

Noise Issues Associated with Gas Turbine Powered Military Vehicles

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ABSTRACT

Noise mitigation has attracted the attention of researchers since the dawn of gas turbine engines. Regulations imposed by Federal Aviation Administration and such agencies resulted in the aviation industry taking the lead in noise mitigation studies. However, the past investments have been mostly in subsonic commercial aircrafts. The introduction of supersonic aircrafts in the military fleet added a new dimension to this issue. Reducing the noise generated by the exhaust jet alone cannot suffice; and a multi field, multidisciplinary holistic approach is required with feed back among researchers to achieve the goal of bringing the environmental noise to allowable thresholds in areas such as carrier decks, engine compartments, and runways; as well as in the surrounding community. It is time to integrate the various efforts in engine and jet noise reduction, ear protection devices, pharmaceutical intervention, and education to cope with the psychological aspects of noise issues, and formulate a unified multi-national approach to resolve this major concern of the present decade. Some of the recent advances are dealt in more detail and others in less detail in this paper.

1.0 INTRODUCTION

“Faced with the choice of going deaf or possibly losing people or equipment, many have chosen to sacrifice our ears.” Nothing can express as vividly, emotionally, and forcefully, the grave danger and impact of noise on the crew working on aircraft carrier decks. As new engines are being developed to cope with the increasing demands of specific thrust and speed, the noise from the exhaust plume also increases. For commercial applications, gas turbine engine manufactures resorted to increasing the by-pass ratio (fan flow/core flow) in order to reduce jet noise. However, for military applications, this is not a viable solution, and the low by-pass ratio and increased jet velocity and temperature, call for other innovative means of noise reduction.

In modern day military aircrafts powered by jet engines, the exhaust noise can be as high as 150 dB. In such a scenario, inadvertent removal of an ear protection device for a few seconds can cause severe hearing impairment and even deafness. In addition to this health hazard, hearing loss results in reduced situational awareness, by decreasing speech intelligibility, leading to misinterpretations, errors and even failure of mission. Monetary losses are not limited to the medical expenses and compensation to the affected personnel alone, but also to increasing community concerns and consequent law suits.

Though decades of research with over a billion dollar investment in the U.S. and European Union, to reduce noise in subsonic commercial aircrafts, the attention paid to supersonic jet noise reduction is very limited. This is partly due to the absence of noise limitations in the manufacturing requirements, and partly due to the lack of awareness of the escalating medical expenses related to noise and the ignorance about the physical trauma crewmen go through. In the U.S., military aircraft noise has become an important issue during the past decade as the number of affected personnel kept on increasing and the

Noise Issues Associated with Gas Turbine Powered Military Vehicles

associated costs escalated exponentially. A host of research has been conducted addressing the various issues associated with noise, and methods to solve them in order to provide a safe environment to the pilots, the crew operating on decks, and in the airfields where take off and landing practices are conducted.

Focused research on reducing noise at the combustion source where the conversion of fuel energy takes place and at the nozzle where the jet exhausts, has indicated unprecedented opportunities. Decades of development has resulted in personal protective equipment (PPE) that can provide attenuation at 45+dB levels. Active noise reduction technology has made this possible. Pharmaceutical intervention to combat hearing loss and tinnitus (ringing sound in the ear) has been very successful. Considering the 150 dB noise levels on a carrier deck and the 85 dB allowable threshold, no single technology or approach can provide a solution. A holistic approach involving noise reduction at the engine source, exhaust jet, advanced ear plugs and PPEs, and preventive and prognostic medical intervention will be necessary, in addition to bring community awareness of the noise implications, to deal with this problem.

2.0 THE EIGHT PRONGED APPROACH

There have been a number of workshops, NATO AVT panel meetings, and sessions in technical society meetings, and dedicated conferences in the past few years which made it possible to better share and understand the state-of-the art in high speed jet engine noise generation, propagation, prediction and reduction. Recent advances in diagnostics with increased spatial and temporal resolution, fast algorithms and numerical simulation and prediction made it possible to perform high fidelity bench mark experiments and to develop new computational methodologies at reduced cost and time. The same is true with PPEs and medical intervention. However, there has never been an integrated research effort combining the fields of sciences, engineering, medicine and psychology in place so far. The experience the author and his colleagues in this field had acquired by participation, management and learning led to the following “Eight Pronged Approach” to solve the noise issues associated with gas turbine powered military vehicles and to prevent sailors, crew and personnel from the hazard.

