5d})	96 dB
TWA Source Level (L_{A8h5d})	97 dB
TWA Source Level, De-rated for PHP	92 dB

Table 17 lists the Military Department and VA costs *before* engineering noise controls are implemented.

Table 17 - Costs Associated with Ships and High Speed Ship Noise Exposure

	Per Person Per Career	Lifetime System Costs	Annual System Costs
Audiograms	$2,034	$8,860,104	$402,732
Hearing Aids	$10,288	$44,814,528	$2,037,024
VA Disability (NIHL)	$530	$2,308,680	$104,940
VA Disability (Tinnitus)	$1,208	$5,262,048	$239,184
Total	$14,060	$61,245,360	$2,783,880

Based on the assumed career profile, source levels, crew size and number of systems, the cost algorithm shows a per person per career cost of $14,060, a lifetime cost over all high speed ships and craft of $61,245,360 and an annual system cost of $2,783,880.

3.3.3 Engineering Noise Control Costs and Return on Investment for Ships and High Speed Craft

Engineering treatments discussed in section 3.3.1 are incorporated into the noise exposure cost analysis and engineering treatment ROIs are computed. Input parameters such as system life, number of systems, crew size and career profile were unchanged from section 3.3.2. Table 18 lists engineering treatments, estimated noise reductions and estimated engineering treatment costs. Appendix B lists examples of noise control treatments and their effectiveness. The reductions listed in Table 18 are general and reductions higher and lower than those listed may be realized.

Table 18 - Engineering Treatment for Ships and High Speed Craft – Implementation Cost

Treatment	Immediate Receiver Space Noise Reduction	Lifetime Treatment Costs			
		Per Ship		All Ships	
		Low	High	Low	High
Lift Fan Re-design	10 dB	$5K	$15K	$0.8M	$2.4M
Hydro-Acoustic Re-design	7 dB	$30K	$70K	$5M	$11.5M
Buy-Quiet	7 dB	$100K	$500K	$16.5M	$82.5M
Corrugated Panel	0 dB	$1K	$3K	$0.2M	$0.6M
Isolation Mounts	0 dB	$3K	$23K	$0.6M	$3.8M
Spray on Damping	0 dB	$10K	$30K	$1.6M	$4.8M
High-Impedance Foundation	0 dB	$1K	$3K	$0.2M	$0.6M
Lightweight, High TL Materials	0 dB	$10K	$20K	$1.6M	$3.2M
Distributed TVAs	0 dB	$10K	$20K	$1.6M	$3.2M

As with all the previous sources, the implementation of a Buy-Quiet program is the most expensive treatment. Its inclusion drives the high end total treatment costs above the estimated noise exposure costs before treatments. Again the additional 7 dB of attenuation achieved with a Buy-Quiet program has negligible impact on the overall noise exposure compensation costs if other noise control treatments are implemented. The following engineering noise controls were included in the ROI analysis: lift fan re-design, hydro-acoustic re-design, corrugated paneling, isolation mounts, spray on damping, high impedance foundations, lightweight high TL materials and distributed vibration absorbers. The incorporation of these design treatments is consistent with best quiet design practices while being conscious of the NIHL compensation costs imposed by the untreated system. Table 19 summarizes the noise exposure cost reduction and engineering noise control ROI.

Table 19 - Costs Due to High Speed Ship and Craft Noise, Before and After Engineering Treatments

	Lifetime System Costs		NIHL Cost Reduction	
	Without Treatments	With Treatment		
Audiograms	$8,860,104	$8,690,220	$169,884	
Hearing Aids	$44,814,528	$0	$44,814,528	
VA Disability[11] (NIHL)	$2,308,680	$0	$2,308,680	
VA Disability (Tinnitus)	$5,262,048	$3,336,696	$1,925,352	
Total	$61,245,360	$12,026,916	**ROI**	
			Low	**High**
			1:1	3:1

Table 19 shows an estimated ROI between 1:1 and 3:1 over a 22 year span. This ROI is due to an estimated overall noise reduction of 17 dB. Again there are multiple treatments listed in Table 17 which do not reduce noise in the immediate vicinity of high source level equipment. However, these treatments reduce the contribution equipment such as lift fans and water jets to the noise in other compartments of the ship.

3.4 Aircraft Carrier Operations – On Deck Stations

Noise in the vicinity of any jet is extremely high. Currently there are programs directed at reducing jet acoustic source levels so this approach is not considered as part of this project (Aubert 2011), (Morris 2011).

[11] The absence of computed/projected VA disability payments doesn't suggest the total control or avoidance of noise-induced hearing loss. Personnel with less than the 55 dB(A) threshold for VA compensation may still experience significant (but non-compensable) levels of hearing loss.

3.4.1 Noise Control Approaches for Aircraft Carrier Operations – On Deck Stations

Other than the use of either portable[12] 'acoustic' shields or 'pop-up' barriers (much like the concept of jet blast deflector on air craft carriers with or without a mechanical lift) there are few options to reduce the exposure of on deck launch crews in the vicinity of the aircraft. The barriers, even if feasible, would provide protection, on the order of 5 to 13 dB in the A-weighted noise depending in the physical size of the barrier. Bear in mind that a 3 dB reduction means a doubling of allowed exposure time – so a 13 dB reduction would change seconds of allowed exposure to minutes at the expected levels of current and future jet engines. Structure-borne noise is an insignificant contributor to on deck noise exposures during aircraft operations. As such structural modifications are not applicable to these sources.

3.4.2 Noise Exposure Cost Analysis for On deck Aircraft Carrier Operations

Aircraft carrier flight deck exposure was assumed to be limited to service members on CVN class carriers. The CVN ships considered are listed in Table A4 in Appendix A. Based on inputs from Navy personnel; a CVN carrier has a flight deck crew of 400 personnel. The total number of affected individuals was based on a 400 person flight deck crew, a 50 year service life for CVN carriers and 20-year career for flight deck crewmembers. It was assumed that a flight deck crewmember's career began at age 18 and ended at age 38. Table 20 summarizes the career path of CVN flight deck crews.

Table 20 - Assumed Career Paths for CVN Flight Deck Crews

Rotation	Sea Tour Length	Shore Tour Length
Training - 2 years	N/A	N/A
1st Tour	5 years	3 years
2nd Tour	5 years	3 years
All Tours after 2nd Tour	4 years	3 years

The severity of flight deck crew noise exposure is highly dependent on the number of flight hours during a carrier's ship cycle. As reported by Tufts, a CVN carrier has a 24 month ship cycle comprised of a 5 month work-up, 6 month deployment and 6 month shipyard maintenance period. The remaining 7 months are spent in port. Based on inputs from Navy personnel 35 flight days were assumed to occur during work up periods and 150 flight days during deployment. The work day for flight deck crewmen was assumed to be 12-hours per day and 7-days per week with a 0.25 of a year of flight noise exposure accrued for each year at sea. The system life was assumed to be the average of all CVN carriers. Based on a report by Bjorn, Albery, Shilling and McKinley, 79% of flight deck personnel received an estimated 0-6 dB of attenuation from earplugs beneath their cranial helmets (Bjorn 2005). Therefore, it was assumed that only the

[12] Would need way to be secured to deck to avoid possible foreign object damage to jet

cranial provides hearing protection. According to Bjorn, cranial helmets alone can reduce noise exposures by 21 dB. Therefore, a worst case assumption assuming cranial helmet protection only was used. Table 21 lists the system life cycle data and source levels used in the noise exposure analysis. The source level was established from NCE data taken aboard CVN-69 during flight operations.

Table 21 - Input Parameters for On Deck Aircraft Carrier Operations (CVN) Cost Analysis

Representative Service Life	50 years
Number of Systems	11 carriers
Affected Individuals over Service Life	11,000
Representative Crew Size	400
Source Level	140 dB
TWA Source Level	143 dB
TWA Source Level, De-rated for PHP	122 dB

Table 22 lists the costs *before* engineering treatments are implemented.

Table 22 - Costs Associated On Deck Aircraft Carrier Noise Exposure

	Per Person Per Career	**Lifetime System Costs**	**Annual System Costs**
Audiograms	$2,168	$23,848,000	$476,960
Hearing Aids	$23,989	$263,879,000	$5,277,580
VA Disability (NIHL)	$85,696	$942,656,000	$18,853,120
VA Disability (Tinnitus)	$18,604	$204,644,000	$4,092,880
Total	$130,457	$1,465,027,000	$28,700,540

Based on the assumed career profile, source levels, crew size and number of systems, the cost algorithm shows a per person per career cost of $130,457, a lifetime cost for all CVN deck crews of $1,230,383,000 and an annual system cost of $24,607,660.

3.4.3 Engineering Noise Control Costs and Return on Investment for On- Deck Aircraft Carrier Operations

Engineering treatments discussed in section 3.4.1 were incorporated into the cost analysis presented in section 3.4.2 and engineering treatment ROIs were computed. Input parameters such as system life, number of systems, crew size and career profile were unchanged from section 3.4.2. Table 23 summarizes the engineering noise controls studied, estimated noise reductions, and estimated noise control costs.

Table 23 - Engineering Noise Controls for On Deck Aircraft Carrier Operations

Treatment	Immediate Receiver Space Noise Reduction	Lifetime Treatment Costs			
		Per Ship		All Ships	
		Low	High	Low	High
Partial Barriers[13]	13 dB	$200K	$500K	$2.2M	$5.5M

Table 24 summarizes the estimated NIHL cost savings with the treatment listed in Table 23.

