Naval Research Advisory Committee

Report on

Jet Engine Noise Reduction

April 2009

This report is a product of the U.S. Naval Research Advisory Committee (NRAC) Panel on Jet Engine Noise Reduction. Statements, opinions, recommendations, and/or conclusions contained in this report are those of the NRAC Panel and do not necessarily represent the official position of the U.S. Navy, or the Department of Defense.

(U) Cover photo: Pacific Ocean on Feb. 5, 2009, a flight deck launching officer gives the final launch signal as an F/A-18E Super Hornet is catapulted from the flight deck aboard aircraft carrier USS John C. Stennis (CVN-74).

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Executive Summary

This study was initiated to investigate the jet engine noise problem that U.S. Navy and Marine Corps personnel experience on carriers and amphibious assault ships and propose actions to reduce noise in existing and next generation tactical jet aircraft engines.

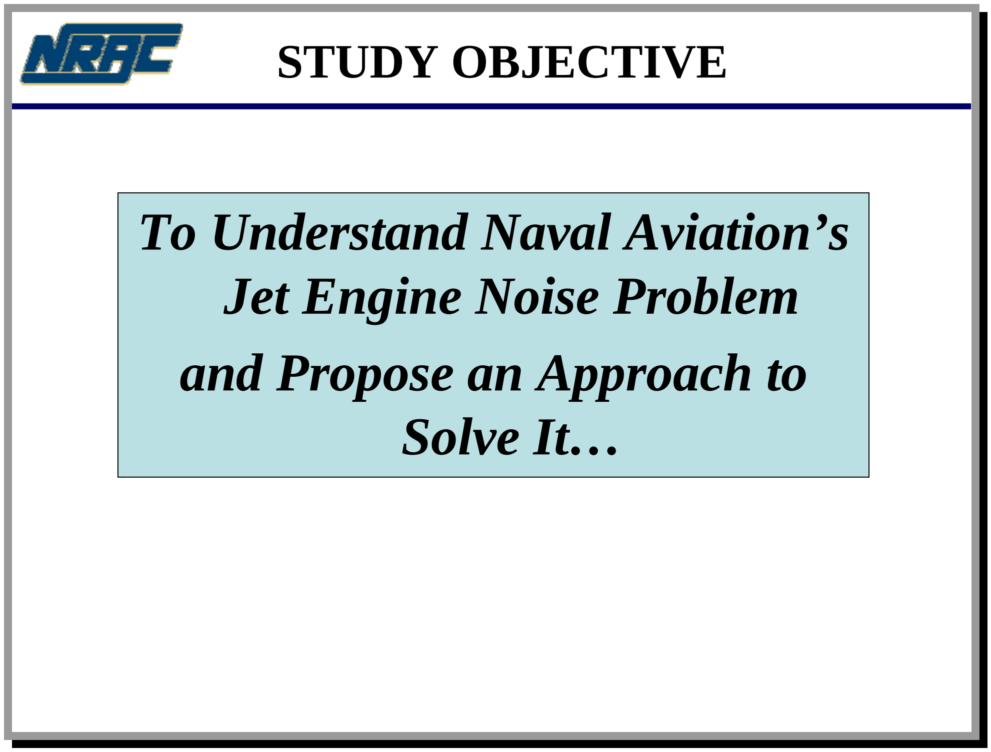
An overarching finding of this study is the paucity of engineering quality data. Standardized engine noise data to compare the engine noise among different aircraft or among various engines do not exist, and the available data do not correlate Sailor or Marine hearing loss with their respective noise exposure environments. Also, standards do not exist for acquiring engine noise data for tactical aircraft. Although the U.S. Department of Veterans Affairs (VA) is spending over $1 billion per year for hearing loss cases, there are no data to correlate hearing loss claims to flight deck noise exposure. Approximately 28% of the VA hearing loss claims are for the Department of the Navy, but data do not exist on the environment that caused the hearing loss.

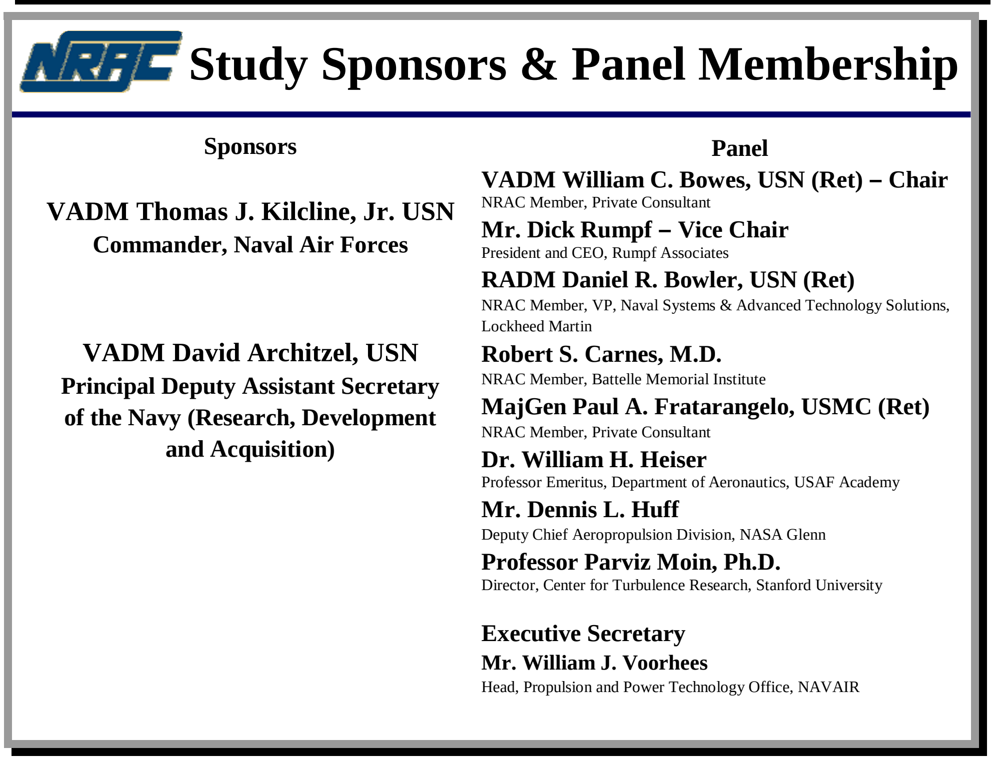
Flight deck noise is a serious health risk. The noise levels on Navy flight decks – up to 150+ dB – exceed the ability of currently available hearing protection to attenuate the noise to safe levels for the time that our personnel are exposed to high noise. On a positive note, significant progress is being made in the development of improved hearing protection equipment, such as the deep insert ear plugs which are undergoing an operational assessment onboard USS Dwight D. Eisenhower (CVN-69).

Although the noise levels of commercial jet airliners have been decreasing, the noise levels of tactical jet aircraft have not. In all likelihood, tactical jet noise levels have increased as the velocity and airflow from these engines have increased to produce added thrust. There are exceptions, such as the RA-5C which made its last deployment in 1979, which is reported to have had the highest noise level of any Navy tactical jet aircraft. The Navy has not routinely measured aircraft noise and does not maintain a data base of the noise levels of its aircraft. Only limited measurements of flight deck noise have been documented, and the Panel cannot determine if the noise levels on the flight deck are increasing. There has never been a requirement for a maximum noise level in military aircraft, and today the Department of Defense does not have adequate understanding of supersonic jet engine noise to establish a realistic maximum noise requirement.

There will be no single solution for addressing the jet engine noise problem, but for progress to be made a DOD champion for noise reduction needs to be identified. DOD must identify a senior person who will be a strong advocate to organize and focus the work for jet aircraft noise reduction. The solution will require reducing the source noise of supersonic jet engines which requires a long-term research program to understand the fundamental mechanics of flow-generated noise. These fundamental mechanics are not well understood today, but when fully understood they should provide insight into new techniques for reducing supersonic jet noise. It will also require continuing investment from the Office of

Naval Research (ONR) and OPNAV funding support for the Naval Air Systems Command (NAVAIR) hearing protection programs. It will require finding ways to limit the exposure of flight deck personnel to areas of high noise. It will require the development of better procedures to monitor the noise exposure and hearing loss of personnel. It will require further development of noise abatement procedures to minimize the noise footprint around Naval and Marine Air Stations. And finally, it will require more research into the physiological effects of the full spectrum of noise – including low frequency pressure levels – on humans.

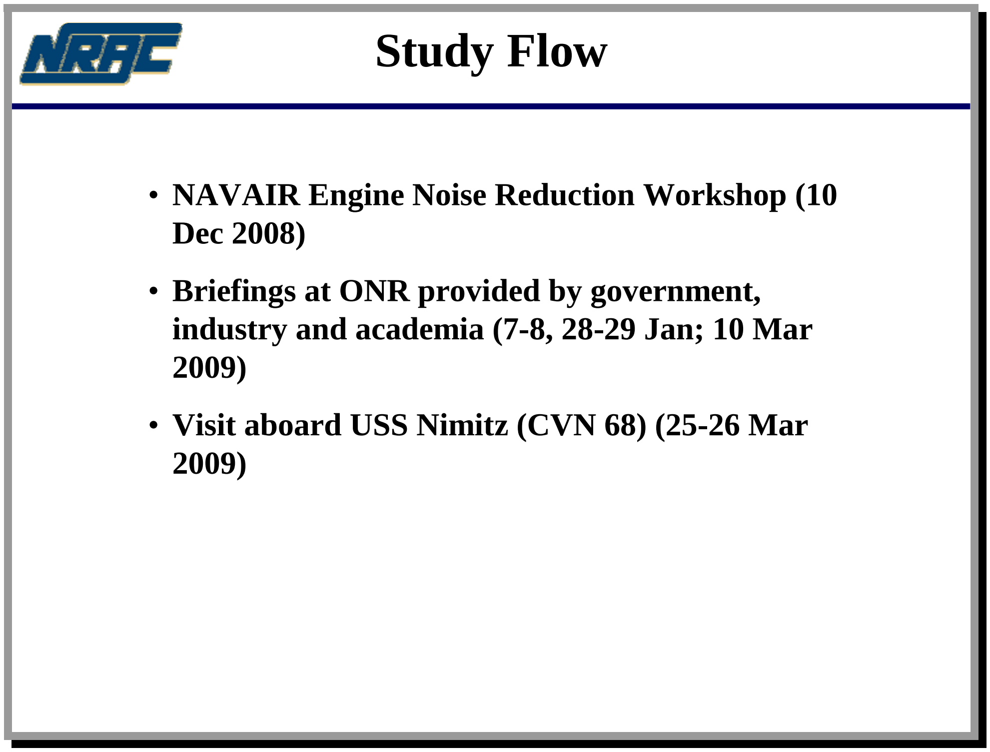




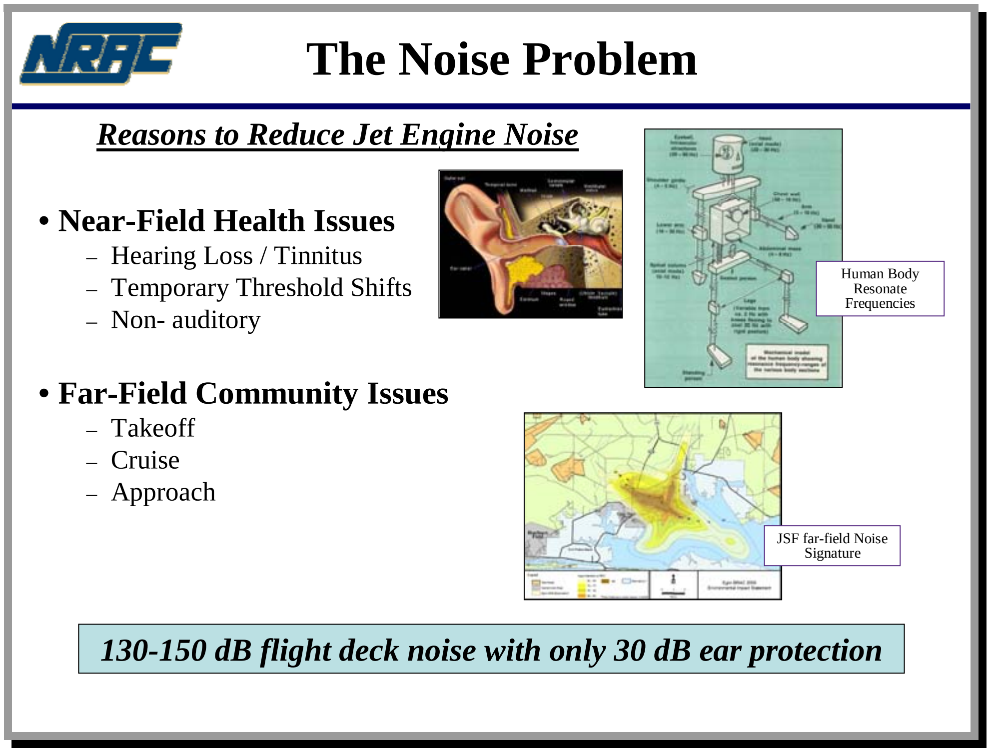
The broad goals of the jet engine noise study were to: obtain a broad understanding of the history of hearing conservation and practices around Navy and Marine jet aircraft; review the available and evolving technologies and procedures to mitigate jet noise; and recommend a way-ahead.

The sponsorship of the study is shared by the Commander, Naval Air Forces (VADM Kilcline) and the Principal Deputy Assistant Secretary of the Navy (Research, Development, Acquisition) (VADM Architzel).