In order to bring the extreme noise levels to acceptable threshold levels to the crew working in high impact areas, and for the surrounding community, the following approach is recommended.

1. Source noise and control: This includes various methodologies to reduce internally the noise generated by the combustion process, turbulence and nozzle flows and associated jet noise, as well as means external to the aircraft, such as treatment of the exhaust plume, on carrier decks, runways, etc.
2. Aero acoustics: Both analytical and computational evaluation of the aero acoustics needs to be revisited with the modern tools available, and the fast computing and simulation capabilities.
3. Measurement Techniques and Diagnostics: This area has seen tremendous advancement in the past decade. The sensor-actuator-control logic should be capitalized to better understand the physical processes and control them, in order to reduce noise impact.
4. Out-door Measurements: Laboratory measurements and methodologies must be verified for their validity in varying out door conditions. Evaluations of ground effects, variation in weather conditions, and the noise directions should form an integral part of the new approach.
5. Noise propagation and Impact Prediction: A valid methodology to quantify the propagation of noise, and predict its impact at various location is necessary.
6. Perception: The impact of noise on an individual could be affected by the perception or psychological response as well. The community should be made aware of differences of

Noise Issues Associated with Gas Turbine Powered Military Vehicles

various sound sources, and their implication on humans should be brought out via simulated noise demonstrations, education, and continuous communication, so that community acceptance and trust can be achieved.

7. Operational Mitigation: Though flight path adaptation may not be an easy solution for military application, the implications of changes in flight path, throttle and after burning should be studied, co-operatively by the researchers and the pilots. External active control, such as noise redirection, absorption, as well as controlling the environment (runways and carrier decks) should be investigated.
8. Human Protection: Ultimately, with all that is possible to reduce noise levels at the sources have been done, and the noise awareness inculcated, the individual subjected to noise must be protected. Advancements in ear plugs, hearing protection aids, active noise controlled head phones, as well as pharmaceutical measures in terms of prevention, treatment, and cure with new medical inventions are vital in the “fight against noise.”

Details relating to a few of the above mentioned subject areas will be discussed further, though not in the same order presented.

3.0 SUPERSONIC JET NOISE

Ever since gas turbines have been in use to power aircrafts, the jet induced noise has always been a problem. As the aircraft size and speed increased, the increased thrust and jet velocity resulted in added noise footprint. The industry has been coping up with the noise standard set forth by FAA and other agencies, by increasing the by pass ratio. Figure 1 shows the effect of by pass ratio on relative noise level. For gas turbines powering military aircrafts, this is not a viable solution since the bypass ratios are very small. Further the acoustic footprint the military jets produce are much higher than a much larger commercial subsonic aircraft. Figure 2 shows a comparison of the noise footprint of a military aircraft with a B737 and B747 (1).

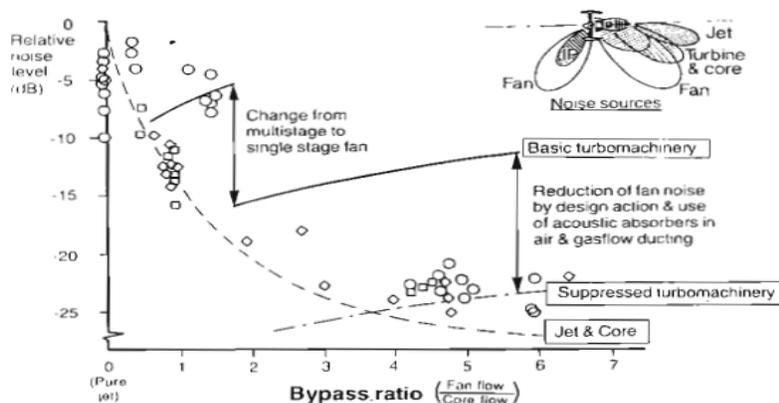


Figure 1. Variation of source noise with Engine bypass ratio.