Table 24 - Costs Due to On Deck Aircraft Carrier Operation Noise, Before and After Noise Controls

	Lifetime System Costs		Lifetime Cost Reduction	
	Without Treatments	With Treatment		
Audiograms	$23,848,000	$23,089,000	$759,000	
Hearing Aids	$263,879,000	$211,244,000	$52,635,000	
VA Disability (NIHL)	$942,656,000	$41,151,000	$901,505,000	
VA Disability (Tinnitus)	$204,644,000	$68,233,000	$1,36,411,000	
			Lifetime ROI	
			Low	**High**
Total	$1,465,027,000	$343,717,000	203:1	509:1

Table 24 shows an estimated ROI for engineering controls as low as 203:1 and as high as 509:1 for CVN flight deck crews over the 50 year life of the CVN carrier.

3.5 Aircraft Carrier Operations – Internal Compartments

Separating noise critical spaces as far as possible from jet operating areas is the most effective noise control. However, for current CVNs, there are other significant sources in addition to the jet noise and these are widely located throughout the aircraft carrier. These include the catapult, arresting gear system, and water brake. For aircraft operations on amphibious class ships, these additional launch/retrieval systems do not exist. However on amphibious class ships the jet-induced noise is compounded by the use of thinner plating for the main deck. It is important that accurate prediction tools are available to understand and optimally reduce noise on aircraft carriers and amphibious class ships due to the likely impact on space, weight, and cost.

[13] Local barriers are effective in a constrained area and their use may be furthered hampered by space and mobility constraints on the aircraft carrier deck.

3.5.1 Noise Control Approaches for Aircraft Carrier Operations – Internal Compartments

Airborne noise can be treated with high TL structures between the source (aircraft) and compartments lower in the ship. These high TL structures would be composed of thick structural plating in combination with high TL insulation, typically 4 to 6 inches of 8 lb density mineral wool insulation. Mid- to high-frequency reductions in the range of 10 to 12 dB are achievable with these structures. Furthermore, the use of acoustical absorptive materials on boundaries of internal compartments, particularly overhead can reduce reverberant noise in compartments by 3 to 5 dB. Likewise, floating rooms which are isolation mounted overhead with joiner bulkheads and false decks can reduce both airborne and structureborne noise by 10 to 15 dB. However, non-acoustical factors such as space and w eight need to be considered. Suspended rigid ceilings have been demonstrated on Italian aircraft carriers to increase airborne TL and reduce radiation from the deck head into the compartment. Overall reductions of mid- to high-frequency noise of 10 dB have been achieved with suspended rigid ceilings. Windows tend to have much lower TL than neighboring steel bulkheads and insulation reducing overall TL by 3 to 5 dB. Improving window TL can reduce transmission of airborne noise with minimal impacts on space. Structure-borne noise due to jet plumes impinging on deck or the deck response due to high levels of jet noise are best affected with damping treatments. Damping treatments can provide 5 to 7 dB reductions in cabin noise below the main deck. However, damping treatments come with the negative non-acoustical impacts of added weight and cost.

3.5.2 Noise Exposure Cost Analysis for Aircraft Carrier Operations – Internal Compartments

Aircraft carrier flight deck exposure was assumed to be limited to service members on CVN class carriers. Based on inputs from Navy personnel, a CVN carrier has a crew of 1400 residing on the area of concern. The total number of affected individuals was based on a 1400 member crew, a 50 year service life for CVN carriers and 20-year career for crewmembers. It was assumed that a CVN crewman’s career began at age 18 and ended at age 38. The career path for CVN exposed to internal compartment noise was assumed to be the same as those exposed to flight deck noise and is listed in Table 20 above. It was assumed that crewmembers exposed to high levels of compartment noise occurred for 12 hours a day 7 days per week while at sea with a 0.5 years of noise exposure accruing for every year at sea. Noise exposure during training or while on shore was assumed to have no impact on NIHL. NCE data for CVN internal compartments was averaged to obtain a representative level of 97 dB which was normalized and de-rated by 5 dB in accordance with recommendations from Tufts. Table 25 lists the system life cycle data and source levels used in the gas turbine noise exposure analysis.

Table 25 - Input Parameters for Aircraft Carrier Operations - Internal Compartment Cost Analysis

Representative Service Life	50 years
Number of Systems	11 carriers
Representative Crew Size	1400
Affected Individuals over Service Life	38,500
Source Level	97 dB
TWA Source Level (L_{A8h5d})	100 dB
TWA Source Level , De-rated for PHP	95 dB

Table 26 lists the estimated costs *before* engineering noise controls are implemented.

Table 26 - Cost Summary for Aircraft Carrier Operations – Internal Compartment Noise Exposure

	Per Person Per Career	Lifetime System Costs	Annual System Costs
Audiograms	$2,051	$78,963,500	$1,579,270
Hearing Aids	$13,011	$500,923,500	$10,018,470
VA Disability (NIHL)	$786	$30,261,000	$605,220
VA Disability (Tinnitus)	$1,611	$62,023,500	$1,240,470
Total	$17,459	$672,171,500	$13,443,430

Based on the assumed career profile, source levels, crew size and number of systems, the cost algorithm shows a per person per career cost of $17,459, a lifetime cost for all CVN internal crews of $672,171,500 and an annual system cost of $13,443,430.

3.5.3 Engineering Noise Control Costs and Return on Investment for Aircraft Carrier Operations – Internal Compartments

Engineering treatments discussed in section 3.5.1 were incorporated into the cost analysis presented in section 3.5.2 and engineering treatment ROIs were computed. Input parameters such as system life, number of systems, crew size and career profile were unchanged from section 3.5.2. However, the overall flight deck noise level was reduced according to a given treatment's performance. Costs associated with engineering treatments have been obtained from experience with past projects and noise control treatment suppliers. Table 27 summarizes all engineering treatments studied, estimated noise reductions and treatment rough order of magnitude costs. Treatments mentioned in section 3.5.1 such as high TL structures, absorptive material, floating floors and suspended rigid ceilings are incorporated into a modular cabin in Table 27. Appendix

B lists examples of noise control treatments and their effectiveness. The reductions listed in Table 27 are general and reductions higher and lower than those listed may be realized.

Table 27 - Engineering Noise Controls for Aircraft Carrier Operations – Internal Compartments

Treatment	Immediate Receiver Space Noise Reduction	Lifetime Treatment Costs			
		Per Ship		All Ships	
		Low	High	Low	High
Modular Cabin	15 dB	$550K	$650K	$6.1M	$7.2M
Spray on Damping	6 dB	$600K	$700K	$6.6M	$7.7M

Table 28 summarizes the estimated cost savings with the treatments listed in Table 27.

Table 28 - Costs Due to Aircraft Carrier Operations – Internal Compartment Noise, Before and After Noise Controls

	Lifetime System Costs		Lifetime Cost Reduction	
	Without Treatments	With Treatment		
Audiograms	$78,963,500	$76,807,500	$2,156,000	
Hearing Aids	$500,923,500	$0	$500,923,500	
VA Disability[14] (NIHL)	$30,261,000	$0	$30,261,000	
VA Disability (Tinnitus)	$62,023,500	$29,491,000	$32,532,500	
Total	$672,171,500	$106,298,500	**ROI**	
			Low	**High**
			37:1	44:1

Table 28 shows an estimated ROI in the range of 37:1 to 44:1, for engineering noise controls of the internal compartments on CVN aircraft carriers. This ROI is over the 50 year service life of the carrier.

Some of the same types of treatments might be considered for other ship classes supporting aircraft. These weren't directly evaluated in this review. The ROI might tend to be higher due to the differences in ship design. Navy vessels supporting aircraft operations include L-class ships such as the LHA and LHD.

[14] The absence of computed/projected VA disability payments doesn't suggest the total control or avoidance of noise-induced hearing loss. Personnel with less than the 55 dB(A) threshold for VA compensation may still experience significant (but non-compensable) levels of hearing loss.

3.6 Tracked Vehicles

For tracked vehicles the track and its drive system are important noise sources (Norris 1977), (Norris 1979), (Hammond 1981). The track includes sprockets, idlers, and wheels. Previous studies indicate that the greatest potential for noise reduction lies in providing a softer compliance between the idler and the track. The other component of concern is the wheels. Military Handbook (MIL-HDBK-767(MI) provides guidelines for "designing quiet tracked vehicles and reducing interior tracked vehicle noise by redesigning vehicle components" (MIL-HDBK-767 nd). Tracked vehicles also share many important noise sources but these are discussed later in Section 3.7

3.6.1 Noise Control Approaches for Tracked Vehicles

Source controls on tracked vehicles would need to be directed at the sprocket/idlers/wheels which may not be feasible given non-acoustic impacts. Tracked vehicles would benefit from having a good acoustic modeling tool in order to better understand the sources and how they couple to the vehicle. This type of tool could be used to optimize the treatment process. Selecting cooling fans that appropriately match to the operating environment and have low source levels can reduce noise by 10 to 15 dB. This could be achieved through the implementation of a Buy Quiet program. Cladding high radiation sections with decoupling can possibly reducing interior noise. However, this approach is unproven. Damping treatments can also be implemented to reduce vibration and structure-borne noise but have also been unproven on tracked vehicles. Tracked vehicles are prime candidates for ANC. Active noise control can reduce overall noise levels by 5 to 10 dB with no layout changes or significant weight or space impacts. However, ANC is only effective below 200 Hz and is less effective with increasing compartment size. Structureborne noise can be reduced by isolation mounting the interior. This approach reduces noise from the drive train and track and may allow other components to be minimally isolation mounted. However, isolation mounting the interior would require a redesign of the interior attachment points. Yoder has proposed the use of hybrid drive systems that could be used to reduce overall system noise (Yoder, nd)

3.6.2 Cost Analysis for Tracked Vehicle Noise Exposure

Public resources were consulted to estimate the number of tracked vehicles in the DoD Inventory. Table A5 lists the tracked platforms considered, the estimated service life, number of vehicles, and number of exposed crewmembers over the system's lifecycle.