The Naval Research Advisory Committee members (Bowes, Bowler, Carnes and Fratarangelo) have broad experiential knowledge of the study issues – and were augmented by pre-eminent experts in the science of jet noise (Heiser, Huff and Moin) plus former and current government officials well acquainted with high performance jet aircraft and the noise challenge (Rumpf and Voorhees).



Prior to drafting the Terms of Reference for the study in December 2008, the chairman and the executive secretary of the Panel attended the NAVAIR Noise Reduction Workshop at the Naval Air Station, Patuxent River, MD. During several meetings commencing in early January, the Panel received extensive briefings from the "jet noise reduction stakeholders" including experts from academia, government, and industry. Many previous reports (listed in Appendices B, C) were provided to the Panel and became part of the reviewed information. The Panel's capstone event was a working visit aboard the USS Nimitz (CVN-68) during airwing carrier qualifications in late March 2009.



The acoustic noise levels on the flight deck of aircraft carriers are among the highest levels in which people routinely work. The noise on US Navy flight decks is 20 to 30 dB greater than any currently deployed technology to protect the hearing of our Sailors and Marines. Noise levels approaching 150 dB are generated by today's tactical aircraft, and the maximum level of hearing protection only provides up to 30 dB of noise attenuation when worn properly, exposing one's ears to up to 120 dB of noise.

Hearing protection standards cannot be met with currently fielded hearing protection equipment with the noise levels of tactical jet aircraft – now or in the future.

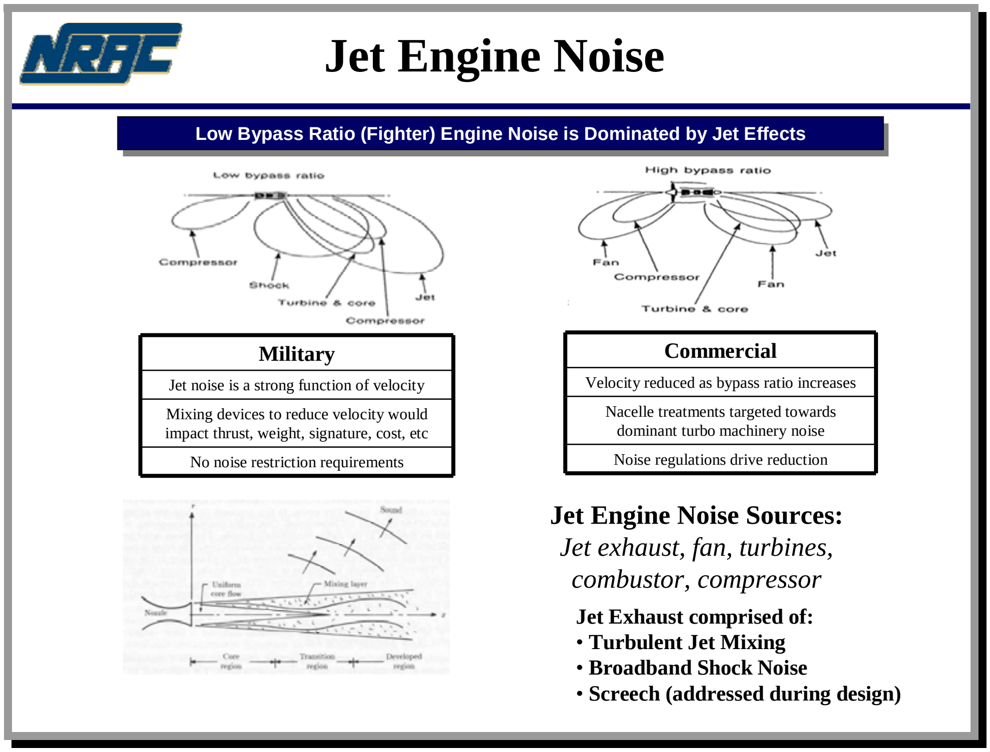
The Occupational Safety and Health Administration standards, OPNAVINST 5100.23F and DOD 6055.12 prescribe maximum exposure times to noise at various levels. For example, the 8 hour OPNAV time-weighted average exposure limit is 84 dB, and for every 4 dB above this limit (note that it's 4 dB for OPNAV and 3 dB for DOD) the time exposure should be cut in half. According to DOD Instruction 6055.12, at a noise level of 150 dB, the maximum daily exposure time with current technology hearing protection that is being worn correctly is only 8.9 seconds!

The noise problem can be broken into near-field and far-field. Near-field is the noise level in close proximity to the aircraft – normally considered to be the flight deck environment. Far-field noise (i.e. longer-range noise) is the noise experienced beyond the perimeter of an airfield. The far-field noise spectrum has, in the past, received the greatest attention.

Excessive noise can cause temporary or permanent hearing loss or tinnitus, a constant ringing in the ear. In addition, excessive exposure to noise can cause disturbances in mood, attention and cognitive function which would be an obvious safety hazard on the flight deck. While levels of VA compensation for hearing loss have been cited as a motivation for managing jet engine noise, the Panel found that the VA data lack sufficient noise source and hearing injury specificity to bound the problem. Accordingly, there is a compelling need to gather sufficiently “granular” data to allow useful comparisons between noise source levels and the human response to that noise.

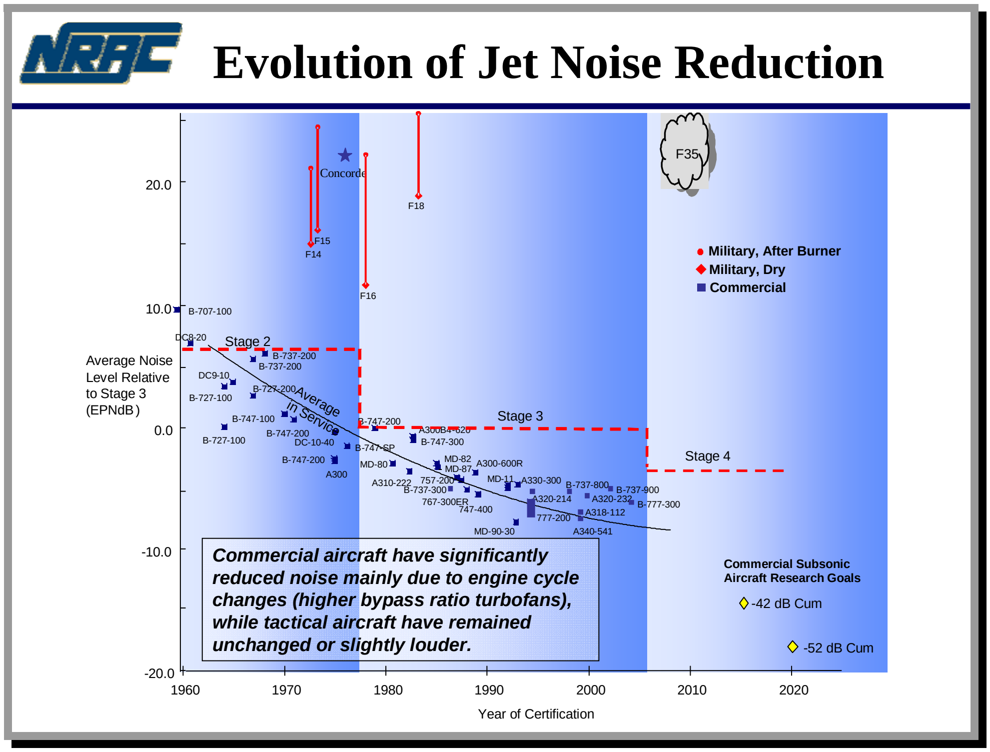
Far-field noise continues to receive interest around many of our airfields. The introduction of new aircraft types requires an environmental impact statement to address the expected noise footprint during take off, approach, landing, and cruise flight conditions around airfields.

Each part of the human body has a different resonant frequency, and received noise has both a frequency and pressure level component. Although humans hear primarily between 80 Hz to 6000 Hz, engine generated near-field acoustic pressure levels are non-linear and comprised of frequencies below 10 Hz to above 10,000 Hz. It must be noted that the impact on the human body when exposed to this wide spectrum of frequencies and pressure levels is not well understood.



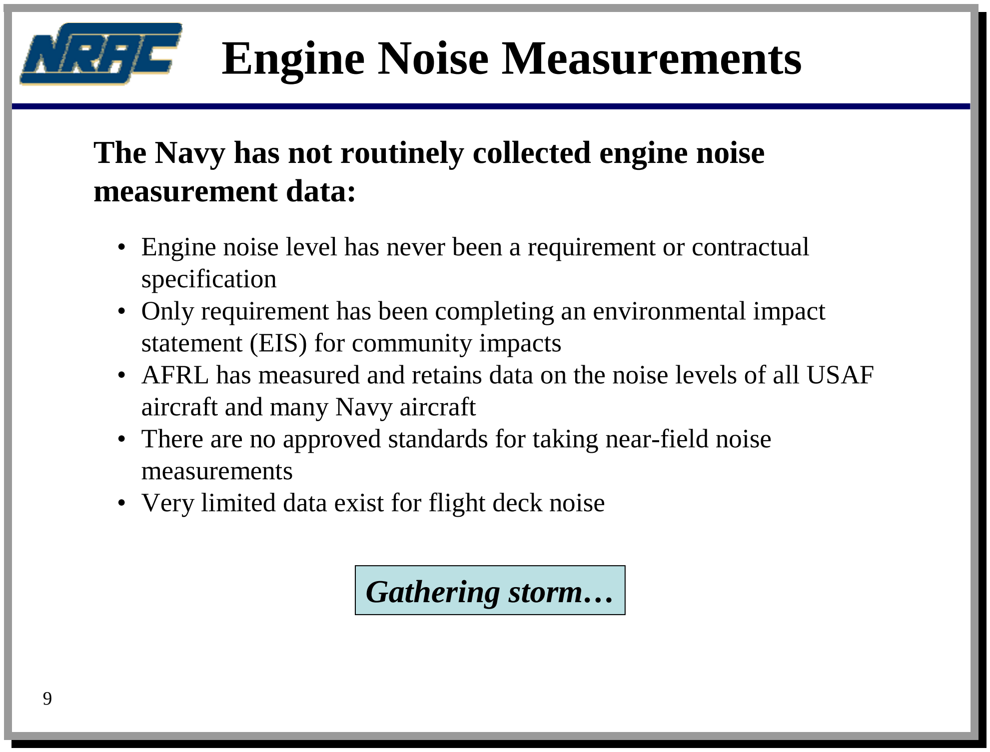
Current jet-powered aircraft typically use turbofan engines with bypass ratios that depend on the type of aircraft. The bypass ratio is a measure of the air mass flow through the bypass duct containing the fan, divided by the air mass flow through the core engine. Turbojets do not have a fan bypass, so for these engines all of the air passes through the core. Military engines for tactical aircraft have lower bypass ratios, which mean the exhaust jet velocities need to be high to produce thrust. The jet noise dominates over other noise sources for tactical aircraft and is a strong function of the jet exhaust velocity. The other noise sources include the fan, turbine, combustor, and compressor. Commercial engines for subsonic aircraft use larger diameter fans to provide most of the thrust, which allow the jet exhaust velocity to decrease. For higher bypass ratio engines, the noise source distribution is significantly different, where the fan noise can be higher than the jet noise. Higher bypass ratios reduce both noise and fuel consumption, which is fortunate for commercial jet engines and unfortunate for high thrust-to-weight military engines.

Jet noise results from highly turbulent air flow exhausting downstream of a nozzle. There are three primary sources: 1) mixing of the shear layers, 2) unsteady motion of shock waves from under/over-expanded jets (i.e., broadband shock noise), and, 3) screech, which is generated by violent combustion instabilities within the afterburner and is usually addressed in the design phase and is not a problem for production aircraft. Noise reduction strategies concentrate on ways to mix the jet with the free stream air flow to effectively slow its velocity after it exits the nozzle. Experiments confirm that the jet noise originates mostly from the end of the potential core – well downstream of the engine, with secondary contributions from the mixing shear layer and shockwaves within the jet. Techniques that reduce the velocity of the jet will reduce all of these noise sources.



Shortly after the introduction of the jet engine for commercial applications, it was clear that jet noise was going to be a major problem near airports. Turbojets have very high exhaust velocities that cause jet noise to dominate over any other noise source on the airplane. Prior to the jet age, residents near airports were used to propeller-driven aircraft sounds that were very different in terms of character and noise intensity. The jet introduced a step change in both sound amplitude and sound character described as a loud, low frequency rumble that is transmitted over long distances and rattles structures. In the late 1950s, research programs involving government organizations, industry and universities commenced an “all out” effort to improve fuel efficiency and reduce jet noise for commercial applications. This led to the development of turbofan engines that were both quieter and more energy efficient. Airport noise regulations were introduced and phased over time (i.e., Federal Aviation Regulations – Stage 2 through the current Stage 4). The regulations are now negotiated internationally through International Civil Aviation Organization (ICAO) based on the technical feasibility and economic viability of new aircraft and engine systems.

The graph shows the evolution of jet powered aircraft and the average certified noise levels over time referenced to the FAA/ICAO “Stage 3” or “Chapter 3” regulations. Several military aircraft and the supersonic Concorde are added for comparison purposes. Noise regulations for commercial aircraft have become more stringent and have followed the reduction of jet noise due to the increasing bypass ratio of turbofan engines. Jet noise levels have remained high for tactical military aircraft and trend higher as the jet velocities and temperatures increase to maximize thrust.



There has never been a requirement for engine noise in the design of engines for tactical jet aircraft, nor does the Navy measure or maintain an engine noise data base for tactical aircraft.