Noise Issues Associated with Gas Turbine Powered Military Vehicles

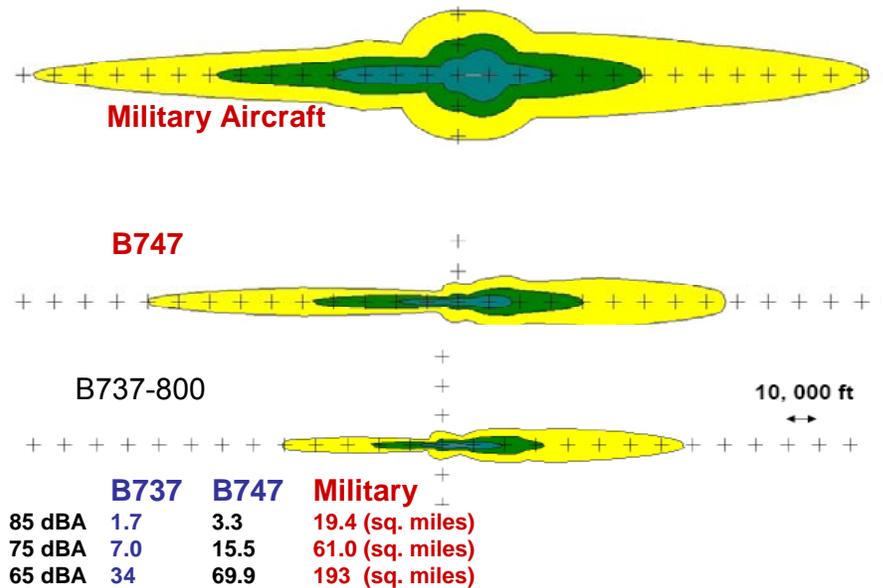


Figure 2. Noise footprint comparison of commercial & military aircraft

It is evident from figure 2 that 85dBA footprint of the former is spread over 6 times the area of the latter. Some of the technologies developed over the past several decades to mitigate noise in subsonic aircrafts need not necessarily apply to supersonic aircrafts, due to the difference in the noise radiation patterns. A diagrammatic comparison of noise radiation pattern from low and high bypass ratio engines is shown in figure 3. In addition to the jet mixing noise to be more pronounced, the low bypass ratio supersonic jet has a large shock noise component, which exhibits as discrete screech tones, and broad band shock noise (see figure 4). The Mach wave radiation which is of short wave length and high frequency, and of high intensity is also shown in figure 4 (2).

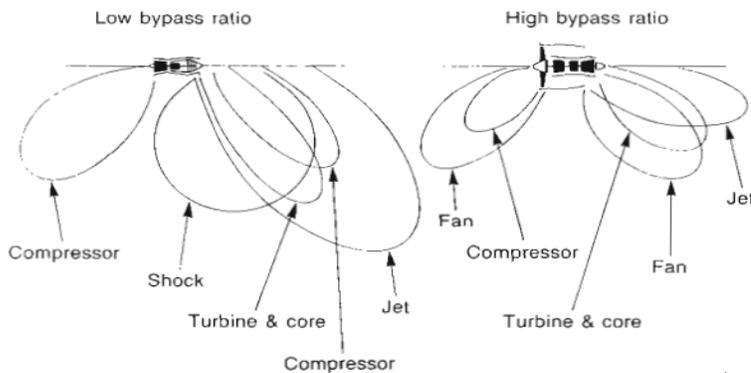


Figure 3. Diagrammatic comparison of noise radiation patterns from low and high-bypass-ratio engines.