Based on discussions with Army personnel, an estimated service profile was established. The service profile is summarized below.

1. Tracked vehicle crews participate in 18 week training cycles, which in turn are broken down into three 6 week training cycles classified as ‘Green’, ‘Amber’ and ‘Red’
    a. Green – Crew is training on the system full-time 12 hours per day, 5 days per week.
    b. Amber – Crew is training on the system only part-time. Crew is also performing system maintenance and participating in individual training at this time. It was assumed that system exposure is 50% of full-time exposure.
    c. Red – Crew is completely away from the system during this time.
2. Deployment lasts 12 months in theater and 9 months at the home base
    a. During the 12 months in theater crews are with the system 24 hours per day 7 days per week. Exposure was assumed to occur at a rate 2.8 times the full time rate of 12 hours per day 5 days per week.
    b. During the 9 months at the home base tracked vehicle crews resume the ‘Green’, ‘Amber’ and ‘Red’ training cycles
3. On average tracked vehicle crews career spans 20 years on average
    a. During the first 7 years of their career the tracked vehicle crewman go from Private to E7. During this phase of their career they work directly on the system and accumulate noise exposure.
    b. After 7 years, the tank crew member achieves E7 and enters a managerial role no longer accumulating noise exposure.
4. It was assumed that tank crews participate in the ‘Green’, ‘Amber’ and ‘Red’ training cycles until they make E7. It was also assumed that tank crewmembers are deployed once in the first 7 years of their careers.

Based on 1 through 4 it was assumed that tank crews are exposed to tank noise 12 hours per day, 5 days per week for 6 years of their 20 year career. Noise exposure was assumed to accrue at a rate of 0.3 years for every year in the service.

Tank noise is highly dependent on vehicle speed. For example MIL-HDBK-767 shows that crew area noise increases from 109 dB(A) at 15 mph to 115 dB(A) at 25 mph. As such, the noise exposure (TWA) experienced by the crew is heavily influenced by the operational profile of the vehicle (i.e. time spent at each speed). Unfortunately information pertaining to operational profiles of tank systems was not available and a representative source level was obtained by averaging overall A-weighted levels across a series of tracked vehicle platforms and operating conditions. The vehicles considered include the M113 A3, M114 A1, AAAV/EFV, M1A2 Abrams, Bradley Fighting Vehicle, M60A3 and ADATS Carrier. Operational conditions of the platforms considered ranged from idle to 40 mph. Based on inputs from Army personnel ear muffs were assumed to be used during normal operation with a worst case NRR of 15 dB.

Table 29 - Input Parameters for Tracked Vehicle Cost Analysis

Representative Service Life	50 years
Number of Systems	97,109 vehicles
Representative Crew Size	2
Affected Individuals over Service Life	485,545
Source Level	111 dB
TWA Source Level (L_{A8h5d})	113 dB
TWA Source Level, De-rated for PHP	98 dB

Table 30 lists the Military Department and VA costs *before* engineering noise controls are implemented.

Table 30 - Cost Summary for Tracked Vehicle Noise Exposure without Engineering Noise Controls

	Per Person Per Career	Lifetime System Costs	Annual System Costs
Audiograms	$2,057	$998,766,065	$20,625,952
Hearing Aids	$14,440	$7,011,269,800	$213,455,293
VA Disability (NIHL)	$984	$477,776,280	$48,573,922
VA Disability (Tinnitus)	$2,014	$977,887,630	$19,975,321
Total	$19,495	$9,465,699,775	$189,313,996

Based on the assumed exposure level and profile, the cost analysis shows a per person per career cost of $19,495, a lifetime cost across all tracked systems of $9,465,699,775 and an annual cost for all tracked vehicle crews of $189,313,996.

3.6.3 Engineering Noise Control Costs and Return on Investment for Tracked Vehicles

Engineering noise controls discussed in section 3.6.1 were incorporated into the cost analysis presented in section 3.6.2 and engineering controls ROIs were computed. Input parameters such as system life, number of systems, crew size and career profile were unchanged from section 3.6.2. Table 31 summarizes all engineering noise controls discussed, estimated noise reductions and estimated engineering noise control costs. Appendix B lists examples of noise control treatments and their effectiveness. The reductions listed in Table 31 are general and reductions higher and lower than those listed may be realized.

Table 31 - Engineering Noise Controls for Tracked Vehicle Crews

Treatment	Immediate Receiver Space Noise Reduction	Lifetime Treatment Costs			
		Per Vehicle		All Vehicles	
		Low	High	Low	High
Buy Quiet	7 dB	$70K	$90K	$6.8B	$8.7B
Re-Design Fan	7 dB	$5K	$15K	$486M	$1.5B
Cladding	6 dB	$2K	$4K	$194M	$388M
Spray on Damping	6 dB	$5K	$10K	$486M	$972M
Modular Cabin/Isolation Mounts	7 dB	$300K	$500K	$29B	$49B
Active Noise Cancellation	7 dB	$30K	$60K	$2.9B	$5.8B
Re-design sprocket	10 dB	$30K	$60K	$2.9B	$5.8B
Vibration Absorbers	5 dB	$10K	$20K	$972M	$1.9B

Examining Table 31 it is clear there are a multiple engineering treatments which can be combined to reduce the hazardous levels within a tracked vehicle. However, due to the vast number of tracked vehicles within the DoD inventory many of these treatments impose a serious cost penalty. Furthermore, the source of noise within a tracked vehicle also depends on speed, thereby limiting a treatment's effectiveness at certain operating conditions. For the ROI analysis spray-on damping, cladding and sprocket re-design were considered. Sprocket re-design does not currently constitute an off-the-shelf treatment and would require a substantial research and development effort to achieve. The overall reduction was not assumed to be cumulative. The treatments studied were estimated to reduce cabin noise by 16 dB(A) and cost between $3.5 to $7.2 billion over the lifetime of all tracked vehicles.

Table 32 - Costs Due to Tracked Vehicle Noise, Before and After Noise Controls

	Lifetime System Costs		Cost Reduction	
	Without Treatments	With Treatment		
Audiograms	$998,766,065	$986,662,275	$12,103,790	
Hearing Aids	$7,011,269,800	$0	$7,011,269,800	
VA Disability[15] (NIHL)	$477,776,280	$0	$477,776,280	
VA Disability (Tinnitus)	$977,887,630	$371,927,470	$605,960,160	
			ROI	
			Low	**High**
Total	$9,465,699,775	$1,340,589,745	0.1:1	1:1

[15] The absence of computed/projected VA disability payments doesn't suggest the total control or avoidance of noise-induced hearing loss. Personnel with less than the 55 dBA threshold for VA compensation may still experience significant (but non-compensable) levels of hearing loss.

Table 32 shows an estimated ROI as low as 0.1:1 and as high as 1:1, for engineering treatments of tracked vehicles. This ROI is over the assumed 50 year service life of all tracked vehicle platforms considered.

3.7 Wheeled Vehicles

Noise on wheeled vehicles is controlled primarily by the mechanical drive system – diesel/gearbox, cooling fan, and tire noise. In many cases the interior noise is controlled by the cooling fan noise – which is generally ‘stalled’ (operating at the wrong flow/pressure). This is the case with many ‘industrial’ trucks; however the U.S. Environmental Protection Agency’s (EPA) 50’ drive-by noise limits has resolved this issue by forcing vendors to design a matched radiator/fan cooling system. Tire noise is strongly dependent on whether one is operating on or off road along with speed. Whereas the EPA drive-by requirements have resolved this for commercial trucks the same technology bridge is not applicable given the operation of wheeled military vehicles. There should be no reason that engine exhaust contributes to a hazardous noise level given the state of current muffler design.

3.7.1 Noise Control Approaches for Wheeled Vehicles

As the fan is one of the largest contributors to interior noise, re-designing the fan can reduce noise by 5 to 10 dB and possibly as high as 15 dB. However, fan re-design requires detailed analysis resulting in higher initial fan cost. Furthermore, fan modifications can add weight and take up more space. Cladding radiating sections of the cabin with a decoupling treatment can possibly reduce interior noise by 5 to 7 dB. As with tracked vehicles, cladding radiating sections is an unproven approach. Isolation mounting the engine is already employed on many vehicles and can have an appreciable effect on interior noise. Softer isolation mounts on higher impedance structures can reduce engine noise by more than 5 dB. Similarly the interior cabin can be isolation mount, reducing contributions from the drive train and tires and relaxing isolation mount requirements on other components. Isolating the cabin would require a re-design of the cabin attachments. Wheeled vehicles are also prime candidates for ANC which could be used to reduce low frequency noise inside the cabin and reduce overall noise by 5 dB.

3.7.2 Cost Analysis for Wheeled Vehicle Noise Exposure

Public resources were consulted to estimate the number of tracked vehicles in the DoD Inventory. Table A6 in Appendix A lists the wheeled vehicles considered in the analysis.

Based on discussion with Army personnel, the service profile of a wheeled vehicle crew is identical to the service profile of the tracked vehicle crew with the following modifications

1. Wheeled crews are in non-combat roles and no special exposure profile was considered during deployment period
2. Wheeled vehicle crew member enter managerial roles at E6. The service member was assumed to make E6 6 years into a 20 year career
3. Overall it was assumed wheeled vehicle crews are exposed to wheeled vehicle noise 12 hours a day, 5 days per week for 3 years out of a 20 year.