The Air Force does maintain the only known acoustic database which includes both tactical and transport aircraft, including many Navy aircraft. This database has flyover measurements and some near-field measurements from engine run-ups. There have not been Navy requirements for similar measurements other than providing an environmental impact statement for the surrounding community.

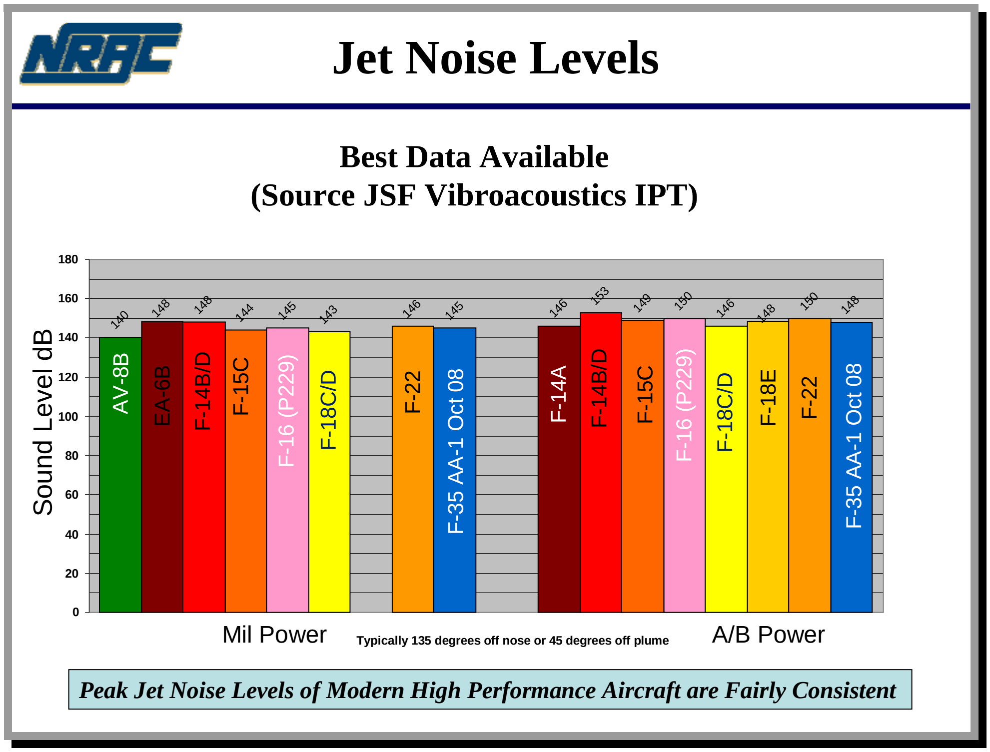
There are currently standards for outdoor far-field noise measurements established by the American Society for Testing and Materials and the American National Standards Institute which are applicable to commercial type aircraft. Standards must be established for acquiring near-field, far-field ground run-up, and flyover noise for tactical jet aircraft. Tactical jet aircraft can have higher noise directivity variations that existing far-field measurement standards for commercial aircraft do not address, and there are no standards for acquiring near-field aircraft noise data. Methods for quantifying near-field, high-amplitude sound levels for sources that vary in time and space will need to be defined. Emphasis should be given on developing methods to enable valid comparisons of noise levels among aircraft. The methods should include overall sound pressure level (SPL) un-weighted and A-weighted spectra.

Accurate comparisons of tactical aircraft noise require that the data be measured in a consistent manner – using established standards.

Although it is desirable to have a single number to measure noise, near-field noise measurements require more than a single dB metric to fully quantify the acoustic pressure levels generated by an engine or to compare one engine to another.

Overall sound pressure levels, i.e., noise, are normally measured in dB, and are a summation of the sound pressure levels across a spectrum of frequencies. Because the human ear is not equally sensitive to all the frequencies of sound across the spectrum, noise levels at maximum human sensitivity between 2 and 4 kHz are factored more heavily into sound descriptions using a process called frequency weighting. Therefore, the noise levels affecting humans are normally shown in dBA (A-weighted decibels), a frequency weighted average.

There were concerns that the Joint Strike Fighter (JSF) F-135 engine would be noisier than existing engines and that hearing protection might possibly be inadequate for speech intelligibility for flight deck personnel. Accordingly, in 2002 the JSF Program Office funded a study of the noise environment during carrier qualification operations aboard USS John F. Kennedy (CV-67) and USS Abraham Lincoln (CVN-72) and during AV-8B operations aboard USS Nassau (LHA-4). This was the first time since a 1971 study that measurements of the noise during flight deck operations were recorded. Note that many of the conclusions and recommendations of reports generated in 1971 and 2002 are similar to those made in this report. (See Appendix B).



Noise levels approaching 150 dB are generated by today's tactical aircraft. This chart represents a graphical representation of the peak jet noise levels (in dB) for several modern, high performance tactical jet aircraft. The noise numbers on the chart represent the maximum sound pressure levels (SPL) in dB measured for each aircraft in both Military and Afterburner (A/B) power settings along a 42 ft line parallel to the aircraft (representing the "foul line" on a modern aircraft carrier).

The data were collected by the Joint Strike Fighter Flight Systems IPT Vibroacoustics Team during the late 1990's and are documented in the reports which are referenced in Appendix C. Additional data from a more recent (Oct 2008) test of the F-35 AA-1 Aircraft was provided by the JSF Program office as part of a brief to the NRAC Panel, and additional data from a test of the F/A-18E aircraft in 2000 was provided by the F/A-18 Program Office and is documented in a report titled "Effect of Jet Blast Deflector on Exhaust Noise of F-18E" also listed in Appendix C.

While the above data are considered the "best" data available, there are some concerns as to their absolute validity and the ability to compare data from one aircraft to another, because of the lack of standards for collecting such data as described previously.

Tests were a "one-off" event, and no attempt to produce repeatable data was documented. The Panel raises this concern because there have been two instances in which later measurements were made of both the F-35 and the F/A-18E/F, and differences of 4 dB and 2 dB, respectively, were measured. This shows that a single test, while an indicator of noise levels, cannot be construed as the true level. This variation could be caused by (at least) several contributing factors such as: test set up and execution, microphone placement, type, calibration, weather conditions, engine variability, etc.

NASA Glenn has estimated that at best a good consistent engine test may be able to yield +/- 1 dB for 1/3 octave spectra and +/- 0.5 dB for overall sound pressure levels with today's techniques and technology. Flight test data will have larger error bars due to other influences such as aircraft position uncertainties and weather, which includes wind, humidity and temperature. Some, but not all, reports documented these variable conditions; however none of the data in the reports were corrected to a standard condition.

The selected test site can also induce variability, and not all aircraft were tested at the same location. This discussion is not meant to degrade the excellent work and effort done to collect the data which were provided to the NRAC, but it is a further justification for the Panel to believe that a set of standards for the measurement of near-field jet engine noise is required.

Jet Engine Noise Reduction

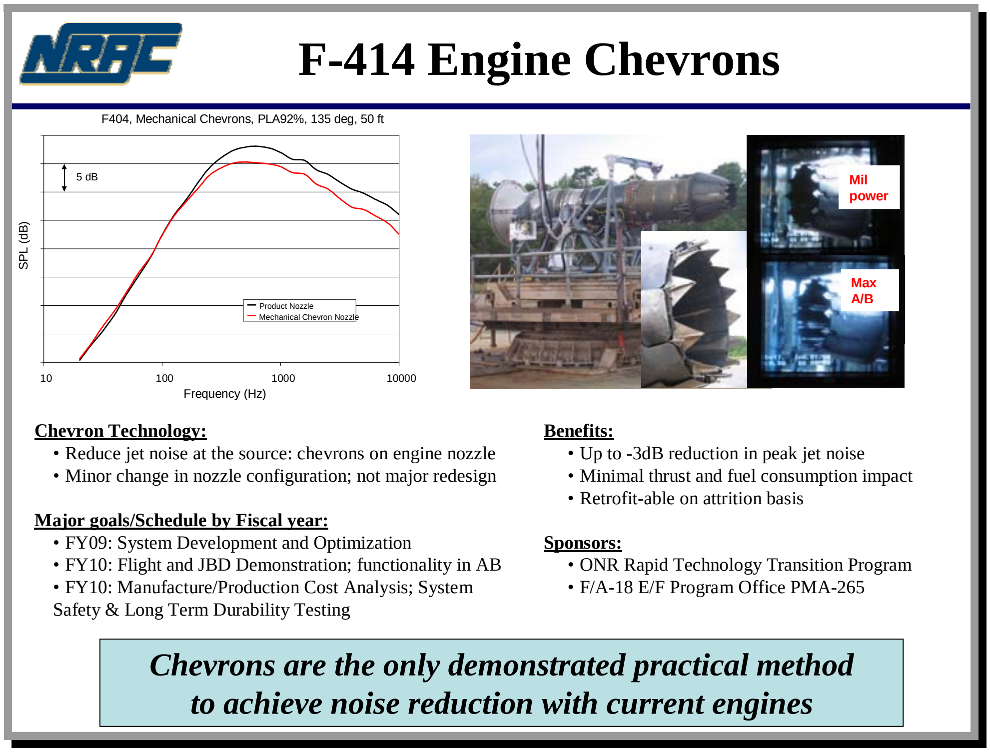
- **Source**
  - Reduce exhaust velocity
  - Enhance jet mixing (like chevrons)
  - Other methods show promise in laboratories, but need further development
- **Path**
  - Hearing protection
  - Acoustic enclosures/barriers
- **Operations**
  - Minimize exposure time
  - Noise abatement procedures

The ideal way to reduce noise is to address the problem at the source. Unfortunately, this is difficult to do for jet noise where the source is distributed over a region well downstream of the aircraft with very high sound amplitude. The flow is highly turbulent and is difficult to control due to the high velocities and temperatures in the jet. In addition, any method for reducing jet engine noise should not impact aircraft performance.

The optimal approach to reducing jet noise is to reduce the velocity of the jet. While this has worked for commercial engines, it is not a viable solution for tactical aircraft due to high performance mission requirements. The next best approach is to carefully mix the exhaust stream using devices such as chevrons. The key is to reduce the low frequency jet noise without significantly increasing the higher frequency noise that results from the mixing process. There have been other methods proposed for jet noise that show promise in laboratories, but need further development before they are ready for real world applications. These include: optimizing the areas for A8/A9 through variable geometry nozzles in order to reduce/eliminate broadband shock noise; fluidic/particulate injection; flexible filaments (i.e., wires attached to the nozzle or tail cone); offset nozzles to reduce the Mach wave emissions and control the sound directivity; high aspect ratio “mailslot” nozzles; inverted velocity profiles using a third flow stream; thermal shielding using a third flow stream; variable cycle engines; and active control of nozzle shear layer modes to promote mixing.

The propagation path is also an important factor for controlling sound. Hearing protection, acoustic enclosures or barriers, and increasing the distance from the source are examples of ways to reduce the noise levels for an observer. Reducing the exposure time is also important for minimizing potential hearing loss.

From a community noise perspective, changing the flight path and engine power during noise sensitive operations can be beneficial. Commercial aircraft use a procedure called "cutback" where the engines are throttled back just after takeoff. The aircraft then climbs at a slower rate until away from the airport community and then resumes a higher climb rate. This procedure is perhaps the most promising and practical for reducing noise near military air fields because it does not require changes to the aircraft – and can reduce jet noise by 10 dB or more. Eliminating afterburner during takeoff will also provide a significant noise reduction benefit. Afterburners increase the jet noise levels by 5 to 10 dB above military power.



Chevrons have proved to be an effective modification to reduce jet engine noise in commercial jet engines. Chevrons incorporated on the nozzle exhaust generate a vorticity which mixes the two exhaust streams (bypass and core airflow) faster, which reduces peak velocity and hence reduces generated noise. The chevrons also alter and weaken shock cell structure which reduces broad-band shock noise.

This chart shows a non production representative F/A-18 F-404 engine undergoing tests at Lakehurst with chevrons on the exhaust nozzle. These tests demonstrated that a 2.5 to 3 dB noise reduction was possible with minimal thrust loss. The chart shows an approximately 3 dB noise reduction at 92% power lever angle, i.e., slightly less than military power.

A Rapid Technology Transition (RTT) program was initiated by the F/A-18 program office, PMA-265 and ONR, with system development and optimization ongoing in 2009 and flight testing and Jet Blast Deflector (JBD) compatibility to occur in 2010. Funding for the retrofit of all F/A-18 F-414 engines will depend upon the success of the testing.

Adaptive Cycle Engine Technology

- **Joint VAATE (Versatile Affordable Advanced Turbine Engines) Program**
  - Includes application of variable cycle engine technology
  - Objective to achieve 10-fold improvement in turbine engine affordable capability
    - Reduction of thrust specific fuel consumption by 25%
- **ADVENT Project under VAATE**
  - Variable cycle engine development
  - Funded primarily by USAF with less USN investment
  - Potential to use the multiple exhaust streams of the variable cycle VAATE configurations to significantly reduce jet noise

VAATE/ADVENT should be augmented to address noise reduction

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A new engine design based upon adaptive cycle technologies is being funded under the Versatile Affordable Advanced Turbine Engines (VAATE) program. VAATE is a joint DOD, NASA, DOE, and industry effort focused on a ten-fold improvement in turbine engine affordable capability by the year 2017. This is following the model of the previously successful Integrated High Performance Turbine Engine Technology (IHPTET) program which had the objective of doubling thrust-to-weight of tactical jet engines.