- Mixing noise
 - Similar to subsonic jet noise
 - Larger scales – low frequency
 - Finer scales – high frequency
- Mach wave radiation
 - High frequency, short wavelength
 - High intensity, highly directional
- Shock associated noise
 - Discrete screech tones
 - Broadband shock noise

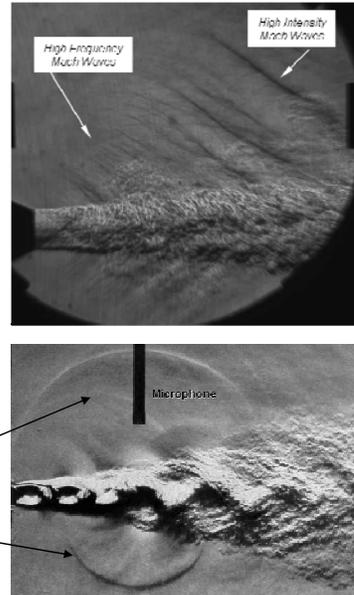


Figure 4. Components of Supersonic jet noise

3.1 Mitigation of Supersonic Jet Noise

Engine manufactures such as GE and Rolls Royce have every effectively employed different forms of chevrons to reduce noise by about 3 dB in the small subsonic executive jets. In terms of perceived noise levels, this is a notable accomplishment. However due to the extreme high noise levels (often of order of 150 dB), due to high velocity of the supersonic jet, boundary layer that is hard to penetrate, innovative approaches are required that will reduce mach wave radiation and the shock noise, as well as the turbulent mixing noise.

3.11 Concepts Tested

Although some investigations have been done at the U.S. NASA and else where, a systematic study to mitigate jet noise from military aircrafts has taken place only during the past few years. In particular, the U.S. Office of Naval Research (ONR) sponsored a multi-year program to focus on innovative approaches that could lower the maximum noise levels by about 10 dBA. In the Netherlands, the National Research Laboratory has launched a multi faceted noise program. In the UK, MoD and universities have several noise reduction research programs.

Under the ONR program four concepts were investigated chevrons. (inwardly inclined, mechanical/fluidic), bevelled nozzle, internally corrugated nozzle, and microjet injection. The chevron (figure 5a) and thermal fluidic shield induce stream wise vortices, whereas the bevelled nozzle (figure 5b) reduces the Mach wave radiation and shock noise by altering the shape of the nozzle exit.

Noise Issues Associated with Gas Turbine Powered Military Vehicles

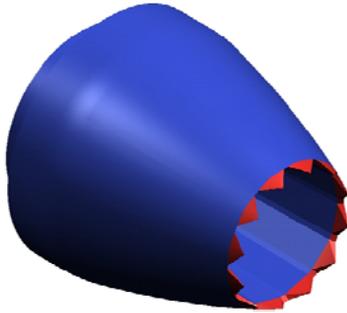


Figure 5a
Mechanical Chevrons



Figure 5b
Beveled Nozzle

The internal corrugated seals (figure 6) in the nozzle reduce Mach wave radiation by passively introducing stream wise vortices into the high speed side of the shear layer. Shock noise is reduced by the fact that the seals correct the exit area to ideally expanded conditions.



Figure 6
Corrugated Seals

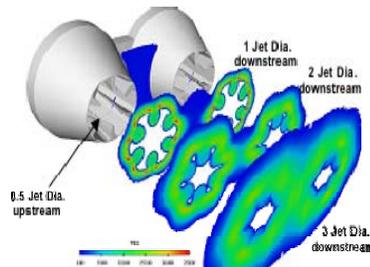


Figure 7 TKE Contours –
Jet Interactions with
Corrugated Seals

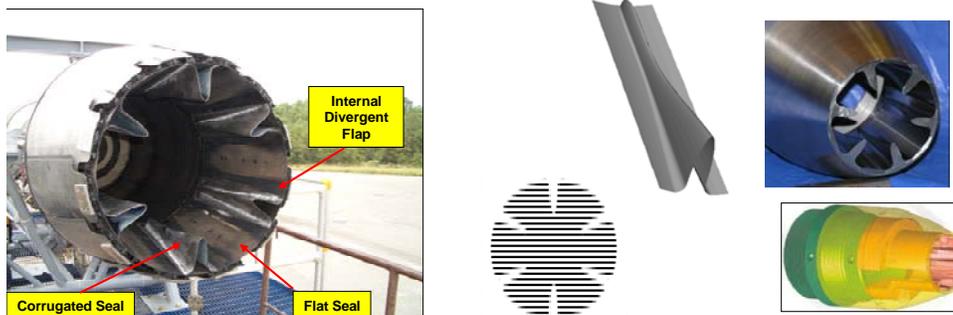
Figure 7 shows the turbulent kinetic energy contours indicating the jet interaction with corrugated seals. As can be seen in a twin engine configuration, the effectiveness improves down stream. Aqueous microjet injection (figure 8) reduces Mach wave radiation by actively introducing stream wise vortices into the high