Wheeled vehicle noise was modeled using an averaged overall A-weighted level obtained from NCE's database. The average included multiple vehicles at various operating conditions. It was assumed that wheeled vehicle crews do not wear hearing protection. Table 33 summarizes the input parameters used in the cost analysis of wheeled vehicles.

Table 33 - Input Parameters for Wheeled Vehicle Cost Analysis

Representative Service Life	30 years
Number of Systems	440,792 vehicles
Representative Crew Size	2
Affected Individuals over Service Life	1,322,376
Source Level	88 dB
TWA Source Level	90 dB
TWA Source Level, De-rated for PHP	90 dB

Table 34 lists the Military Department and VA costs *before* engineering noise controls are implemented.

Table 34 - Cost Summary for Wheeled Vehicle Noise Exposure

	Per Person Per Career	Lifetime System Costs	Annual System Costs
Audiograms	$2,013	$2,661,942,888	$88,731,430
Hearing Aids	$5,376	$7,109,093,376	$236,969,779
VA Disability	$424	$560,687,424	$18,689,581
VA Disability (Tinnitus)	$966	$1,277,415,216	$42,580,507
Total	$8,779	$11,609,138,904	$386,971,297

Based on the assumed exposure level and profile, the cost analysis shows a per person per career cost of $8,779, a lifetime cost across all wheeled vehicles of $11,609,138,904 and an annual system costs for all wheeled vehicles of $386,971,297

3.7.3 Engineering Noise Control Costs and Return on Investment for Wheeled Vehicles

Engineering noise controls discussed in section 3.7.1 were incorporated into the cost analysis presented in section 3.7.2 and engineering noise control ROIs are computed. Input parameters such as system life, number of systems, crew size and career profile remain unchanged from section 3.7.2. Table 33 summarizes the engineering noise controls discussed, estimated noise reductions, and estimates of the engineering noise control costs. Appendix B lists examples of noise control treatments and their effectiveness. The reductions listed in Table 35 are general and reductions higher and lower than those listed may be realized.

Table 35 - Engineering Noise Controls for Wheeled Vehicle Crews

Treatment	Immediate Receiver Space Noise Reduction	Lifetime Treatment Costs			
		Per Vehicle		All Vehicles	
		Low	High	Low	High
Buy Quiet	7 dB	$3K	$6K	$1.3B	$2.6B
Re-Design Fan	7 dB	$5K	$15K	$2.2B	$6.6B
Cladding	6 dB	$2K	$4K	$0.8B	$1.6B
Spray on Damping	6 dB	$2K	$7K	$0.8B	$3.1B
Modular Cabin/Isolation Mounts	7 dB	$10K	$20K	$4.4B	$8.8B
Active Noise Cancellation	7 dB	$30K	$60K	$13.2B	$26.4B
Tire Tread Re-design	5 dB	$0.8K	$2K	$0.3B	$0.8B
Distributed TVA's	5 dB	$10K	$20K	$4.4B	$8.8B

The ROI analysis only considered the effect of re-designing the fan. This treatment was studied because the fan is one of the largest contributors to wheeled vehicle noise. Table 36 summarizes the NIHL cost reduction and engineering treatment ROI for wheeled vehicles with only a re-designed fan.

Table 36 - Costs Due to Wheeled Vehicle Noise, Before and After Engineering Treatments

	Lifetime System Costs		Lifetime Cost Reduction	
	Without Treatments	With Treatment		
Audiograms	$2,661,942,888	$2,638,140,120	$23,802,768	
Hearing Aids	$7,109,093,376	$0	$7,109,093,376	
VA Disability[16] (NIHL)	$560,687,424	$0	$560,687,424	
VA Disability (Tinnitus)	$1,277,415,216	$1,012,940,016	$264,475,200	
Total	$11,609,138,904	$3,651,080,136	**ROI**	
			Low	**High**
			2:1	5:1

With a 7 dB noise reduction due to a re-designed fan, Table 36 shows a lifetime ROI ranging from 2:1 to 5:1 over the lifetime of all wheeled vehicles

3.8 Modular Cabin/Capsule/Pod

Pre-outfitted 'modular' cabins/capsules/pods are standard on many cruise boats. They are not utilized to any great extent on naval vessels. There are two distinct applications for this technology on military ships-for berthing areas to allow the ears to 'recover' and as isolation booths in high noise areas to physically separate the worker from hazardous noise.

Though there is currently limited measured data, the use of modular staterooms, workstations, or prefabricated berthing, has high potential with regards to noise and vibration control. In concept, pre-fabricated berthing or work station units would be structurally isolated from the rest of the vessel; they can be isolated from the deck using standard resilient mounts and all other connections such as HVAC, piping and electrical can also be made resiliently. This structural isolation creates a "room in a room" which maximizes the reduction in noise due to both structureborne and airborne contributions.

The concept has been tested on a CVN and found to provide a 10 dB noise reduction, which given the multiple sources and paths is significant (see Sections 3.4 and 3.5) (Kanyuck 2001). This is an approach used by the cruise industry to provide cabins with low noise.

3.9 Cockpit Interior Noise

The controlling sources on tactical jet aircraft are flow induced noise around the canopy and noise from air conditioning and cooling flow into the cockpit. Jet engine noise is a primary

[16] It should be noted that reduced noise levels also reduce, but may not eliminate noise induced hearing loss

contributor in interior noise on jet aircraft, which is generally broadband (with some high frequency tonal components from the various compressor stages). For instance, compressor tones in the kilohertz range are quite evident on the Harrier (James 2004). Turbo-prop (wing) and rotary aircraft have additional tonal components at blade passage rate and from drive components, particularly gearboxes. In some cases, due to poor designs, the defogging system can produce hazardous noise levels in cockpits. Levels also vary with altitude and speed and mid-air refueling. STOVL and VTOL craft would have additional lift fans contributing to internal noise.

3.9.1 Noise Control Approaches for Cockpit Interior Noise

As noted previously, reductions in jet source levels based on other DSOC programs (Morris 2011) would also lead to corresponding reductions in cockpit noise on jets (assuming other sources such as the defogger system). Reductions in airborne noise of 10 to 15 dB can be achieved if cooling fans for avionics are matched to the environment. Furthermore, implementing a Buy Quite plan to ensure selected fans have low source levels can reduce airborne noise from cooling fans. In the future passive, fan-less cooling could be implemented to eliminate fan noise all together. Noise from the defogger can be reduced by designing the de-fogger for acceptable flow rate versus noise (SAR No. 12-00005). Reductions of 10 to 20 dB are possible. However; a large duct cross-sectional area would be required for a lower flow rate. Achieving some of these improvements might be hindered by the already crowded configuration of cockpits and environmental control systems. However, some space might be gained by efficiencies that would allow use of smaller, more efficient fans and power supply systems. Similar to tracked and wheeled vehicles, cladding or damping treatments could be applied to radiating components within the cockpit area. Kochan has shown that ANC can be used to cancel low frequency rotary induced noise within the cockpit resulting in overall noise reductions of 5 to 10 dB (Kochan 2011). Sidewall treatments for turboprop and rotor aircraft have also been demonstrated (Vaicaitis 1983). These treatments were composed of non-load carrying masses attached to the skin and provided a 15 dB reduction with only a 2% increase in gross take-off weight.

3.9.2 Cost Analysis for Cockpit Interior Noise Exposure

The Air Force, Navy, Army and Marine Corps fact files were used to determine the number of aircraft interior systems for the NIHL analysis. The aircraft analyzed were limited to planes which could be classified as “fighter jets” (i.e. crew of 4 or smaller, jet propelled). All helicopters analyzed were limited to helicopters in the Army and United States Marine Corps (USMC) inventory. Table A7 in Appendix A lists the aircraft interior end items considered. Based on inputs from Air Force personnel, all pilots were assumed to have a 20 year career and fly on average 330 hours per year (1 hour per day 6 days per week). Table 37 summarizes the system life cycle data and source levels used in the aircraft interior analysis.

Table 37 - Input Parameters for Aircraft Interior Cost Analysis

Representative Service Life	35 years
Number of Systems	9,613 aircraft
Affected Individuals over Service Life	16,823
Representative Crew Size	1
Source Level	106 dB
TWA Source Level	98 dB
TWA Source Level, De-rated for PHP	93 dB

Table 38 lists the Military Department and VA costs *before* engineering treatments are implemented.

Table 38 - Cost Summary for Aircraft Noise Exposure without Engineering Controls

	Per Person Per Career	**Lifetime System Costs**	**Annual System Costs**
Audiograms	$2,061	$34,672,203	$990,634
Hearing Aids	$13,841	$232,847,143	$6,652,776
VA Disability (NIHL)	$744	$12,516,312	$357,609
VA Disability (Tinnitus)	$1,611	$27,101,853	$774,339
Total	$18,257	$307,137,511	$8,775,357

Based on the assumed exposure level and profile, the cost analysis shows a per pilot per career cost of $18,257, a lifetime system cost of $307,137,511 and an annual cost of $8,775,357 for the airframes considered.

3.9.3 Engineering Noise Control Costs and Return on Investment for Cockpit Interior

Engineering treatments discussed in section 3.9.1 were incorporated into the cost analysis presented in section 3.9.2 and engineering noise control ROIs were computed. Input parameters such as system life, number of systems, crew size and career profile were unchanged from section 3.9.2. Table 39 summarizes the engineering noise controls discussed estimated noise reductions and engineering noise control costs. Appendix B lists examples of noise control treatments and their effectiveness. The reductions listed in Table 39 are general and reductions higher and lower than those listed may be realized.