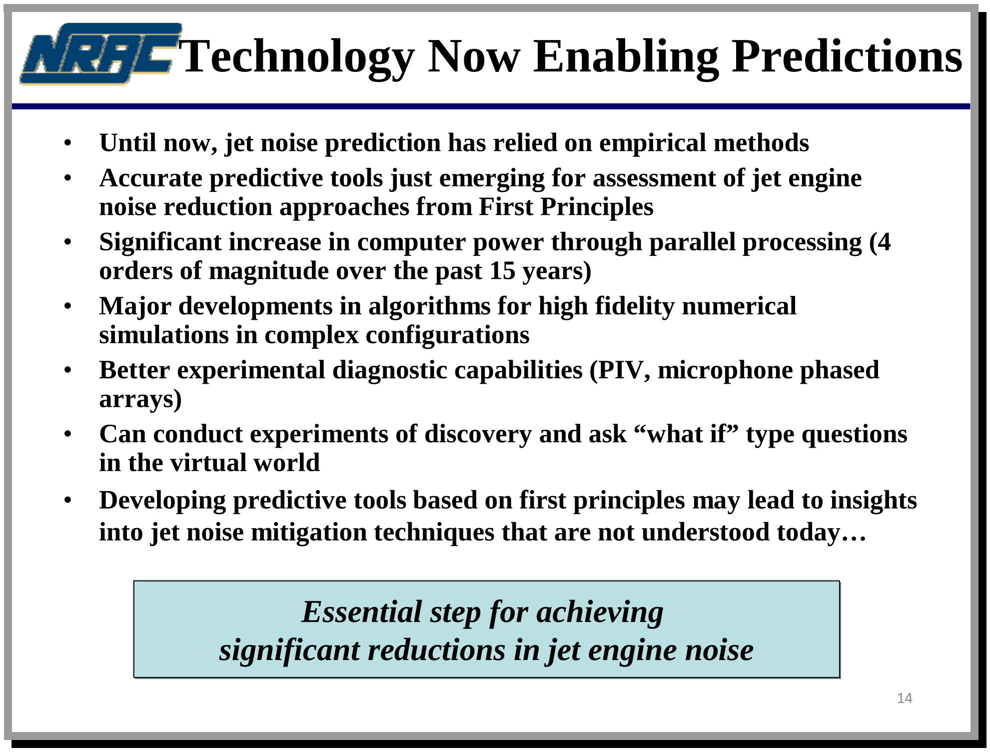
The VAATE program is funded primarily by the Air Force at approximately $175 million per year, and the Navy funds approximately $15 million per year.

The ADaptive Versatile ENgine Technology (ADVENT) is a project under VAATE investigating adaptive cycle technologies. Current turbine engines are optimized for either high performance, as in the case of a low bypass fighter engine, or fuel efficiency, as delivered by a high bypass transport engine.

The ADVENT project will combine these developments into a single propulsion system that can change internal configuration to operate in either an increased thrust mode for performance or an increased efficiency mode for lower fuel consumption.

Currently, the ADVENT project does not have noise reduction as part of its goal set. However, it is believed that adaptable cycle technologies – by utilizing the additional bypass stream in conjunction with other integration technologies – could result in a greater than 5 dB reduction in jet noise.

While Navy scientists are coordinating with the Air Force on ADVENT, Navy investment has been limited to $2 million for studies to assess potential mission benefits of an ADVENT type engine for an Unmanned Combat Air System (UCAS) “like” system. Investments are needed to address Navy specific engine size and cycle requirements for future systems such as a naval UCAS or F/A-XX and to assess the potential noise reduction and system performance benefits of this very promising technology.



The early development of methods for predicting jet noise was initiated in the 1950s. The main source of sound derived from these and subsequent predictions was shown to be the unsteady turbulent motion of gas in the jet. Turbulent flows consist of a broad range of eddy motions in space and time and exhibit a mix of chaotic and deterministic behavior. Although the governing equations describing fluid flows, the Navier Stokes equations, are based on Newton’s Laws and have been known for over a century, their analytical treatment has been formidable. Only limited insight and scaling rules (e.g., average sound level as a function of jet speed) have been obtained analytically. There is a fundamental lack of understanding of the mechanics of flow-generated noise, in part due to lack of data and the complexity of the underlying turbulence. Better fundamental understanding of the mechanics of noise sources may lead to insights into jet noise mitigation techniques that are not understood today.

In the 1970s, numerical simulation of the Navier Stokes equations for viscous flows emerged as an important tool in engineering analysis and design. However, when applied to turbulent flows, because of the limited computer power, only the statistical averages of flow were computed. Unfortunately, the governing equations for these statistical quantities are not self-contained and require phenomenological closure techniques often casting doubt on the accuracy of the resulting predictions.

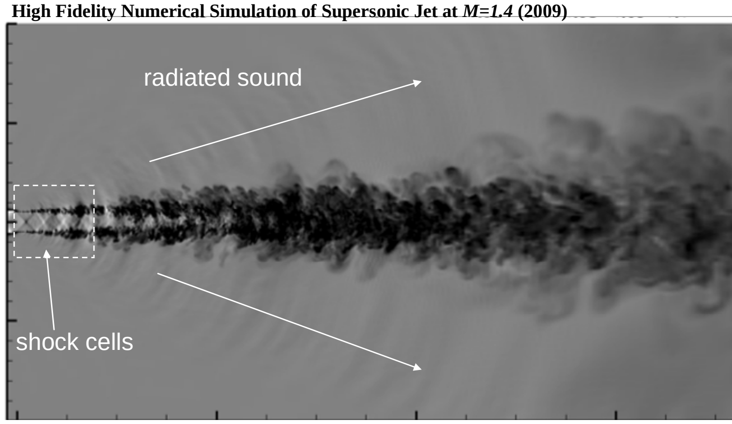
With the advent of parallel computing and its widespread use in the 1990s, the outlook for computational science and engineering has changed dramatically. Over the past fifteen years, computer power has increased by four orders of magnitude (see Appendix F). The hardware now exists for computation of turbulent flows in realistic conditions based on First Principles requiring limited or no ad hoc modeling. In addition to the dramatic increase in computer hardware, over the past decade major advances have been made in the development of numerical algorithms for high fidelity computation of turbulent flows in complex engineering systems. An example of potential applicability to turbulent fluid flow analysis is the use of verified and validated physics based algorithms running on teraflop/petaflop computers developed to examine components of nuclear weapons down to the atomic level by the Department of Energy (DOE) Laboratories. The instantaneous jet flow field and sound (shown on the next page) were recently computed at Stanford University with the support of NASA.

Alongside advances in computing tools, experimental diagnostic techniques such as Particle Image Velocimetry (PIV) and microphone phased arrays have significantly increased capabilities, allowing for advanced validation of the numerical predictive technologies. These developments in computational and measurement tools provide for instantaneous access to three dimensional and time dependent flow field data and the associated sound. These data can then be thoroughly studied to understand the mechanics of noise generation in supersonic exhaust jets. This increased understanding could lead to strategies for noise reduction, which can be evaluated using the same tools in a cost effective manner. The high fidelity computational technology can also be used to answer “what if” type questions for noise mitigation in a virtual setting, and for development of reduced order models for practical engineering design.

In summary, the development and application of high fidelity prediction tools is critical to the understanding of jet noise source mechanisms and the ability to evaluate noise reduction concepts. This is deemed to be an essential step to reducing jet engine noise beyond 3-5 dB.

Successful Jet Exhaust Simulation

High Fidelity Numerical Simulation of Supersonic Jet at *M=1.4* (2009)



Breakthrough calculations of flow field and sound have been applied for prediction of noise with some success

Very promising start in predicting Jet Noise

This breakthrough calculation, in 2009, of a supersonic jet with an exhaust velocity of 1.4 Mach was the first to include the flow inside the nozzle. The code is capable of predicting the effects of modifications to the nozzle geometry such as chevrons. The chart shows the density field of a cold supersonic jet which highlights the turbulence downstream, the radiated sound, and the shock cells near the nozzle exit.

Jet Noise Prediction Olympics

- **Establish a "Jet Noise Prediction Olympics" to establish benchmarks and state-of-the-art prediction methods**
  - Similar to turbulence workshops at Stanford and the NASA Computational Aero-Acoustics series
  - Identify specific objectives for predicting flow field and acoustic spectra
  - Participants compute the benchmark cases without having seen corresponding experimental data (blind test)
- **Form a small government planning group to define requirements and conduct open competition**
  - 3-4 year effort starting with simple nozzle geometries and working toward cases relevant for tactical jet noise
  - Fund participants for these time consuming, difficult problems
- **Some experimental data available from NASA**
  - Need additional data for tactical jets
  - Some model scale nozzle hardware already exists

A "Jet Noise Prediction Olympics" is proposed to establish benchmark problems that are relevant for tactical jet aircraft noise prediction. This would be an opportunity to define the current state-of-the-art for jet noise prediction methods and assist in determining where to make investments and what it will take to accurately predict jet engine noise. There have been previous benchmark prediction workshops that can be used as a guide. They include a boundary layer/transition workshop at Stanford and the series of four Computational Aeroacoustics (CAA) Workshops on benchmark problems. The latter has been used to compare numerical predictions with analytical (i.e. exact) solutions and experimental data. There are currently no benchmark problems that have direct application to tactical jet noise applications.

Experience from previous workshops shows that participants need to be funded for difficult benchmark problems that require considerable time and effort. The Panel proposes that a small government planning group be formed to define the prediction and experimental requirements (e.g., nozzle geometries, flow field prediction/measurements, acoustic spectra). An open competition including academia, DOE laboratories and industry should be conducted to identify participants. Multiple benchmark problems should be identified starting with simple round nozzles and working toward cases relevant for tactical jet noise with complex geometries and flow fields. Cases should also be included that evaluate the ability to predict benefits of noise reduction technologies. An important feature of this exercise will be that the participants will be required to predict benchmark cases using their codes without having access to the corresponding experimental data (blind tests). NASA already has some experimental data that are relevant for the tactical jet noise problem. There are existing model scale nozzles simulating F-18 configurations. Flow field measurements have been obtained in addition to the far-field acoustics. It may be possible to add a few test cases that would provide a complete set of data needed for the benchmark cases. These should include under/over-expanded jets, twin jets, scalability, and jet blast deflector simulations with near-field flow measurements that can be correlated with the far-field noise. Some full-scale data will be needed to assess scalability of flow field and acoustic measurements.

Any resulting computational tools that are developed should be useable independently by the propulsion technical community.

Fundamental Research Investment

- **Large Noise Reduction (>3-5 db) will require a long term basic research program which includes:**
  - Imaging techniques – e.g., PIV (Particle Image Velocimetry), coherent phased arrays – to identify and quantify distributed sources of sound in well understood supersonic hot jets
  - High fidelity numerical simulations
  - Noise reduction strategies
  - Validation experiments designed to stress the models including uncertainty levels in both flow and noise
  - Development of improved computational design tools

A long term research program which includes fundamental studies, leveraging modern diagnostic and computational tools, is essential to achieve maximum noise reduction. Navy's investment into a pertinent fundamental research program should include the following five areas managed under a unified and coordinated effort:

1. Imaging measurement techniques to identify *distributed* sources of sound in supersonic hot jets in realistic conditions. Typically these measurements have been made in *localized* regions. Improved understanding of the correlations between unsteady flow events and the radiated noise should be stressed. The experiments probably should be carried out in government facilities in order to achieve realistic conditions.

2. High fidelity numerical simulations. Recently developed high fidelity computational tools should be used to compute turbulent flow in hot supersonic jet at as near as possible to realistic conditions allowed by the most advanced computer resources available. The resulting 3D unsteady database should be probed – potentially by several independent investigators – to study the mechanics of sources of noise. This simulation can also be used as benchmark for validation of predictive methods, which should also include the effects of forward flight.

3. Noise reduction strategies. An important part of the program would be noise mitigation strategies incorporating the understanding gained. This effort should clearly involve engineering experts from industry.

4. Validation experiments designed to stress the models including uncertainty levels in both flow and noise.

5. Development of improved computational design tools. Computational tools used in design must have rapid turnaround times. Validation data and insights obtained from the aforementioned fundamental studies should also be used to develop more accurate and improved computational design tools.

Noise Reduction in Future Aircraft

- **Airframe Primes should have total system responsibility**
  - Desired aircraft performance, signature control and noise levels are only possible through system integration and total system optimization, not individual component optimization
- **Noise must become a KPP**
  - The aircraft system contract must have realistic Key Performance Parameters (KPPs) - including a noise KPP
- **Initiate design competition for a notional tactical aircraft**
  - To help in defining the design space for achieving noise reduction

The propulsion community (i.e., government, industry and academia) agree that in order to achieve significant reductions in tactical jet engine noise, a path similar to that followed by commercial aviation must be followed. This involves the airframe prime contractor having the responsibility for the noise signature of the airplane. Today the engine is developed and procured as government furnished equipment (GFE) to the airframe prime contractor. As a result the airframe prime contractor does not have total system design responsibility. How the engine is integrated into the airframe can have a big impact on the total noise signature of the aircraft.

The DOD strategy has been to separately specify and contract for the performance and signature requirements of the aircraft and its propulsion system. This acquisition strategy leaves no one company responsible for successfully meeting the full system of systems requirements. In older aircraft designs, very little attention was required or paid to signatures, e.g., radar cross section, infrared, visual, acoustic. With the advent of stealth awareness and its benefits to survivability, aircraft designs had to evolve to feature an integrated aero-structural and propulsion system of systems.