Noise Issues Associated with Gas Turbine Powered Military Vehicles

speed side of the jet shear layer. Shock noise and turbulent mixing noise are reduced due to the screening effect of the aqueous particles.



Figure 8
Aqueous Microjet Injection



- 6-Lobe Configuration Provides ~ 5-6 dB EPNL (Perceived) Noise Reduction Noise in Both Model and Full-Scale engine Tests
- CFD Studies Show No Performance Penalty at FCLP But,
 - Small Thrust Loss for Altitude Operations Due to Reduced Nozzle Expansion
- Thermal Issues Related to Concept Survivability Using Internal Cooling From By-Pass Stream Being Evaluated
 - Additional Noise Attenuation Over Baseline Lobe

Figure 9 Details of corrugated nozzle

Noise Issues Associated with Gas Turbine Powered Military Vehicles

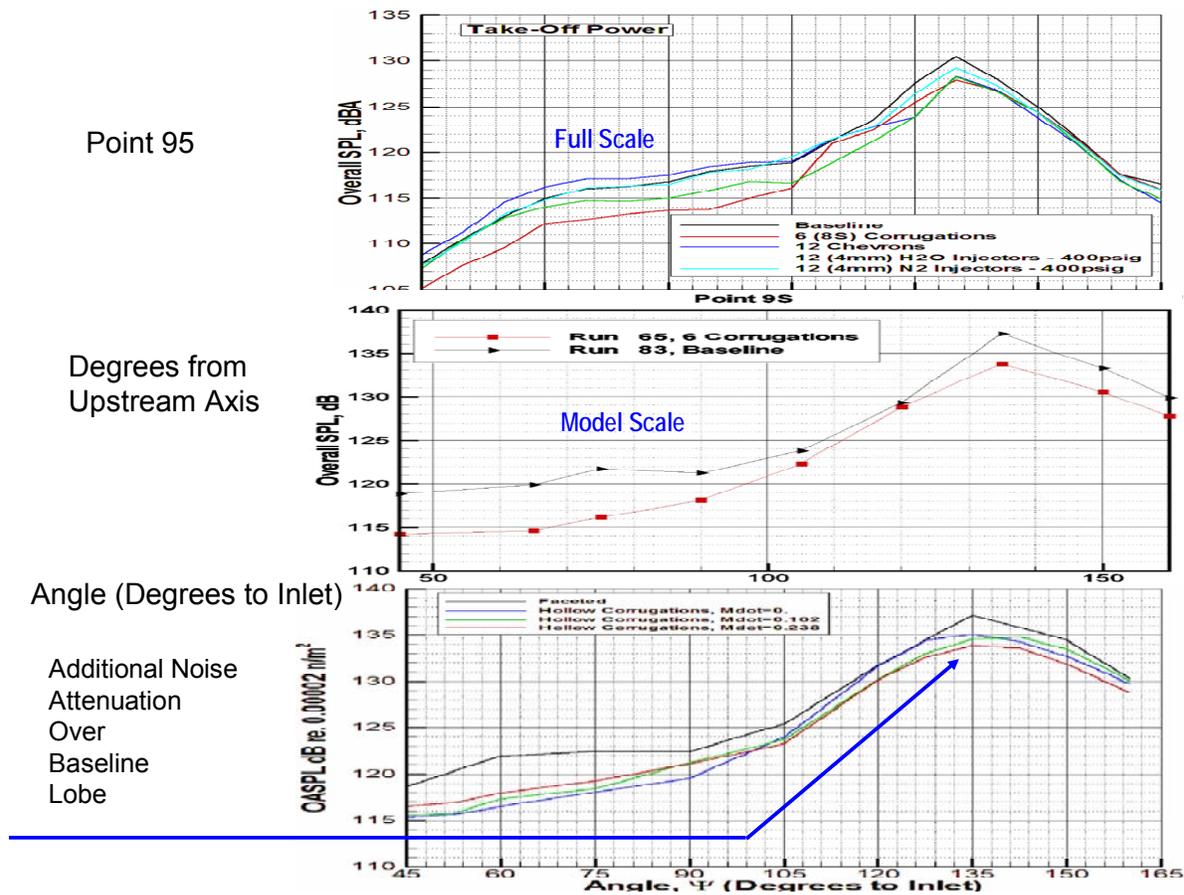


Figure 10 Performance Comparisons of Various Concepts

Of all the methodologies tested, the corrugated nozzle proved to be the best with about 5-6dBA noise reduction. Figure 9 shows more details of this configuration, and figure 10 performance comparison with other methods.