Table 39 - Engineering Treatments for Aircraft Cockpit Noise

Treatment	Immediate Receiver Space Noise Reduction	Lifetime Treatment Costs			
		Per Aircraft		All Aircrafts	
		Low	High	Low	High
Buy Quiet	7 dB	$3K	$6K	$28M	$56M
Cooling Fan Design	12 dB	$5K	$15K	$48M	$144M
Cladding	6 dB	$2K	$4K	$19M	$38M
Passive Cooling	6 dB	$2K	$7K	$19M	$67M
Active Noise Cancellation	7 dB	$30K	$60K	$288B	$576B

In the ROI analysis, only cooling fan re-design was considered. Fans are one of the largest contributors to cockpit noise and treatment of the fan can result in greatest reductions of noise when compared to other treatments. Table 40 summarizes the cost reduction and engineering noise control ROI for cockpit interiors with only a re-designed fan.

Table 40 - Costs Due to Cockpit Interior Noise, Before and After Engineering Treatments and Engineering Treatment ROI

	Lifetime System Costs		Lifetime Cost Reduction	
	Without Treatments	With Treatment		
Audiograms	$34,672,203	$33,561,885	$1,110,032	
Hearing Aids	$232,847,143	$0	$232,847,143	
VA Disability[17] (NIHL)	$12,516,312	$0	$12,516,312	
VA Disability (Tinnitus)	$27,101,853	$12,886,418	$14,215,435	
Total	$280,035,658	$33,561,885	**ROI**	
			Low	**High**
			0.8:1	4:1

With a 12 dB noise reduction due to a re-designed cooling fan, Table 40 shows a lifetime ROI as low as 0.8:1 and as high as 4:1 over the lifetime of all airframes considered.

3.10 Shipboard Equipment Noise

Noise in shipboard machinery compartments (and in some cases adjacent compartments and on deck) is high due to a large variety and high density of noise produced in relatively small

[17] The absence of computed/projected VA disability payments doesn't suggest the total control or avoidance of noise-induced hearing loss. Personnel with less than the 55 dBA threshold for VA compensation may still experience significant (but non-compensable) levels of hearing loss.

(compared to industrial plants) centralized compartments. Diesels and gas turbines have already been discussed in the preceding sections. This section addresses auxiliary equipment; including ventilation systems that must bring in large quantities of air and distributed at high speed through high-aspect ducting due to space limitations relative to land based plants. Even the smallest pump, compressor, or transformer can by itself produce high noise levels. Thus, the combination of all auxiliary equipment needed on a ship will generally result in hazardous noise levels. Hand held equipment, such as grinders, are used all over ships generate high noise levels. Sailors in Deck and Engineering support roles perform considerably more maintenance than merchant marine counterpart during deployment and provide extensive maintenance support during shore rotations and shipyard availabilities. Thus, a Buy Quiet program for powered hand tools would have significant benefits for both military and civilian industrial workforce

Controlling (designing) the flow characteristics to minimize flow induced noise and cavitation significantly reduces noise from pump and fan systems. The difference in noise between a cavitating pump and non-cavitating pump is 15 dB. Quiet fans exist and should be selected based on their noise level. Both aero- and pneumatic- (hydraulic) silencers/mufflers can be integrated into the design to control machinery intake/exhaust noise, piping/hydraulic system noise or HVAC system noise. Specialized vessel such as dredgers for the Army Corps of Engineers may require additional custom treatments.

3.10.1 Noise Control Approaches for Shipboard Equipment

As mentioned above, auxiliary shipboard machinery, such as pumps, compressors and fans can benefit from a Buy Quiet program. Using purchase specifications to identify allowable noise and vibration levels, stipulating required testing and compliance levels and reduce contributions to airborne and structureborne noise. A Buy-Quiet program would ensure the use of low source level components with improved balance, lower speed and better materials. Using existing ‘quiet design guidance’ for layout such as separating machinery spaces with storerooms and lockers can lower the impact of noise from auxiliary shipboard equipment. The use of acoustic insulation can reduce the reverberant noise in machinery compartments. Airborne noise can be further reduced through improved HVAC design. Improvements include lower duct speeds, turning vanes to minimize turbulence, duct linings and silencers. Structureborne noise can be reduced by isolation mounting machinery and piping systems. Hydraulic mufflers and silencers on hydraulic systems can reduce noise by 5 to 10 dB. Damping, both in spray-on or tile form can reduce vibration levels. Active noise control can used to effectively cancel low frequency noise in HVAC ducts and has been demonstrated on Holland American Lines M/S Veendam.

3.10.2 Cost Analysis for Shipboard Noise Exposure

All diesel and gas turbine powered ships listed previously in this report were included. It was assumed that the entire crew for a particular ship was exposed to noise. It was assumed that all sailors began their military service at the age of 18 and had a 20 year career ending at age 38. Noise exposure was assumed to accrue at a rate of 0.5 years for each year at sea in accordance with analyses presented prior. The source level was averaged from NCE's shipboard noise database. Table 41 lists the system life cycle and source levels used in the analysis.

Table 41 - Input Parameters for Shipboard Noise Exposure Cost Analysis

Representative Service Life	40 years
Number of Systems	602 ships
Representative Crew Size	385
Affected Individuals over Service Life	463,540
Source Level	92 dB
TWA Source Level	95 dB
TWA Source Level De-rated for PHP	90 dB

Table 42 lists the Military Department and VA costs *before* engineering treatments are implemented.

Table 42 - Cost Summary for Shipboard Noise Exposure

	Per Person Per Career	Lifetime System Costs	Annual System Costs
Audiograms	$2,028	$940,059,120	$23,501,478
Hearing Aids	$8,805	$4,081,469,700	$102,036,743
VA Disability (NIHL)	$484	$224,353,360	$5,608,834
VA Disability (Tinnitus)	$1,128	$522,873,120	$144,218,883
Total	$12,445	$5,768,755,300	$144,218,883

Based on the assumed exposure level and profile, the cost analysis shows a per sailor per career cost of $12,445, a lifetime system cost of $5,768,755,300 and an annual cost of $144,218,883 for all the ships considered.

3.10.3 Engineering Noise Control Costs and Return on Investment for Shipboard Noise

Engineering treatments discussed in section 3.10.1 were incorporated into the analysis presented in section 3.10.2 and engineering treatment ROIs are computed. Input parameters such as system life, number of systems, crew size and career profile were unchanged from section 3.10.2. However, the overall shipboard noise level was reduced according to a given treatment's performance. Costs associated with engineering treatments have been obtained from experience with past projects and noise control treatment suppliers. Table 43 summarizes all engineering treatments discussed, estimated noise reductions and engineering treatment costs. Appendix B lists examples of noise control treatments and their effectiveness. The reductions listed in Table 43 are general and reductions higher and lower than those listed may be realized.

Table 43 - Engineering Treatments for Shipboard Noise

Treatment	Immediate Receiver Space Noise Reduction	Lifetime Treatment Costs			
		Per Ship		All Ships	
		Low	High	Low	High
Buy-Quiet	10 dB	$100K	$300K	$60M	$180M
Cladding	3 dB	$12K	$24K	$7.2M	$14.4M
Acoustic Insulation	3 dB	$12K	$24K	$7.2M	$14.4M
CFD for HVAC Design	10 dB	$4K	$6K	$2.4M	$3.6M
Hydraulic Silencer	7 dB	$1K	$3K	$0.6M	$1.8M
Spray-On Damping	6 dB	$70K	$100K	$42M	$60M
Distributed TVA's	5 dB	$10K	$20K	$6M	$12M
Hi-Impedance Foundation	6 dB	$1K	$3K	$0.6M	$1.8M
Isolation Mounts	10 dB	$30K	$60K	$18M	$36M
Active Control – Intake/Exhaust	12 dB	$10K	$20K	$6M	$12M

The controls listed in Table 43 do not simultaneously reduce noise in a given ship compartment. For the ROI estimation an average noise reduction of 7 dB due to the combination of treatments listed in Table 43 was assumed. Table 44 summarizes the cost reduction and engineering control ROI for shipboard noise.

Table 44 - Costs Due to Shipboard Machinery Noise, Before and After Engineering Noise Controls

	Lifetime System Costs		Lifetime Cost Reduction	
	Without Treatments	With Treatment		
Audiograms	$940,059,120	$926,152,920	$13,906,200	
Hearing Aids	$4,081,469,700	$472,810,800	$3,608,658,900	
VA Disability (NIHL)	$224,353,360	$106,150,660	$118,202,700	
VA Disability (Tinnitus)	$522,873,120	$373,613,240	$149,259,880	
			Lifetime ROI	
			Low	**High**
Total	$5,768,755,300	$1,878,727,620	11:1	40:1

With a 7 dB noise reduction, Table 44 shows a lifetime ROI as low as 11:1 and as high as 40:1 over the lifetime of the ships considered.

3.11 Abrasive Blasting

Blast operators are exposed to high broadband noise which is controlled by numerous parameters, including the type of blasting equipment (nozzle and delivery system), size and composition of the item being blasted, blasting area, and even the angle of the work piece. The primary concern is with operators having a hand held nozzle, not blasting or cleaning in automated rooms. Critical components are air blaster nozzle, air supply to hood, the impact of the abrasive on the surface being blasted; air compressors; exhaust ventilation systems; and air releases during grit pot blow-down. Dust exhaust fans and waste separation systems also create high noise.

3.11.1 Noise Control Approaches for Abrasive Blasting

As noted previously, noise reduction at the 'source' usually proves to be the most cost-effective solution to noise problems. The nozzle is expected to be a critical 'source' of noise in this system. Industry has faced and addressed noise issues associated with nozzles for delivery of high-pressure air (Sneckdecker 1975). This technology may also prove effective for abrasive blasting. The obvious difference is the various media entrained in the pressurized air and delivered by the nozzle. The controlling factors – velocity of the media, mass volume of the media, etc. are needed to assess whether nozzle modifications may prove effective.