Unfortunately, acoustic signatures have not been critical performance parameters in military tactical aircraft system development programs. For future aircraft programs, concern should be paid to acoustic signature effects on the hearing of our Sailors and Marines as well as the environmental affects on the local air base communities. The Navy must rethink how to incorporate lower noise signatures into a full system parameter requirement. This new contracting strategy will allow the prime contractor, in concert with the propulsion system contractor, to initially tradeoff the contributions of the various signature elements with the normal system performance elements (e.g., speed, range, and maneuver) and perform a system level optimization taking all elements into consideration. Without integrating all performance and signatures together, there can not be a system of systems optimization. In order to make significant reductions in aircraft noise, aircraft system contracts need to specify a noise requirement. This can be done by establishing noise as a Key Performance Parameter (KPP) and incentivizing the prime contractor and the propulsion system subcontractor to develop designs which meet this KPP.

In preparation for the next generation tactical aircraft, the Panel believes there should be a KPP for noise. The Navy should initiate a competitive design study to identify the technologies critical to minimizing mid-field and far-field noise for the next generation, high performance tactical aircraft. This design study should include the definition of the multi-dimensional vehicle design space available and the tradeoff factors between vehicle design characteristics and vehicle performance. In addition, the study should indentify the critical technologies, vehicle configuration and integration features to reduce jet noise and the realistic bounds of vehicle KPPs, including key mission performance and noise. Such a competitive design should be one of the steps in order to define a noise KPP for the next generation tactical aircraft.

Community Noise

Differing Approaches to the Jet Noise Reduction Problem

- **Commercial aircraft noise reduction**
  - 1960s: Commercial Airport Authorities institute noise limits
  - 1971: FAA established noise limits (FAR Part 36)
  - Commercial airports establish Noise Abatement Programs
  - Aircraft manufactures respond with quieter aircraft
  - Air Traffic Control makes procedural changes to minimize noise
  - Noise monitors fielded to measure noise impact on community
  - Notification to residential property owners for noise disclosure prior to sale
- **Military aircraft noise reduction**
  - Noise limits waived for military aircraft
  - No requirement for military aircraft/engine manufactures to reduce noise
  - EIS/AICUZ document noise contours
  - Noise abatement procedures adopted
  - Local governments giving voice to citizen noise complaints
  - Anticipate push by military airport communities for restrictions similar to those enjoyed by commercial airport communities

Community noise is the driving issue…

While aircraft noise has always been a concern, commercial airports did not begin addressing aircraft noise in earnest, until the introduction of the turbojet engine powered Boeing 707 beginning in 1958. Following a series of lawsuits in the United States and public outcry in Europe, the major commercial aviation authorities instituted noise limits for airports and the Federal Aviation Administration (FAA) implemented its own rules in Federal Aviation Regulations (FAR) Part 36. FAR Part 36 established limits on the maximum noise that could be produced at an airport at three points – two on either end of the runway beneath takeoff and landing paths, and one lateral to the runways at points of nominal take-off rotation. It also established a sliding scale for allowable noise versus takeoff weight for large aircraft.

Although military aircraft are exempt from FAR Part 36 and all other noise limitations, military aircraft noise has come under scrutiny – beginning in the mid-1990s – with the implementation of Base Realignment and Closure Commission (BRAC) recommendations and subsequent requirements for Environmental Impact Assessments and Statements. In short order, "Sound of Freedom" supporters were challenged by angry citizens concerned about military aircraft noise that was impacting the quality of their lives in their homes and work places beyond military airfield boundaries.

The development of high-bypass turbofans for commercial aircraft engines was prompted by greater thrust and fuel efficiency requirement, but also resulted in a significant reduction in noise levels around commercial airports. The smaller size of military fighter and attack aircraft, as well as the requirement for afterburner capability, denies military aircraft manufactures the same noise reduction benefit.

Military planners have relied primarily on locally instituted noise abatement procedures, i.e., flight patterns and power settings, to reduce noise signatures. These procedures, however, need further study and probably will be inadequate to compensate for the higher noise footprints associated with major aircraft realignments. An example is the decision to conduct joint-service F-35 training at Eglin AFB, as well as the introduction of new military aircraft at other military airfields.

It is likely that communities around military bases will seek – through legislative measures – noise limitations and methods to enforce them that are similar to those implemented around commercial airports. As a result DOD could be forced to institute a jet engine noise reduction program establishing time-phased realistic noise limits based on available technology, especially as the noise of commercial aircraft rapidly diminishes.

Physiological Impact of Noise

- **Known: humans lose their hearing based on time and intensity of sound between 500 and 6000 Hz**
- **Known: high variability in hearing loss due to genetics, smoking and non-occupational noise (e.g. iPods)**
- **Known: hearing provides information about azimuth and distance to noise source**
- **Not well known:**
    - Impact on humans from low-frequency sound (<500Hz)
    - Impact of sustained exposure to noise on cognition
    - Impact of hearing protection on noise direction (azimuth) sense/situational awareness

The useful range of hearing for humans is between 80 and 6000 Hz, with a particular speech-sensitivity in the middle of this range. Humans have a permanent loss of hearing when the cochlear hair cells of the inner ear die. These cells represent the final transduction mechanism that converts sound energy to nerve impulses to the brain. Noise levels above 85 dBA, that are transferred to the cochlear apparatus, either by air or bone conduction, begin to cause permanent loss of hair cells after continuous exposure for over eight hours. This death is the product of exposure over time, so that the longer an individual is exposed, and the higher the noise level, the greater the loss of cochlear cells. High noise levels produce what is known as "oxidative stress," a process whereby the cell's metabolic machinery produces high levels of free radicals. These free-radicals, in high enough concentrations, precipitate a phenomenon known as programmed cell death, or "apoptosis."

The relationship between noise levels and hearing loss and the mechanism of cell-death is well established and understood. While the process is the same, individuals vary in their sensitivity. Some people are more sensitive than others and will lose hearing at lower levels of noise exposure. This is common in all biological responses to both the environment and disease.

We know much less about other factors that impact on hearing loss. These are considered "confounding" factors, because they limit the ability to measure occupational noise – making it impossible for a direct, one-to-one association between noise and hearing loss. Examples of confounding factors include smoking – which increases cellular oxidative stress – and other non-occupational exposures, such as iPod use or exposure to pollutants. Some of these factors can be managed by good records of occupational exposure, preenlistment audiograms, etc, and some cannot be completely quantified. In the aggregate, the natural variability and the confounding factors compel us to take an "individualized" approach to hearing risk. We have to be able to measure, individually, hearing noise exposure, and the human response to that exposure.

Hearing provides humans with other information of critical importance to the aviation environment. We perceive, and react, to sound based on not only its presence, but also on its location and distance. Through mechanisms not fully understood, humans process sound in both azimuth and distance. One can assume that phenomena such as Doppler shift and other physical features of sound play a role in our ability to determine the direction and distance to a sound source. "Situational awareness" gained from perceived noise is of critical importance to flight-deck personnel – who must move in close proximity to loud, dangerous objects moving in all quadrants. It is also important in the design of hearing protection devices that can confound or obliterate these cues. This is a critical uncertainty in the Panel's findings because it appears that advanced development of new hearing protection devices do not test or measure alternations in perceived azimuth and distance to a sound source.

Finally, there are areas of human response to noise for which there is a compelling need for more research and understanding. The impact of high-intensity, low-frequency sound (i.e., below 500 Hz), is not well understood. Studies in the 1960s focused entirely on subjective responses to low-frequency sound in a non-pure-tone environment, and of necessity, did not consider harmonic resonance features, or long-term effects on any organ. Likewise, the impact of long-term noise exposure on cognition – the ability to process, objective data – is not documented. Anecdotal data, or limited research data, suggest that long-term, unrelieved noise, can impact cognition. How much of this is due to associated sleep deprivation or alteration of mood is not known.

Inadequate Measurement of Risk

- **Current pure tone audiometry is dependent on the test subject's cooperation**
- **Inability to correlate aircraft noise exposure to hearing loss**
  - Confounding factors—smoking, recreational noise, other occupational noise (i.e. berthing spaces on CVNs)
- **Hearing Conservation (HC) Program reports do not document increase in hearing loss in aviation classes of ships**
  - No documentation breaking out personnel exposed to flight deck noise
- **CNA study of 2005**
  - Hearing loss highest on surface ships – attributed to less awareness of high noise environment and less discipline in wearing hearing protection
  - No data on NEC or job position with respect to noise exposure
- **Measurement of sound by location and duration of exposure is not recorded by HC Program**
  - No "personal dosimeter" for noise exposure

Pure tone audiometry has been the means of measuring threshold levels of hearing for over 50 years. It is a test conducted in sound-deadened room where the subject is given single-frequency tones in step-wise amplitudes until he/she records hearing the sound by pressing a button. The natural hearing frequencies are incrementally tested, in each ear, and the subsequent "audiogram" represents the hearing profile for that individual.

A significant threshold shift (STS) is an occupational health feature that reports a frequency-averaged loss of 10dB of hearing from a previous study. This is considered significant if repeated measures rule out a temporary shift due to a brief exposure to high noise. STS are cumulative and are monitored by the Navy Hearing Conservation Program (HCP). Most Navy data that detail hearing risk or hearing loss are reported in rates of STS shift by some dependent variable – location, ship class, rating, etc.

In spite of its long history of usage, the 'Pure Tone Audiogram" is not an ideal tool for measuring hearing loss. The most notable problem is its intra-subject variability. The test subject must cooperate with the study in order for it to be useful. Any condition that reduces the level of absolute cooperation confounds the data. Malingering or deliberately poor performance to win disability compensation are just the obvious causes of a poor test result. Also fatigue, failure to understand the nature of the test, and temporary hearing shifts can also skew the results.

There are modern technologies that side-step the subject's cooperation and are entirely objective. Navy medical researchers suggest that Tympanography or OtoAcoustic Emissions studies both offer 21st Century applications to the hearing conservation process. Both deserve some consideration if we are to properly match individual hearing loss to noise risks.

Matching hearing loss to individual exposure to noise has been an indirect goal of our study. VA levels of monetary compensation for service-connected hearing loss are often a source of motivation to study the problem of occupational noise exposure. But, the VA compensation system is an administrative process, not an epidemiological process. Veterans who can document a service-connected loss of hearing will receive a disability award. A shift from enlistment audiogram to discharge audiogram determines the level of disability awarded by the VA. It says nothing about the source of the noise, and therefore fails to address the cause of the hearing loss.

The Navy's Hearing Conservation (HC) Program and a recent Center for Naval Analysis study document varying levels of hearing loss (as measured by incidence of STS) by ship class and/or enlisted rating. Both the HC Program consultants and the authors of a 2005 CNA study conclude that risk stratification and injury mitigation will not occur until we can identify noise exposure at a much more "granular level." The CNA study suggests organizing hearing data by Navy Enlisted Classification (NEC), however that still may be insufficient. Two Aviation Boatswain's Mates (ABH), may have the same NEC, but be positioned in entirely different noise envelopes, based on their daily assignments.

This leads us to the conclusion that individualized sound-level dosimetry is needed to fully match hearing profiles to occupational assignment and noise source engineering. Because of the complexity of such a system, the device might be limited to epidemiological studies of the noise environment or as an R&D tool. Approximations of noise environments will not match up with the flexible use of flight deck personnel. Therefore, without some kind of personal dosimetry, there is a significant risk of over or under estimating individual risk.

Hearing loss is not exclusively an "aviation-class" health problem. One may find that Sailors properly equipped with the current hearing protection aboard aviation-class ships fare better than Sailors assigned to non aviation-class surface ships. Clearly, the current Hearing Conservation Program has made a significant contribution to hearing protection for flight deck personnel. Both the CNA and HC Program data suggest that Sailors not enrolled in the formal HC Program are probably at greater risk.

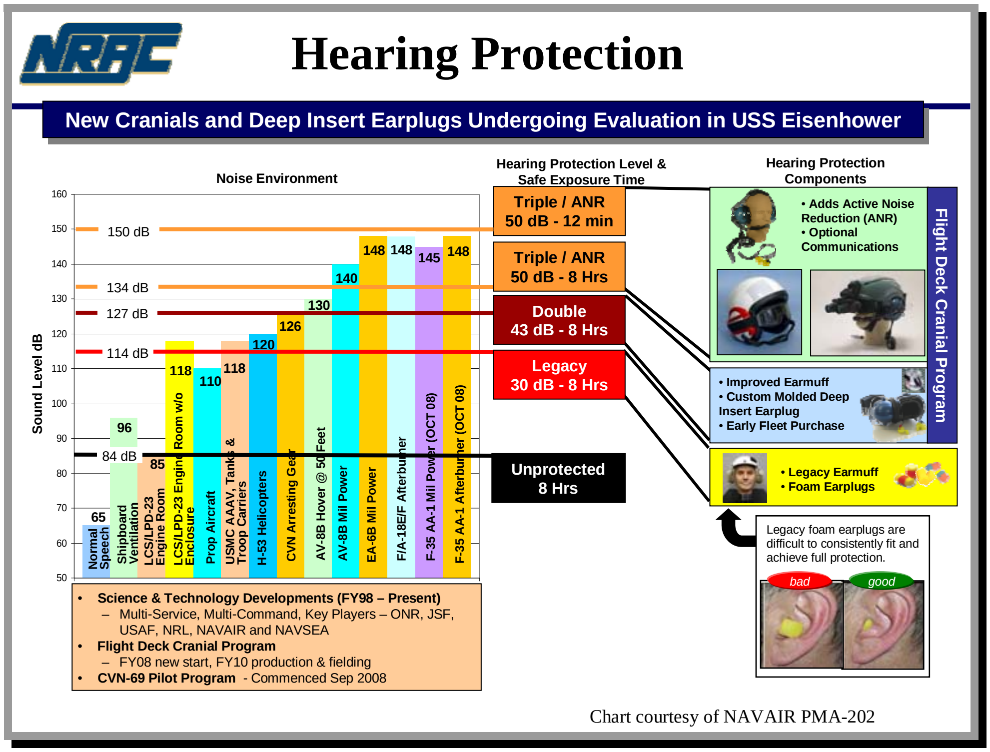


Chart courtesy of NAVAIR PMA-202

The interest in fielding better hearing protection has existed for at least the past 20 years. Recently, the Navy in cooperation with the other services, developed significantly improved hearing protection equipment which is now undergoing an initial operational assessment aboard USS Eisenhower (CVN-69).