Prediction models and even diagnostic data that can be used to determine the critical noise sources and mechanisms do not exist. These should be developed to characterize noise external and internal to the blaster hood, evaluate passive treatments approaches and determine optimal noise controls.

However, new closed loop systems are available that can blast the coated and corroded surfaces (particularly pipes) and have lower noise levels than many existing systems. Vendors are providing systems with noise levels below 95 dB[18].

A critical additional mitigating technology is the use of communication headsets with combined noise attenuation properties. Trials of CAVCOM (www.cavcominc.com) and SENSEAR (www.sensear.com) technology at Puget Sound Naval Shipyard indicate a preference for the former product. Application in a range of industries has suggested the effectiveness of this technology. Discussion with civilian users in the Gulf Coast oil industry suggests a marked reduction in effective noise levels and an increased ability to communicate between blasters and

[18] Pinovo – http://www.pinovo.no

support personnel. However, use of such communication equipment doesn't control the source of noise, address ancillary ergonomic issues and leaves exposures in surrounding locations unmitigated. The communication option does provide necessary emergency communication between personnel and its application should be considered in support of OSHA requirements for confined space safety.

Improved abrasive blasting helmets are also needed. Many commercial products do not accommodate hearing protection. The MSA Abrasi-blast™ low-profile abrasive blast respiratory does accommodate low profile earmuffs. A competitor, North Honeywell is introducing a similar product with some improvements in field of vision that was recently approved by National Institute for Occupational Safety and Health (NIOSH) certification testing and is expected to be commercially available in June 2013. It also accommodates low profile earmuffs. Only one currently-available abrasive blasting hood with hard helmet (hard hat) protection is designed to reduce noise to operators through some insulation of the hood, the rpb respiratory abrasive blasting hood (www.rpbsafety.com/products)

3.11.2 Cost Analysis for Abrasive Blasting Noise Exposure

Input from USMC, Army and Navy personnel was used to determine the number of individuals exposed to abrasive blasting noise and the hours worked. In this study it was assumed that 500 people across all services used abrasive blasting and when they were used for 4 hours per day, 5 days per week. The abrasive blasting source level was assumed to be 97 dB in accordance with Navy data. The source level was normalized and de-rated by 5 dB in accordance with Tufts. The input parameters are summarized in Table 45.

Table 45 - Input Parameters for Abrasive Blasting Operations Cost Analysis

Representative Service Life	50 years [19]
Number of Systems	500 blasters
Representative Crew Size	1
Affected Individuals over Service Life	1250
Source Level	97 dB
TWA Source Level	94 dB
TWA Source Level, De-rated for PHP	89dB

Table 46 lists the Military Department and VA costs *before* engineering treatments are implemented.

[19] Refers to service life a major support system such as an abrasive blasting booth

Table 46 - Cost Summary for Abrasive Blasting Noise Exposure without Engineering Noise Controls

	Per Person Per Career	Lifetime System Costs	Annual System Costs
Audiograms	$2,037	$2,546,250	$50,925
Hearing Aids	$10,349	$12,936,250	$258,725
VA Disability (NIHL)	$500	$625,00	12,500
VA Disability (Tinnitus)	$14,014	$17,517,500	$350,350
Total	$14,014	$17,517,500	$350,350

Based on the assumed exposure level and profile, the cost analysis shows a per person per career cost of $14,014, a lifetime system cost of $17,517,500 and an annual cost of $350,350 for all the ships considered.

3.11.3 Engineering Noise Control Costs and Return on Investment for Abrasive Blasting

Engineering noise controls discussed in section 3.11.1 were incorporated into the cost analysis presented in section 3.11.2 and ROI's were computed. Input parameters such as system life, number of systems, crew size and career profile were unchanged from section 3.11.2. Table 47 summarizes the engineering noise controls studied, estimated noise reductions and estimated noise control costs. Table 48 lists the disability compensation savings and estimated ROI for the abrasive blasting noise controls listed in Table 46.

Table 47 - Engineering Noise Controls for Abrasive Blasting

Treatment	Immediate Receiver Space Noise Reduction	Lifetime Treatment Costs			
		Per Blaster		All Systems	
		Low	High	Low	High
Nozzle Re-design (CFD)	3 dB	$10K	$20K	$1M	$2M
Partial Barrier on Nozzle	3 dB	$10K	$20K	$1M	$2M

Table 48 - Costs Due to Abrasive Blasting Noise, Before and After Engineering Noise Controls

	Lifetime System Costs		Lifetime Cost Reduction	
	Without Treatments	With Treatment		
Audiograms	$2,546,250	$2,497,500	$48,750	
Hearing Aids	$12,936,250	$1,308,750	$11,627,500	
VA Disability (NIHL)	$625,00	$286,250	$338,750	
VA Disability (Tinnitus)	$17,517,500	$1,107,500	$16,410,000	
Total	$17,517,500	$5,200,000	**Lifetime ROI**	
			Low	**High**
			2:1	5:1

With a 6 dB noise reduction, Table 48 shows a lifetime ROI as low as 2:1 and as high as 5:1 for abrasive blasting over 50 years.

4.0 CONCLUSIONS

Noise exposure is one of the most common occupational health hazards in DoD operations and support processes. Noise mitigation in the acquisition and procurement processes is receiving increased attention at the Flag/Senior Executive Service level. Control in design requires application of a systems engineering methodology to integrate control measures into defense capabilities requirements (e.g., Joint requirements documents) and applied design processes. This report describes the feasibility and technical guidance to control several key noise sources relevant to DoD. It acknowledges the challenges of noise control in the acquisition setting with potentially competing requirements of legacy design issues, current cost, schedule and other technical performance considerations. Even for some of the highest DoD noise sources, the report shows noise control is feasible, cost effective and will reduce NIHL compensation costs incurred by the Military Departments and the VA. This report is available for use by the Defense Department and their contractors as a roadmap for future noise control in acquisition.

Some next steps that may help forward noise control in acquisition, include:

- Incorporating existing noise control requirements and detailed guidance into development joint capabilities (requirements) documents and derivative contractual documents. (Refer to: http://www.public.navy.mil/navsafecen/Pages/acquisition/noise_control.aspx)
- Updating MIL-STD 1474, "Design Criteria Noise Limits" to increase ease of use and better address impulsive noise, ship noise control and aircraft noise control.

- Implementing noise control guidance once it is added to MIL-STD 882E, "Standard Practice for System Safety: ESOH Risk Management Methodology for Systems Engineering," Updated Task 207 (Health Hazard Evaluation). This document will provide more detailed guidance for risk evaluations, including noise. This standard is the primary document for acquisition safety risk reduction and acceptance of risk.
- Partnering to use the systems engineering approach to manage for efficiency in energy consumption and noise. Improved efficiency in ventilation and other fluid handling systems offer significant concurrent reduction in energy consumption and noise generation.
- Designing systems for sustainability. Noise has recently been selected as one of the key areas for sustainability within DoD, meaning that there will be increased focus on noise control in acquisition.
- Linking noise to energy consumption. Excessive noise can be an indicator of inefficient energy use. Since an acquisition Key Performance Parameter (KPP) has been identified for energy consumption, consideration should be given to linking noise control to this KPP.
- Working to develop a DoD list of "technologically achievable" and "promising" noise controls. This may be linked to a "Buy Quiet" using approaches such as those applied in other technically challenging-settings by NASA, FAA and the mining community.
- Applying existing acoustic modeling methods and further develop these tools to allow for optimizing noise control approaches.
- Documenting noise control successes in future acquisitions.
- Monitoring the effectiveness of noise mitigation in the system safety process and external program reviews to support risk management, accountability and life-cycle cost mitigation.

Program managers are urged to utilize the technical guidance provided in this report to integrate noise management into the iterative systems capabilities/requirements definition; implementation and integration processes in a cost-effective manner. Systems engineers, human systems integration and system safety practitioners are invited to apply the processes and approaches described in this report to demonstrate the feasibility of alternative noise mitigation approaches during design. Noise mitigation will reduce the life-cycle costs, optimize communications, combat-effectiveness and maintain human effectiveness during weapons systems operations and maintenance. Effective noise control will also prevent irreplaceable degradation of human health and its social and economic impacts among military and supporting civilian personnel.

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APPENDIX A – DoD Platforms with High Noise Sources Considered in ROI Analysis

Table A1: Ships used in Diesel Analysis

Ship Class	Hull No.	Ship Service Life (years)	Total Number of Ships	Number of Diesels per Ship	Number of Exposed Crew per Ship[20]
Avenger	MCM	30	14	4	21
Cyclone	PC	15	10	4	7
Freedom/Independence	LCS	25	55	6	10
Harpers Ferry	LSD	40	4	4	105
San Antonio	LPD	40	12	4	90
Whidbey Island	LSD	40	8	4	103
Landing Craft Utility	LCU	25	34	2	4
America	LHA	50	1	1	265
Wasp	LHD	50	8	1	265
Tarwa	LHA	50	5	1	241
Blue Ridge	LCC	70	2	1	211
Austin	LPD	40	7	1	105
Sea Fighter	FSF	20	1	1	7
Spearhead	JHSV	20	10	4	10
Landing Craft, Air-Cushioned	LCAC	30	61	1	1
E.S. Land	AS	50	2	1	341
Kilauea	T-AE-32	40	1	1	41
Supply	T-AOE	40	4	1	47
Lewis & Clark	T-AKE	40	14	4	34
Henry J. Kaiser	T-AO	40	14	2	36
Invincible	T-AGM	40	1	4	5
Observation Island	T-AGM	40	1	1	25
Howard O. Lorenzen	T-AGM	40	1	4	15
Pathfinder	T-AGS	40	1	4	14
Waters	T-AGS	40	1	2	25
John McDonnel	T-AGS	33	1	2	8
Victorious	T-AGOS	40	4	4	11
Impeccable	T-AGOS	40	1	3	11
Bennet	T-AK	40	1	1	6
LTC John U.D. Page	T-AK	40	1	1	5
SSG Edward A. Carter Jr.	T-AK	40	1	1	6
Mohegan	T-AK	40	1	1	4
Sgt. Matej Kocak	T-AK	40	3	1	11
Sgt. 2nd Lt. John P. Bob	T-AK	40	5	2	12
1st Lt. Harry L. Martin	T-AK	40	1	1	10
Gunnery Sgt. Fred W. Stockham	T-AK	40	1	1	10
Lance Cpl. Roy M. Wheat	T-AK	40	1	1	10
TSGT John A. Chapman	T-AK	40	1	1	5
Lighter Aboard Ship	T-AK	40	2	1	8
Algol	T-AKR	40	8	1	18
Shughart	T-AKR	40	2	1	19
Gordon	T-AKR	40	2	3	19

[20] - Affected Crew Assumed to be 25% of Total Crew

Ship Class	Hull No.	Ship Service Life (years)	Total Number of Ships	Number of Diesels per Ship	Number of Exposed Crew per Ship
Bob Hope	T-AKR	40	7	4	19
Watson	T-AKR	40	8	1	19
Cape Island	T-AKR	40	1	1	2
Cape Intrepid	T-AKR	40	1	1	8
Cape T	T-AKR	40	3	1	7
GTS Admiral W.M. Callaghan	T-AKR	40	1	1	6
Cape Orlando	T-AKR	40	1	1	6
Cape-D	T-AKR	40	5	1	7
Cape Inscription	T-AKR	40	1	1	8
Class H	T-AKR	40	3	1	7
Cape Edmont	T-AKR	40	1	1	7
Cape Inscription	T-AKR	40	1	1	8
Cape Knox	T-AKR	40	1	1	6
Cape Kennedy	T-AKR	40	1	1	6
Cape V	T-AKR	40	2	1	6
Cape R	T-AKR	40	3	2	7
Cape W	T-AKR	40	2	1	7
Cape May	T-AKR	40	1	1	9
Cape Mohican	T-AKR	40	1	1	9
Government Owned Tanker	T-AOT	40	3	1	7
Wright	T-AVB	40	2	1	91
Powhatan	T-ATF	40	7	2	5
Safeguard Class	T-ARS	40	4	4	8
Mercy Class	T-AH	40	2	1	19
Zeus	T-ARC	40	1	2	22
Keystone	T-AC	40	7	1	20
VADM K.R. Wheeler	T-AG	40	1	1	7
Frank S. Besson Jr.	LSV	40	8	2	7
Stalwart	T-AGOS	40	1	1	9
Runnymede	LCU	40	35	2	3
Mgen. Nathanael Greene	LT	40	6	2	6
Totals			429		

Table A2 - Ships used in Gas Turbine Analysis

Ship Class	Hull No.	Ship Service Life (years)	Total Number of Ships	Number of Gas Turbines per Ship	Number of Exposed Crew per Ship[21]
Arleigh Burke	DDG	35	63	4	69
Freedom	LCS	25	28	2	10
Independence	LCS	25	27	2	10
Oliver Hazard Perry	FFG	30	26	2	54
Ticonderoga	CG	35	22	4	91
Wasp	LHD	50	1	2	265

[21] - Affected Crew Assumed to be 25% of Total Crew

Ship Class	Hull No.	Ship Service Life (years)	Total Number of Ships	Number of Gas Turbines per Ship	Number of Exposed Crew per Ship
America	LHA	50	1	2	265
Zummwalt	DDG-1000	40	2	2	37
Totals			170		

Table A3 - Craft used in Ships and High Speed Craft Analysis

Ship Class	Hull No.	Ship/Craft Service Life (years)	Total Number of Ships and Craft	Number of Exposed Crew per Ship/Craft[22]
LCAC	LCAC	30	61	5
Freedom/Independence	LCS	25	55	40
High Speed Vessel	HSV	20	4	35
MK V Special Operations Craft	MKVSOC	20	20	5
Fast Sea Frame	FSF	20	1	26
Spearhead	JHSV	20	10	41
Cyclone	PC	20	13	28
Spearhead	TSV-X1	20	1	30
Totals			165	

Table A4- Ships used for Aircraft Carrier Operations

Ship Class	Hull No.	Ship Service Life (years)	Total Number of Ships	Number of Exposed On Deck Crew per Ship	Number of Exposed Compartment Crew per Ship
Nimitz	CVN	50	10	400	1400
Enterprise	CVN-65	50	1	400	1400
Totals			11		

Table A5 - Vehicles Considered for Tracked Vehicle Analysis

Vehicle	Vehicle Service Life (years)	Total Number of Vehicles	Crew per Vehicle
Abrams Tank	50	8343	4
Bradley Tank	36	6724	3
Hercules – M88A2	50	698	3
M113	58	80000	2
Assault Amphibious Vehicle (AAV7A1)	50	1311	3
Assault Breacher Vehicle (ABV)	50	33	2
Totals		97,109	

[22] - Assumed Whole Crew is Affected by High Speed Ships and Craft Noise

Table A6 - Vehicles Considered for Wheeled Vehicle Analysis

Vehicle	Vehicle Service Life (years)	Total Number of Vehicles	Crew per Vehicle
FMTV	30	45429	2
HEMTT	30	13000	2
HMMWV	35	304000	2
M1070 - HET	25	2600	2
PLS	25	432	2
Stryker	25	4187	4
Light Armored Vehicle (LAV)	32	700	4
Marine Personnel Carrier (MPC)	30	630	2
Interim Fast Attack Vehicle (IFAV)	30	157	2
Internally Transportable Vehicle (ITV)	30	353	1
Logistics Vehicle System (LVS)	30	439	2
Mine Resistant Ambush Protected (MRAP)	30	2453	2
HMMWV	30	10716	2
Joint Light Tactical Vehicle (JLTV)	30	55000	2
M88A2 Heavy Equip Recovery Combat Utility Lift Evac Sys	30	66	3
Marine Personnel Carrier (MPC)	30	630	2
Totals		440,792	

Table A7- Airframes Considered in Cockpit Noise Analysis

Aircraft	Service Life (flight hours)	Total Number of Aircraft	Crew per Aircraft	Branch
B-1B Lancer	15200	66	4	Air Force
B-2 Spirit	40000	20	2	Air Force
F-15 Eagle	10000	249	1	Air Force
F-15E Strike Eagle	16000	219	2	Air Force
F-16 Fighting Falcon	8000	1018	1	Air Force
T-38 Talon	12500	459	2	Air Force
Apache Longbow	10000	722	2	Army
Black Hawk	10000	1471	2	Army
Chinook	10000	61	3	Army
Kiowa Warrior	10000	539	2	Army
EA-6B Prowler	10000	120	4	Navy
EA-18G Growler	10000	96	2	Navy
F-5N/F	10000	2246	1	Navy
F-16A/B Fighting Falcon	8000	924	2	Navy
F/A-18 Hornet	6000	409	1	Navy
S-3B Viking	11000	187	3	Navy
T-38 Talon	12500	10	2	Navy
T-45A Goshawk	14400	223	2	Navy
AV-88 Harrier II	11250	175	1	USMC
EA-6B Prowler	14000	20	4	USMC
CH-53E Super Stallion	10000	160	3	USMC
AH-1Z Super Cobra/Viper	10000	147	2	USMC
F/A - 18 Hornet	6000	72	2	USMC
Totals		9,613		

Table A8 - Cost, Space and Weight Matrix for Diesel Treatments

Treatment	**Cost**	**Space**	**Weight**
Enclosure	$15,000	Volume of Equip + 2ft	Approximately 15 lbs/sqft
Buy-Quiet	$100,000-500,000 (10% of Original)	Minimal impact	Approximately 10% increase due to damping
Cladding	$10/sqft	1/2 inch to 1 inch thick	2 lbs/sqft
Isolation Mounts	$300-$1000 per mount	4 to 6 inches height	32 to 200 lbs
High-Impedance Foundation	$2000 – for materials	2-4 inches tall	Approx. 2000 lbs
Passive Vibration Absorbers	$1,000	3ft long cantilever (4"x4" Cross-Section)	No more than 100 lbs
Active control - intake/exhaust	$15,000 for transducers and control system	Minimal impact	Minimal impact
Active control - vibration	$50,000 to $100k per system	6 inches tall 6 inches wide 1 ft across	200 lbs per actuator
Hydraulic Mounts	$500 to $2000	Slightly smaller than regular mounts	32 to 200 lbs
Distributed vibration absorbers	$10,000 to $20,000	4 inches tall	1000 lbs
Enclosure	$15,000	Volume of Equip + 2ft	Approximately 15 lbs/sqft