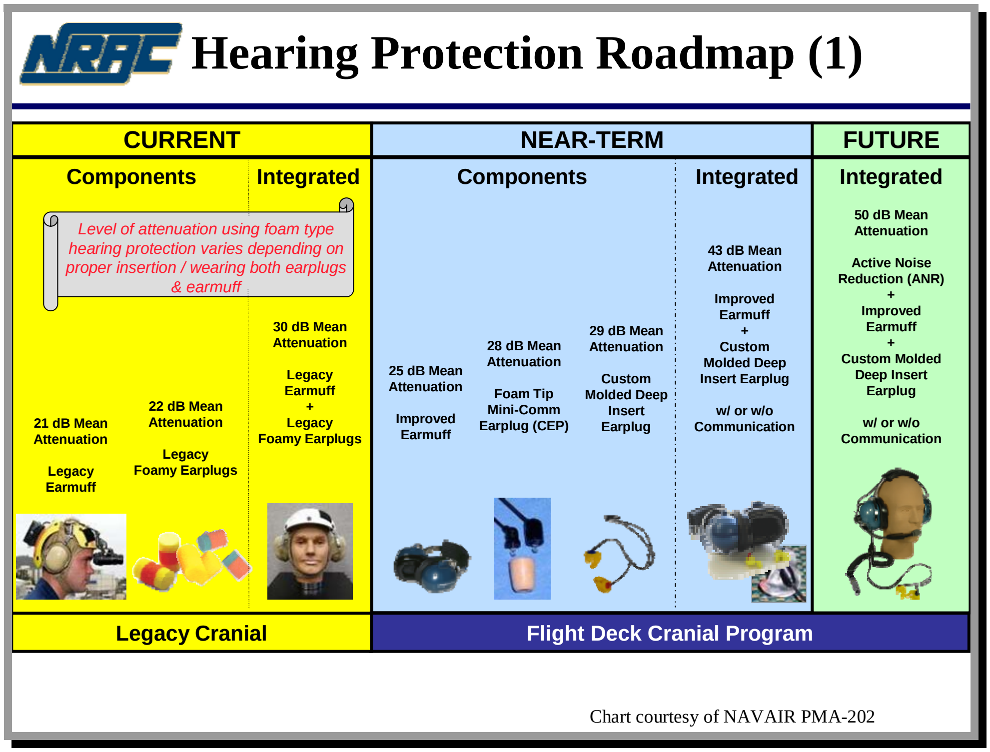
The chart shows the noise levels from various noise sources as well as the levels of noise attenuation that different hearing protection devices can provide that safely allow someone to be exposed to for 8 hours.

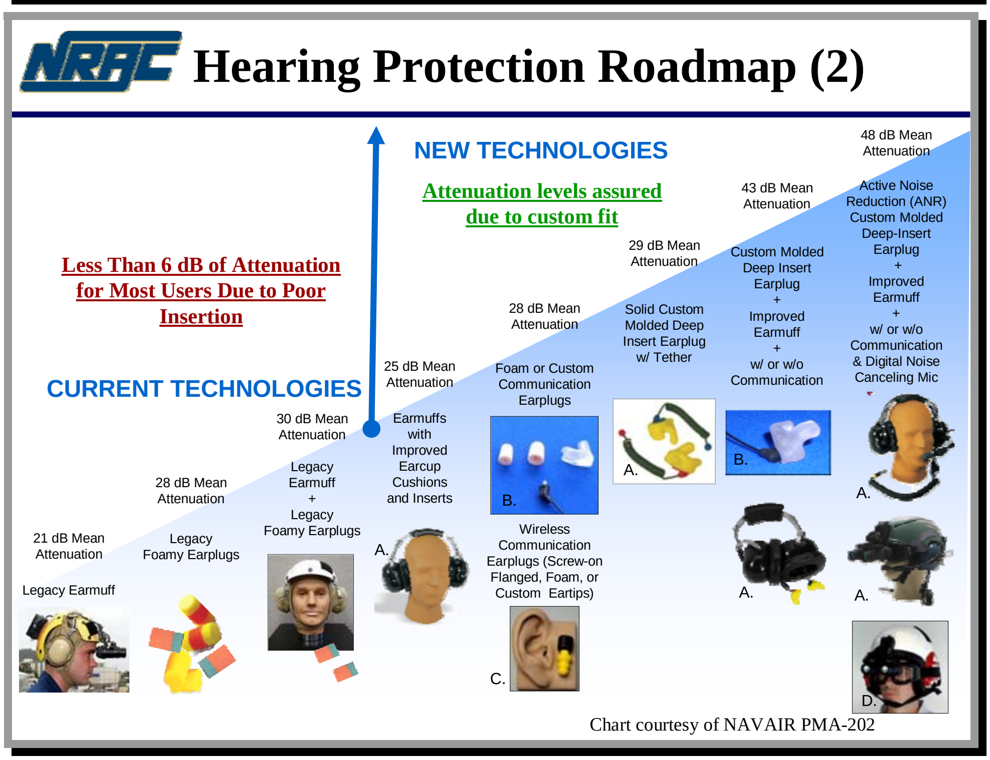
Note that with currently fielded hearing protection, the maximum level of attenuation is only 30 dB – assuming that the foam ear plugs are inserted properly and the cranial helmet fits properly. Surveys show that an estimated 79% of personnel on the flight deck have only 0 to 6 dB (not 30 dB!) of attenuation because of the lack of earplugs or shallow earplug insertion. However, during the Panel's time aboard USS Nimitz the Panel found good evidence of a serious hearing conservation program with foam ear plug dispensers located in many locations throughout the ship. Those Sailors who were questioned were very conscious of the need for both ear plugs plus cranial helmets, unless their need for hearing voice commands precluded double protection, such as in the arresting gear control rooms.

Through a combination of funding from the Joint Strike Fighter (JSF) program and Small Business Innovative Research (SBIR) projects, NAVAIR PMA-202, AIR 4.6 and ONR have developed significantly improved components for providing an integrated suite of hearing protection equipment: an improved earmuff; a foam-tipped mini-communication earplug, and a “custom-molded deep insert” earplug. These should provide 43 dB of mean attenuation.

Further improvements using active noise reduction technology are being developed – and with the improved earmuff and deep insert ear plugs, could provide 50 dB and possibly up to 60 dB of mean attenuation.

One caution that needs to be made is the new component’s dependence on custom-molded deep insert hearing plugs. It is estimated that approximately seven percent (7 %) of the population will not be able to wear deep insert earplugs because of a physical incompatibility – requiring the exclusion of these personnel from certain high noise environments.





A more detailed depiction of this new suite of hearing protection equipment is shown as well as the incremental improvement in hearing protection provided by each component.

The NAVAIR plan is to provide only the level of hearing protection needed for the noise environment in which the Sailor or Marine will be exposed. Cost estimates for the various combinations of components vary from $400 to over $5000 per individual.

Program success requires continuous coordination among the acquisition community, the medical community, and the Fleet. Initial funding has been provided in the current budget, but significant funding shortfalls exist in the out-years. It is expected that this shortfall will be corrected if the pilot program on CVN-69 is successful.

More Research for Hearing Protection

Progress made but more needed:

- Improvements for measuring noise environment needed
- Develop ways to measure, and then limit, noise exposure time limits based on type of hearing protection being worn
- Digital methods to measure an individual's ear for deep insertion ear plug
- Better understanding of bone-conducted noise energy and its impact on hearing loss and how to mitigate injury.
- Expand protection beyond just "more hearing protection" (i.e. pharmacological protection)
- Model low-frequency noise impacts on humans

Research in hearing protection has led to significant gains in attenuation, but S&T needs to be expanded and diversified to reach full protection potential. To date, research to improve personal protective equipment has focused on attenuating hazardous levels of noise before they reach the tympanic membrane either with improved earmuffs or earplugs of various types. This should be continued and diversified to include additional factors that bear on both the protection of hearing and human performance in high-noise environments, such as in-ear dosimeters and digital capture methods to improve the collection and storage of ear canal data for deep insert earplugs.

Essential to any noise mitigation program is accurate and highly-detailed data on the noise field and the location of humans in that noise field. Although a considerable amount of data on noise fields exist, the location and duration of noise exposure do not. This lack of data compromises the issuing of the correct protection based on expected exposure level. It also jeopardizes future research to optimize protection by location. We are unable to fully understand the level and duration of sound exposure by discrete job assignment – particularly on the flight deck – and are unable to assess injury and hearing loss. Although these data are thought to exist, there is no searchable data base that tracks individual exposure history by location. Accurate recording of individual exposure to jet noise is essential to reconcile hearing loss data, to optimize hearing protection for individual exposures, and to assess device effectiveness.

As previously discussed, advanced design approach for jet noise hearing protection is based on the use of individually-molded deep insert earplugs (past the second bend in the ear). These inserts will have to be custom-fitted to each individual's ear canal. The occlusion of the ear canal has the potential for a variety of side effects that will need to be tested prior to, and after, deployment of the next generation of hearing protective devices. The factors include:

- Maceration of the thin skin of the ear canal leading to pain/and or infection.
- Ear canal infection (external otitis).
- Loss of situational awareness secondary to distortion of frequency shifts or other cues to location and distance to sound sources.

While many of these factors are considered in the current program (they have not proven to be an issue for the hearing aid industry), the Panel strongly recommends that the next generation hearing device program include scientifically credible product evaluation studies to seek out unanticipated complications associated with deep insertion earplugs.

When noise levels exceed 85 dBA, for a period of greater than eight hours, humans run the risk of permanent hearing loss. Even with state-of-the-art protection providing 47 to 53 dBA of attenuation, one is still at risk in the high noise environments (145 – 150 dB) around jet aircraft. The magnitude and impact of noise transmitted via bone and other media such as fluid is largely unknown. The ear canal, if maximally protected, will reduce the noise by 47 – 53 dB. As the sound intensity increases past 110 dB, noise can be transmitted to the hearing apparatus via other routes – most notably bone conduction. In high noise environments noise is transmitted by bone, so attenuating the noise only in the ear canal will never be sufficient at noise levels above 150 dB. The Navy must anticipate that some fraction of the "at-risk" population of Sailors and Marines could lose their hearing, even when outfitted with protection that occludes 100% of the noise. Navy medical research into anti-oxidant therapy for brief impact noise in Marine subjects, suggests that there may be an effective "pre-exposure" therapy available that will increase noise-level tolerance. Data also suggests that post exposure therapies can potentially re-grow damaged hair cells. This kind of research needs to be expanded to include chronic noise exposure on the flight deck.

Noise levels below 500 Hz are normally not recorded by either dosimeters or medical audiograms. Although in the research environment audiograms routinely record down to 125 Hz. Various anecdotal reports have noted both the presence and absence of subjective discomfort attributed to "low-frequency" noise. Those who have stood near an F-22 or F-35 at high power levels report uncomfortable sensations and believe their internal organs are moving, such as could be caused by low frequency noise. Other occupational environments — undersea sound and human physical vibration — have produced human injury and disease. Critical organs of the body have harmonic resonances ranging from a few Hz to 400 Hz. For these reasons, greater bio-medical research into the adverse effects of low frequency, air-propagated, sound is needed. As is the case with our hearing conservation research recommendations, we recommend that this research be guided by individual, job-specific, noise level exposure data.

In summary, the Panel recommends that the following areas require additional research / oversight:

- 3D Digitization of ear canals and surrounding tissue to optimize fit of deep insert earplugs,
- Longitudinal study of deep insert users to assess problems associated with use,
- In-ear / structure mounted dosimeters – optimize spectra, min- max, recording duration,
- Searchable database to track individual exposures by job position,
- Physics based model of bone / fluid noise conduction,
- Pharmacological intervention to decrease sensitivity to noise / facilitate regenerative processes following exposure.

Engine Noise Reduction Investments

NASA/FAA
- 1990- 2009: Civil applications $287M
- $80M Supersonic/$207M Subsonic

Navy
- 2003 – 2009: approx $15M
- Largely S&T for Jet Noise Reduction

Air Force
- 2003 – 2009: approx $5M
- Testing and far-field model focus

JSF Program Office
- Baseline noise measurements supporting Hearing Protection
- One Study on potential Noise reduction technology (Netherlands Funded)
- GE and P&W reports on ways to reduce jet engine noise

Investment in tactical Jet Engine noise reduction has been inadequate…

Interest in tactical jet engine noise reduction technologies has grown in recent years, but the funding needed to make improvements has not followed.

The NASA investments in noise reduction have been and are focused on the civil aviation area, and only their limited investments in supersonic jet noise reduction have military application. Many of the technologies investigated by NASA involved heavy or complex nozzle arrangements which can cause a huge penalty on tactical jet performance.

Since 2003, the Navy has invested approximately $15 million in tactical jet noise reduction research. This research has focused primarily on university basic research and sub-scale/lab demonstrations. One full-scale demonstration was conducted to assess several technologies, and did lead to the current chevron rapid technology transition effort for introducing chevrons into the F/A-18 E/F F414 engines.

The Air Force investments in engine noise have been solely focused on measurement and modeling, largely for community noise which has been and remains the focus for the Air Force. The JSF Program has invested in numerous acoustic surveys of baseline noise data for the F-135 engine and also the F-35A aircraft. However, these efforts were focused on characterizing the noise level for hearing protection, and providing adequate hearing protection for the aircrew and maintenance personnel – a requirement of the JSF contract.

The JSF Joint Program Office initiated a study (by Pratt & Whitney, General Electric Aviation, and National Aerospace Laboratory – funded by the Netherlands) to investigate reducing the F-35 near-field personnel noise and far-field community noise. This study was a low-detail, high-level assessment of noise impacts. It evaluated and estimated the effectiveness and viability of currently available and emerging “public domain” technologies for reducing the propulsion system’s contribution to the F-35 acoustic footprint.

It was the conclusion of the study that shock noise control and mechanical chevrons are the two most promising technologies that may warrant continued studies for practical product implementation. Although these concepts show promise, at best they only appear to offer a few decibels (dB) of reduction and even less for the peak noise at a distance of 1,000 ft from the aircraft.

Another factor that became clear during the course of this study is that there has been significantly more investigative work in the past decades on subsonic jet noise, and the understanding is much more advanced than the understanding of supersonic jet noise. It is clear more fundamental work in supersonic jet noise – leading to better knowledge of the noise sources, generation, and flow features – are required to lower the generated noise. The resulting innovative technologies could be applied to the JSF and follow-on systems.

Advocates for Noise Reduction

- **ASN(I&E) and Safety & Survivability Office**
  - Concerned about noise reduction
- **Bureau of Medicine**
  - Growing concern over permanent hearing loss of naval personnel
- **Operational Navy and Marine Corps**
  - Growing concern over flight deck noise environment and community noise

Hearing protection program has greater than $100 million shortfall across the FYDP…and no champion…

As previously stated, there is an increased awareness of the hearing damage that our Sailors and Marines are receiving as a result of the noise environments in which they work. In each of the past three years, NAVAIR has conducted a Jet Engine Noise Reduction Workshop. Also, Dr. Delores Etter, then Assistant Secretary of the Navy (Research, Development, Acquisition), convened a Global War on Noise Workshop in 2007. Additionally in 2007, Vice Admiral Kilcline, commander of the Naval Air Forces made mitigating the high noise on aviation ships one of his highest S&T priorities.

The Assistant Secretary of the Navy for Installations and Environment and his Deputy for Safety have been very vocal on the need to reduce jet engine noise and provide improved hearing protection. In addition, the Bureau of Medicine has increasing evidence of Naval personnel permanent hearing loss from several sources – not just flight deck aircraft engine-generated noise. However, neither of these organizations is responsible for the funding to reduce jet engine noise or to develop and procure improved hearing protection.

DOD does not have – but needs to have – a strong advocate for jet engine noise reduction. History within the Pentagon suggests that in order to make a significant change, such as developing a noise requirement on tactical jet aircraft, requires a strong senior DOD advocate. Successful past examples are Mr. Don Dix, Deputy Director Defense Research and Engineering (DDR&E), in leading the engine IHPTET effort to improve thrust to weight by a factor of two; the honorable John Lehman, Secretary of the Navy, in the introduction of Pioneer UAVs to the Navy; and in the late 1970s, Dr. William Perry, then DDR&E, and Mr. James Wolsey, then Under Secretary of the Navy, in their support for the Tomahawk weapons system – despite difficult development challenges.

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The Panel's Bottom-line Conclusions

The Panel concludes that there is a lack of fundamental noise data or hearing damage data, and noise remains a significant health risk on flight decks.

<u>There will be no single solution for the jet engine noise problem – it will require a combination of:</u>

- Reducing jet engine noise source, which requires a long term research program;
- Developing a requirement for noise in future tactical jet aircraft;
- Continuing to make improvements to hearing protection;
- Finding ways to limit exposure to excessive noise levels;
- Developing better methods to monitor noise exposure and hearing loss of our personnel.

And finally, DOD does not have a "champion" for jet engine noise reduction.

Detailed Panel Conclusions

Today's Problems:

- Noise levels on today's flight decks (up to 150+ dB) exceed ability to protect hearing,
- There is a lack of reliable and comparable data on the near-field noise of tactical jet aircraft and the noise environment on aircraft carrier and amphibious ship flight decks,
- Standards do not exist for acquiring tactical jet aircraft noise data,
- There are no requirements for military aircraft noise levels,
- The Navy does not maintain a data base of the noise generated by its aircraft,
- There is no senior DOD official who acts as the "champion" for jet noise reduction
- Navy hearing loss problems extend beyond the flight deck,
- Community noise concerns growing and could become the tipping point for requiring jet engine noise reduction.

Human Hearing Protection:

- Significant progress has been made in hearing protection technology with pilot production hearing protection components which provide up to 43 dB attenuation being tested at sea,
- There are inadequate data on hearing loss for Sailors/Marines correlated to an individual's noise exposure environment,
- Individualized sound-level dosimetry is needed to fully match hearing profiles to occupational assignment and noise source exposure.

Jet Engine Technology:

- Predictive tools are now emerging with potential for more accurate assessment of jet engine noise reduction approaches,
- Large reductions (>3-5 dB) in jet engine noise will only be possible if the investments are made in the research and experimentation to reduce jet engine source noise,

– Should start now with design studies that include a noise requirement for the next generation tactical aircraft.

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Panel Recommendations

1. Identify a senior DOD champion/advocate for jet aircraft noise reduction.
(Action: USD(AT&L), ASN(RDA))

2. Initiate a long term research program to obtain the needed understanding of the physics of jet noise.
- Conduct a "Noise prediction Olympics" to obtain the best knowledge,
- Fund a competitive multi-year research effort with academia and DOE that includes both modeling and experimentation.

(Action: CNR)

3. Conduct a competitive design among the airframe prime contractors to start identifying the design space for noise reduction in tactical aircraft in order to help develop a noise KPP.
(Action: NAE)

4. Augment the VAATE/ADVENT program to address noise reduction.
(Action: DDR&E and COMNAVAIR)

5. Support the hearing protection roadmap and fund the procurement of needed improved hearing protection.
- Develop dosimeters for individuals to measure and record the total daily exposure (TDE) of noise.

(Action: CNO N8)

6. Develop standards for the measurement of near-field engine noise.
(Action: COMNAVAIR)

7. Expand the distribution of improved hearing protection beyond aviation personnel.
(Action: CNO N86/87)

8. Expand and diversify Navy medical research into physiological effects of noise.
- Improve the collection of hearing loss data to correlate with the noise environment in which the Sailor or Marine has been exposed,
- Better define at risk personnel,
- Quantify the non-auditory risks from low frequency noise,
- Search for mitigation beyond hearing protection.

(Action: Chief, BuMed)

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Appendix A

Terms of Reference

NRAC Tactical Jet Engine Noise Reduction Study

Objective

The noise on the flight decks of our carriers is 20 to 30 dB higher than any technology we have to protect the hearing of our Sailors and Marines. We are not in compliance with OSHA standards, and to quote the DASN for Safety, "We are creating a hearing loss certainty, not just a risk." The noise problem cannot be solved by only hearing protection devices. The source of the noise must be reduced in addition to finding better ways to decrease the noise exposure times of our Sailors and Marines. The technology does not exist to achieve the needed decreases in engine noise from tactical aircraft jet engines without significant adverse impacts to performance. This study will investigate current technology for reducing tactical jet engine noise and will make recommendations for actions that can be taken to both reduce jet engine noise in existing engines and to be able to achieve lower noise levels in the next generation of tactical jet aircraft.

Background

Progress is being made in developing improved hearing protection devices to replace the current day cranial helmets that were designed in the 1950's and are still in use on the flight deck. However, there has been no focused effort to reduce tactical aircraft jet engine noise. In fact noise has never been a design parameter for designing a new tactical aircraft, but rather aircraft such as the JSF/ F-35 have a contract specification to only mitigate the noise. No requirement exists for engine noise staying below any threshold noise level. The needed design tools to make such advances do not exist.

F-35A noise levels have undergone some measurement and appear to be comparable to the dB levels of other current tactical aircraft in Mil and afterburner. However, the noise power, watts per square meter, not just dB, generated by the F-35A is two times greater than that generated by the F/A-18 E/F. All tactical aircraft engines grow in thrust over time, and that equates to even greater noise in the future.

Specific Tasking

1. Describe the Navy/Marine Corp tactical aircraft noise problem in terms that are understood and will stimulate the needed actions to develop a joint service vision on tactical aircraft jet engine noise.
2. Assess the noise levels that are likely on our flight decks in the future as the planned replacement aircraft are acquired.

3. Near term reductions of up to 3 dB in engine noise are possible. Determine the benefits of achieving a 3 dB noise reduction in F-35 engine noise.
4. Review the hearing protection programs and make recommendations for any needed improvements to achieve the physiologically possible levels of hearing protection.
5. Identify any non-auditory risks to personnel from the intensity of sound produced by the JSF engine.
6. Propose an investment strategy that should yield the needed technology improvements to reduce the source noise of tactical aircraft jet engines without incurring unacceptable performance degradations.
7. Propose an approach to develop the technologies and the requirements to achieve lower engine noise for the next generation tactical aircraft: F/A-XX.

Appendix B

Conclusions and recommendations from two previous Jet Noise Studies

Conclusions and recommendations from the 2002 JSF flight deck noise study and the findings/recommendations from the 2000 DUSD (S&T) study on military aircraft noise reduction are quoted below. (Note that many of the recommendations from these two studies are similar to those made in this NRAC report.)

Quoted Documents:

1. Joint Strike Fighter Flight Systems Integrated Product Team Vibroacoutics Team, "Acoustical Noise Fields Generated on the Flight Deck During Operations of F/A-18C/D, F-14B, EA-B and S-3B Aircraft", 2002.

2. Office of the Deputy Under Secretary of Defense (Science and Technology), "High Performance Military Aircraft Emissions and Far-Field Noise Reduction Science and Technology Plan Final Report", 2000.

Conclusions from the JSF study:

"1. The acoustic levels on the flight deck of aircraft carriers are among the highest levels in which people routinely work. The acoustic data measured during the EA-6B, F/A-18C/D, F-14B, and S-3B mil power catapult launches and arrested landings demonstrated sound pressure levels reaching maximums of 148 dB. The calculated levels for A/B catapult launches at the worst case locations for the F/A-18C/D, and F-14B reach levels of 148 dB (146 dBA). The catapult launch exposure levels were within acceptable limits for most locations for a single 30-second event. However, for a typical operational day such as the JSF JMS specified 60 launches and 60 recoveries many personnel locations will significantly exceed the exposure criteria. The primary areas of concern are the areas around the catapults, the forward landing area, and the Landing Signal Officer (LSO) platform. Measurements have indicated that flight deck personnel located aft of the ship will have acceptable TDEs if double hearing protection is used.

2. The noise exposures are excessive for a large number of locations and personnel on the flight deck during operations. Appropriate mitigation strategies include improved hearing protection equipment, changes in operations to move personnel from the noise hazardous areas, new technology to monitor aircraft and ship systems and automatically transfer information to allow safe flight deck operations with fewer personnel in noise hazardous areas. It should be noted that all this assumes that the noise levels below the deck during rest and sleep periods of time are below 80 dBA, which preliminary findings by NAVSEA have shown are much higher. This will affect the TDE of the pilot and the maintainer during each 24-hour period.

3. It is important to note that the JSF program was only measuring and researching methods to mitigate the aircraft noise on the flight deck of the ship. No work was being done by the JSF program to change the acoustic environment and noise exposure below the flight deck. This was an area which needs significant improvement to reduce the incidence of noise induced hearing loss."

Recommendations from the JSF Study:

"Noise levels and the associated noise exposures was a complex problem. Clearly from the data provided in this report the noise environment in many flight deck locations was very high and very hazardous to hearing. Many of the recommendations from Webster's 1971 (NAVELEX) report on flight deck noise and their effects were still good recommendations in 2002. The list of recommendations below was not intended to be an exhaustive list but a start. However, action must be taken on recommendations in order that they be effective. There was not one recommendation that will solve this problem. Action will be required on many before substantial results will be seen. The resulting integrated solutions must have the input and guidance of the personnel who own and operate the flight decks of aircraft carriers.

1. Improved hearing protection for flight deck personnel approximately 50 dB total attenuation.

2. Investigate ways to move personnel who are in locations with TDEs>1 to locations with TDEs<1. The highest priority should be the final checkers and JBD operators between cats 1&2.

3. LSOs need hearing protection better than foam earplugs but with a technology that still allows them to perform their very critical function. Custom fit communication earplugs with a localization capability might be one type of possible solution.

4. Technology solutions to launch bar/holdback bar checking, final checking, etc, should be investigated and developed, if feasible, to remove personnel from very high noise areas.

5. A dynamic model of flight deck noise will be required to accurately correlate the noise levels at individual locations and estimate flight deck noise levels for new aircraft such as JSF (F-35).