Table A9 - Cost, Space and Weight Matrix for Gas Turbine Treatments

Treatment	**Cost**	**Space**	**Weight**
Enclosure	$10,000 or less	1 inch over original vol.	3 lbs/sqft
Intake/exhaust silencer	Driven by CFD $5,000 + Duct modifications approx.. $5,000	Minimal impact	500 - 1000 lbs
CFD to reduce turbulence	$5,000 + GT modifications	Minimal impact	Minimal impact
Buy-Quiet	$200,000 to $1,000,000 (~10% premium)	Minimal impact	Approximately 10% increase due to damping
Isolation Mounts	$300-$1000 per mount	4 to 6 inches height	32 to 200 lbs
High-Impedance Foundation	$2000 - materials	2-4 inches tall	Approx. 2000 lbs
Active control - intake/exhaust	$15,000 for transducers and control system	Minimal impact	Minimal impact
Active control - vibration	$50,000 to $100k per system	6 in. tall 6 in. wide 1 ft across	200 lbs per actuator
Hydraulic Mounts	$500 to $2000	Slightly smaller than regular mounts	32 to 200 lbs
Distributed vibration absorbers	$10,000 to $20,000	4 inches tall	1000 lbs

Table A10 – Cost, Space and Weight Matrix for High Speed Craft Treatments

Treatment	Cost	Space	Weight
Lift Fan Design	$10,000	Minimal impact	No Impact
Hydro-acoustic design	$50,000	Minimal impact	Approx. 10% weight penalty
Buy-Quiet	10% cost premium on ship equipment	Minimal impact	Approx. 10% weight penalty
Corrugated panel	10% to 20% increase	2 inch footprint increase	Weight savings
Isolation Mounts	$300-$1000 per mount	4 to 6 inches height	32 to 200 lbs
Spray on Damping	$10,000-30,000	0.020" to 0.060" thick	0.23 lbs/ft^2 dry
High-Impedance Foundation	$2000 - materials	2-4 inches tall	Approx. 2000 lbs
Active control - vibration	$50,000 to $100k per system	6 inches tall 6 inches wide 1 ft across	200 lbs per actuator
Hydraulic Mounts	$500 to $2000	Slightly smaller than regular mounts	32 to 200 lbs
Distributed vibration absorbers	$10,000 to $20,000	4 inches tall	1000 lbs
Lightweight, High TL materials	$20-30/sqft	2" thick	3 lbs/sqft

Table A11 - Cost, Space Weight Matrix for Aircraft Carrier Operations

Treatment	Cost	Space	Weight
Partial Barrier	$200,000	10 ft long, 8 ft tall, 4 in thick	10,000 lbs
Improved TL - Structo Guard (1.31lbs/sqft)	$7/sqft	Less than 1/2 inch thick	1.3 lbs/sqft
Improved TL - Metal Joiner	$1.68/sqft	4" (2" thick 2" space)	2 lbs/sqft
Floating Deck	$15-30 per sqft	4" tall	8 lbs/sqft
Spray on Damping	$600K to $700K	0.020" to 0.060" thick	0.23 lbs/ft^2 dry

Table A12 - Cost, Space and Weight Matrix for Tracked Vehicle Noise Treatments

Treatment	Cost	Space	Weight
Re-design fan	$5,000 to $15,000	Minimal impact	Minimal impact
Clad - Limp Mass Layer	$4/sqft	2"	2 lbs/sqft
Buy Quiet	10% equipment premium	Minimal impact	10% weight penalty
Isolation Mounts	$300-$1000 per mount	4 to 6 inches height	32 to 200 lbs
Spray on Damping	$5,000 to $10,000	0.020" to 0.060" thick	0.23 lbs/ft^2 dry
Modular Cabin	$10 to $20k	3 to 4" all around on the interior	2 lbs/sqft
Active Noise Cancellation	$35 to 60k	Minimal impact	Minimal impact
Hybrid Electric Drive	$30 to 60k	1 ft^3	1000#
Distributed vibration absorbers	$10,000 to $20,000	4 inches tall	1000 lbs
Re-designed sprocket	$30 to 60k	2 inch diameter increase	Minimal impact

Table A13 - Cost, Space and Weight Matrix for Wheeled Vehicle Noise Treatments

Treatment	Cost	Space	Weight
Re-design fan	$5,000 CFD + Fan mods	Minimal impact	Minimal impact
Clad - Limp Mass Layer	$4/sqft	2"	2 lbs/sqft
Buy Quiet	10% equipment premium	Minimal impact	10% weight penalty
Isolation Mounts	$300-$1000 per mount	4 to 6 inches height	32 to 200 lbs
Spray on Damping	$2,000 to $7,000	0.020" to 0.060" thick	0.23 lbs/ft^2 dry
Modular Cabin	$10 to $20k	3 to 4" all around on the interior	2 lbs/sqft
Active Noise Cancellation	$35 to 60k	Minimal impact	Minimal impact
Hybrid Electric Drive	$30 to 60k	1 ft^3	1000 lbs
Distributed vibration absorbers	$10,000 to $20,000	4 inches tall	1000 lbs
Tire Tread	$200-500	Minimal impact	Minimal impact
Hydraulic Mounts	$500 to $2000	Slightly smaller than regular mounts	32 to 200 lbs

Table A14 - Cost, Space and Weight Matrix for Cockpit Interior Noise Treatments

Treatment	Cost	Space	Weight
Quiet cooling fans/defogger	$1,000	Minimal impact	Minimal impact
Clad - Limp Mass Layer	$4/sqft	2"	2 lbs/sqft
CFD	$10-20k	Minimal impact	Minimal impact
Isolation Mounts	$100-$500 per mount	4 to 6 inches height	15 to 100 lbs
Active Noise Cancellation	$35 to 60k	Minimal impact	Minimal impact
Cooling w/o fans	$2,000/system	3 in^3 volume	50 to 100 lbs

Table A15 - Cost, Space and Weight Matrix for Shipboard Equipment Noise Treatments

Treatment	**Cost**	**Space**	**Weight**
Buy Quiet	10% equipment premium	Minimal impact	10% weight penalty
Design Quiet	CFD approximately $5k	Lower flows - increase cross-sectional area (15% area increase)	Larger ducts (15% cross-section increase)
Quiet Hand Tools	10% - 20% equipment premium	Minimal impact	Minimal impact
Acoustic Insulation	$2-4/sqft	2"	2 to 8lbs/ft^3
Hydraulic Silencer	TBD	Minimal impact	30 lbs
Hydraulic Mounts	$500 to $2000	Slightly smaller than regular mounts	32 to 200 lbs
Isolation Mounts	$300-$1000 per mount	4 to 6 inches height	32 to 200 lbs
Spray on Damping	$70K to $100K	0.020" to 0.060" thick	0.23 lbs/ft^2 dry
Distributed vibration absorbers	$10,000 to $20,000	4 inches tall	1000 lbs
Buy Quiet	10% equipment premium	Minimal impact	10% weight penalty

APPENDIX B – Noise Control Engineering, Inc., Noise Control Treatment Examples

1. Aircraft carrier (CVN) accommodations noise control – NCE demonstrated by analysis and on-board testing on CVN 69 that a 5 -7 dB reduction in A-weighted can be achieved in accommodations below the flight deck; primary control is new developed spray-on damping; PEO Carriers is implementing these controls. This spray-on material has similar potential in wheeled and tracked vehicles. Weight impact only, no space impact. (ONR SBIR w/Mr. Yankaskas + 12 pack). Same type of material was shown to be effective based on testing on FSF-1 – SEAFIGHTER. Material is now commonly used on commercial vessels to control noise induced by bow thruster – a difficult source to treat. Also used on high speed ferries which have stringent weight restrictions. (references to be provided).
2. MTRV – NCE recently demonstrated by testing that fan induced noise is a controlling factor on this vehicle. In 1980, BBN (Ray Fischer was one of the engineers involved) designed a skewed fan that reduced noise on Ford tractors by 15 dB. This technology, improved by CFD, has been used by cars for many years. Weight and space impact – none. (ONR NIHL program with Mr. Yankaskas).
3. Using CFD, NCE and M&I demonstrated that noise within 10 ft of a 20,000 cfm fan can be reduced by 15 dB by appropriate design features (weight impact minimal; space impact none). In a similar vein, NCE was also the prime contractor in the design and use of a forward skewed propeller on a commercial research vessel that reduced the underwater signature by 20 dB. (Ref paper).
4. NCE is involved with a program to install active isolation mount on a diesel generator. Low frequency tones from this system can be reduced by 5 to 10 dB by the system under development. Weight and space impacts minimal.
5. NCE has designed two-stage isolation systems for use on research vessels that make their low frequency signature as low at that considered for many foreign combatants. Done for both government and commercial vessels. The additional measured vibration reduction provided by this type of system is 10 to 20 dB over that of a typical single stage system. Reference published papers. Significant weight and space impacts.
6. NCE and M&I designed replacement Gas Turbine silencer within original volume/space that provided 5-7dB greater noise reduction and low back pressure (using CFD) reference NATO paper. No space, no weight impact, improved fuel efficiency.
7. Provided design and got regulatory approval for novel stanchion isolator providing 5 to 7 dB of additional TL between engine room and accommodations above (Ref sulfur carrier). No weight, no space impacts.
8. Designed and measured performance of floating floors and resiliently attached surfaces on naval and commercial craft. Noise reduction on order of 12 -15 dB. Weigh and space impacts.
9. Demonstrated by testing that the potential for airborne flanking of isolation mounted systems could be significant and can reduce mid- to high-frequency effectiveness by 10 to 20 dB. (S)V ref). Minimal weight/space impact.
10. Designed and installed a high impedance foundation on a commercial vessel that reduced low frequency structureborne noise by 15 – 25 dB (not yet published) weight impact, minimal space impact.
11. Designed novel cradle, double mount suspension system for small naval vessel.

12. Measured on over 200 vessels the installed acoustic performance of hundreds of isolation-mounted systems – including diesel, pumps, compressor, etc; cladding installed on equipment and structures; damping treatment performance; and impact of insulation and high TL treatments.

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APPENDIX C – NSRCDPS Summary Slides

NSRCDPS SUMMARY SLIDES

APPENDIX D – Final Brief

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