6. Hearing protectors just like any other device need periodic maintenance to perform at their peak levels. Earcushions and earcup foam on cranials should be replaced at least annually and headband force should be measured/adjusted annually in order to maintain the protective noise attenuation performance of the cranial. Earplugs should be readily available and used religiously by ALL flight deck personnel. Training in proper insertion and use of earplugs by an audiologist or other trained medical professional should occur annually.

7. A high level, service or DOD, office should be assigned the permanent task of hearing protection/conservation. This office should continually search for and support the development of better hearing protection technology and improved hearing conservation

programs/techniques. The office should also be the one approving authority for hearing protection devices purchased for the DOD.

8. Technology methods, such as improved nozzles, should be investigated for reducing the noise levels generated by Navy carrier aircraft.

9. Noise levels below decks, especially in dining and berthing areas need 80 dBA or less in order that flight deck and other noise exposed personnel can adequately recover from duty related noise exposures and not accumulate any additional noise exposure in non-duty areas.

10. Input noise related issues to the designers of future Navy aircraft carriers to reduce the probability of noise induced hearing loss in Navy personnel.

Many of the recommendations from the 1971 NAVELEX report were still valid in 2002:

> 1. Insure that sealing rings for the sound-attenuating earmuffs are on board in adequate number to allow prompt replacement of damaged seals and routine replacement at least once a year (or at the start of each deployment).
> 2. Assign to some DOD activity the permanent task of continually searching for and evaluating better hearing protectors.
> 3. Either insure that new naval aircraft do not generate noise levels greater than those currently in use, or provide better hearing protection and/or less exposure time for flight-deck personnel.
> 4. Encourage any study or engineering effort that will reduce the number of personnel required on the flight deck after engines have started.
> 5. Provide "quiet" crew shelters for flight deck personnel to used between tours of duty on the flight deck and insure that the shelters remain quiet …"

Findings from the USD (S&T) Report:

“Far-Field Noise:

1. Increased military engine performance is derived from higher cycle temperatures and pressures, which produces higher jet velocities resulting in increased noise.
2. Military aircraft have no existing noise level requirements, and DoD has no accepted military measurement standards or procedures.
3. Current mathematical models do not accurately predict noise levels.
4. NASA low-speed noise efforts have limited relevance to military high performance aircraft because of the significant difference between civil and military engine designs, and the substantial performance and weight penalties involved.
5. Technology solutions have the potential of reducing JSF predicted noise levels by 2-4 EPNdB in the near-term (2005), which can meet legacy noise levels (but this may not be sufficient at some basing locations in the future).
6. The requisite S&T efforts are only a fractional portion of the total cost involved.

Recommendations from the USD (S&T) Report:

Far-Field Noise:

1. Adopt a DoD community noise measurement standard.

2. Update existing noise models to account for non-linear noise propagation and thrust vectoring affects, as recommended by the Air Force Working Integrated Product Team (WIPT).

3. Measure current JSF noise levels to establish a noise baseline.

4.Quantify the weight, cost, signature, and performance impacts of potential technology solutions to meet legacy aircraft community noise levels.

5. Investigate the physics of jet noise generation (particularly in the JSF flow field regime) to develop new technical approaches for reducing noise impacts below legacy levels.

6. Leverage NASA/Industry civil sector investments to the extent feasible.”

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Appendix C

Other References Providing Insight to the NRAC Panel

D. Huff, "A Historical Perspective on Jet Noise", 2009.

U.S. Air Force, "Proposed Implementation of the BRAC 2005 Decision and Related Actions at Eglin AFB, FL", 2008.

Richard L. McKinley, "60 Years of Hearing Conservation and Hearing Protection Research and Development at Wright-Patterson Air Force Base", 2007.

V. S. Bjorn et al, "U.S. Navy Flight Deck Hearing Protection Use Trends: Survey Results", 2006.

DOD Instruction Number 4715.13, "DOD Noise Program", 2005.

G. B. Shaw and R. P. Trost, "CNA's Statistical Analysis of Hearing Loss Among Navy Personnel", 2005.

Joint Strike Fighter Flight Systems Integrated Product Team Vibroacoutics Team, "Acoustical Noise Fields Generated on the Flight Deck During Operations of F/A-18C/D, F-14B, EA-B and S-3B Aircraft", 2002.

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Joint Strike Fighter Flight Systems IPT Vibroacoustics Team, "Measurement of the Cockpit Noise of an AV-8B", 2002.

Joint Strike Fighter Flight Systems IPT Vibroacoustics Team, "Acoustical Noise Generated during Ground Operations of an EA-6B Aircraft", 2002.

Joint Strike Fighter Flight Systems IPT Vibroacoustics Team, "Acoustical Noise Generated during Ground Operations of an F-14A Aircraft", 2002.

Joint Strike Fighter Flight Systems IPT Vibroacoustics Team, "Acoustical Noise Generated during Ground Operations of an F-18F Aircraft", 2002.

Joint Strike Fighter Flight Systems IPT Air Vehicles Systems Engineering & Integration Team Environment Vibroacoustics Team, “F/A-18 C/D Cockpit Noise Measurement”, 2002.

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Joint Strike Fighter Air Vehicles Systems Engineering & Integration Team Environment Vibroacoustics Team, “Effect of Jet Blast Deflector on Exhaust Noise of F-18E”, 2002.

Office of the Deputy Under Secretary of Defense (Science and Technology), “High Performance Military Aircraft Emissions and Far-Field Noise Reduction Science and Technology Plan Final Report”, 2000.

S. J. Kent et al, “Analysis of the Potential Association between Noise-Induced Hearing Loss and Cardiovascular Disease in USAF Aircrew Members”, 1986.

A. A. Atchley et al, “Preliminary Analysis of Nonlinearity in F/A-18E/F Radiated Noise”, undated.

Appendix D

Topics & Briefers

Topic	Briefer
Jet Noise Trends	CDR Mike Singleton, Officer In Charge Aircraft Handling Team, N73, CNAF
Tactical Jet Noise Reduction Study NAVSEA Perspective	Ms. Patricia Hamburger, Mr. Kurt Yankaskas, Human Systems Integration Directorate, SEA05
F/A-18 Jet Noise Reduction Program	Mr. Mike Rudy, PMA-265 Environmental Safety & Health
Exhaust Jet Noise Reduction for Tactical Aircraft	Dr. John T. Spyropoulos, Ph.D., Propulsion and Power Dept., Naval Air Systems Command
Hearing Protection: Technologies, Transitions & Recommendations	Dr. James B. Sheehy, Human Systems Department, NAVAIR
Noise Induced Hearing Loss Program	LCDR Matthew Swiergosz, MSC USN; ONR-342
F-35 Noise Efforts; Aeroacoustic Research Complex; F-35 AA1 Flyover and Ground Run-up Noise Measurement	Mr. Richard McKinley, Air Force Research Laboratory/JSF JPO, Vibroacoustics lead
Community Noise Concerns of the Defense Noise Working Group	Mr. Alan F. Zusman, Naval Facilities Engineering Command
Naval S&T Investments and Accomplishments in Noise Reduction Research	Dr. Gabriel D. Roy, ONR-351
USN Propulsion S&T Noise Roadmap	Mr. William Reardon, Propulsion and Power Department; Naval Air Systems Command
Jet Noise Research at NASA	Dr. Brenda Henderson, Mr. Dennis Huff, NASA Glenn Research Center
GE’s view of Tactical Jet Noise Reduction	Steve Martens, GE Global Research Center
P&W Perspective on Exhaust Jet Noise Reduction	Mr. Morford, Pratt & Whitney
Tactical Jet Noise Reduction from Academia	Dr. Tim Colonius, Caltech; Dr. Robert H. Schlinker, United Technologies Research Center
Hearing Loss Prevention and Treatment	Dr. James B. Sheehy, Human Systems Department, Naval Air Systems Command
Non-Auditory Effects of Low Frequency Noise	Edward Chudahy, Ph.D.; NAVMED
More Acoustics 101 and Possible Solutions	Mr. Dennis L. Huff, NASA Glenn Research Center
Near-Field Measurements for Jet Noise	Dr. James Bridges, NASA Glenn Research Center
Lockheed Martin Perspective on Tactical Jet Noise Reduction	Mr. John W Vinson, Vehicle Sciences & Systems, Lockheed Martin ADP
Boeing: Jet Engine Noise Reduction for Tactical Fighter Aircraft	Mr. Tom Kaemming, K. Viswanathan, Ph. D.
Tactical Jet Noise Reduction, Northrop Grumman Capabilities and Perspective	Dr. David B. Schein; Low Observables Design and Integration, NGC
Fundamental Studies of Supersonic Jet Noise	Prof. Parviz Moin, Stanford University

Versatile Affordable Advanced Turbine Engines (VAATE) Overview	Dr. Larry Burns, AFRL, Propulsion Directorate
VAATE: ADVENT Adaptive Features Contributing to Noise Reduction	Mr. Jeffrey Stricker AFRL, Propulsion Directorate
Excerpts from CNAF Brief on Exhaust Jet Noise Reduction for Tactical Aircraft	Dr. Katherine A. Stevens, Air Warfare and Weapons Dept., ONR
Joint Strike Fighter F-35B, Marine Aviation Perspective	LtCol Tim “Nugs” Golden, USMC, HQMC Aviation
Auditory Physiology and Noise Induced Pathophysiology	Ben J Balough, CAPT, MC, USN, Department Of Otolaryngology, Naval Medical Center, San Diego
Navy Policy and Programs for Hearing Conservation	CDR David McMillan, MD, MPH, Occupational and Environmental Medicine
The Navy’s Hearing Conservation Program	Tom Hutchison, MA, MHA , Navy & Marine Corps Public Health Center

Appendix E

Acronyms

A/B	After Burner
AFRL	Air Force Research Laboratory
AICUZ	Air Installation Compatible Use Zone
ANSI	American National Standards Institute
ASN(RDA)	Assistant Secretary of the Navy for Research, Development, Acquisition
ASTM	American Society for Testing and Materials
BRAC	Base Realignment and Closure Commission
CAA	Computational Aeroacoustics
DDR&E	Deputy Director Defense Research and Engineering
DOE	Department of Energy
EIS	Environmental Impact Statement
EPNdB	Effective Perceived Noise in Decibels
GFE	Government Furnished Equipment
ICAO	International Civil Aviation Organization
IHPTET	Integrated High Performance Turbine Engine Technology
JBD	Jet Blast Deflector
JSF	Joint Strike Fighter
KPP	Key Performance Parameter
LSO	Landing Signal Officer
MIL Power	Military Power
NAE	Naval Aviation Enterprise
NAVAIR	Naval Air Systems Command
NEC	Navy Enlisted Classification
NLR	National Aerospace Laboratory
OSHA	Occupational Safety and Health Administration
PIV	Particle Image Velocimetry
SBIR	Small Business Innovative Research
SPL	Sound Pressure Level
RTT	Rapid Technology Transition
TDE	Total Daily Exposure
UCAS	Unmanned Combat Air System
VA	U.S. Department of Veterans Affairs
VAATE	Versatile Affordable Advanced Turbine Engines
WIPT	Working Integrated Process Team.

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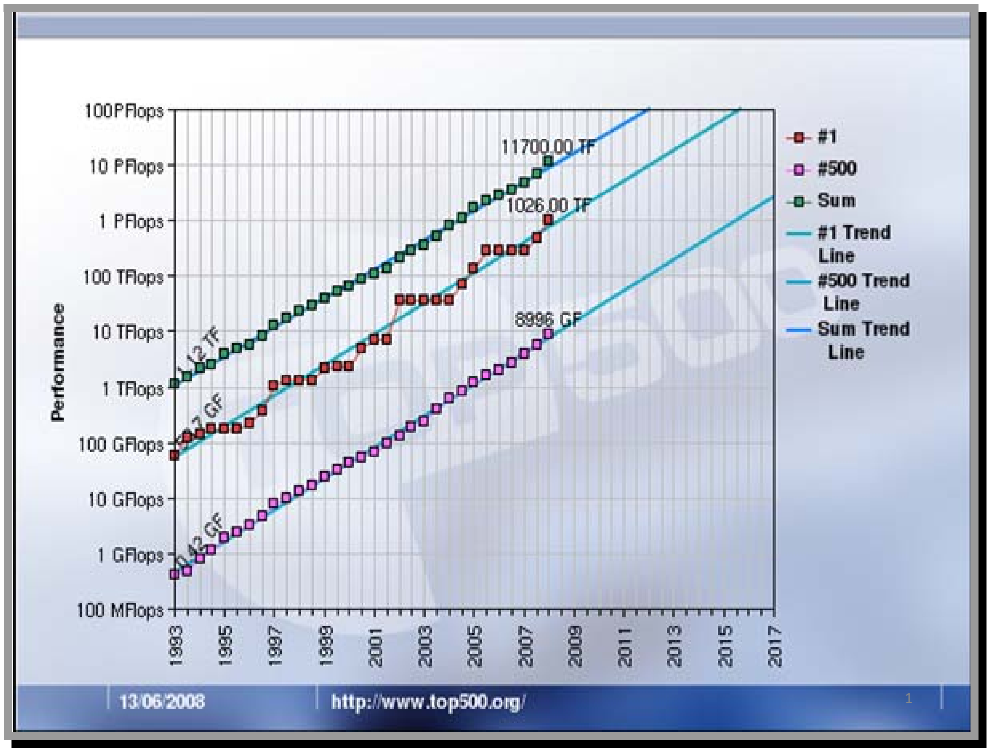
Appendix F

Computer Performance Trend



This chart depicts the evolution and expected growth in computer performance since the early 1990s. Some government computers have already reached peta-flops performance and more impressive advances are on the way. A peta-flop represents a thousand trillion flops (floating point operations per second).