Different chevron configurations were also tested at laboratory scales and also with a full size engine on static test stand. In 2004, tests were conducted at Lakehurst Naval Center with, inward facing chevrons (figure 11a) to improve penetration into the supersonic shear layer, in order to obtain more noise reduction. But this led to reduction in thrust. In 2007, tests were conducted on the same test stand with chevrons aligned with the seals, and also employing fluid shields (figure 11b). Though the thrust loss was minimal, only much smaller noise reduction (2dB) could be achieved. Fluid shield requires large amounts of air, and so is not feasible for retro jet in present engines.

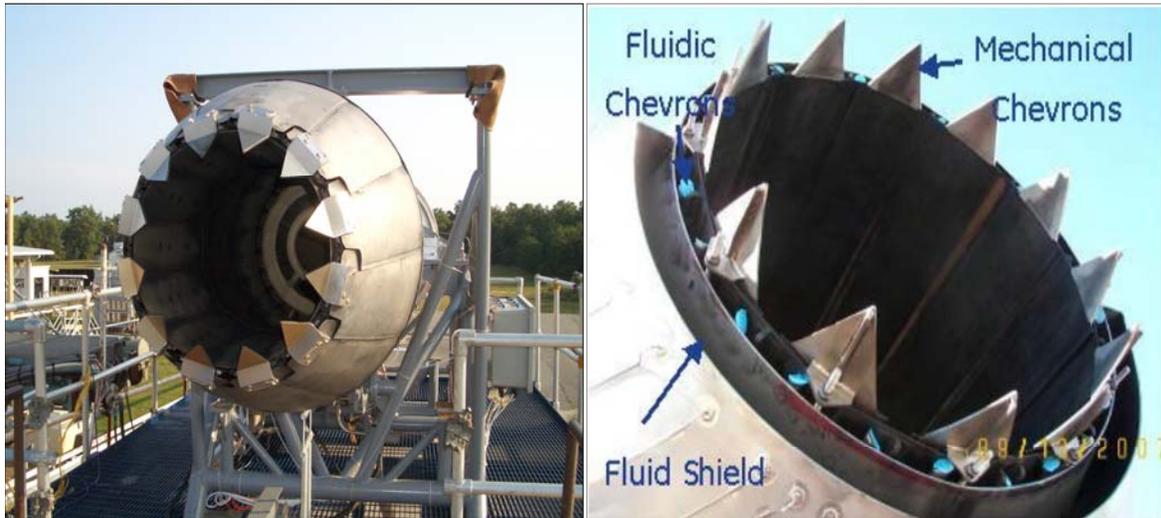


Figure 11 Chevron Evaluation Studies (2004, 2007)

(a) Chevron test 2004 (UM), (b) ONR Chevron test 2007 (GE)

Tests with twin engine and microjet injection showed substantial noise reduction as indicated in figure 12. The canting of the nozzles has an influence on the noise reduction, and the consequence of this on the various methodologies should be characterized. It is evident that microjets external to the nozzle have a clear potential in reducing the environmental noise.

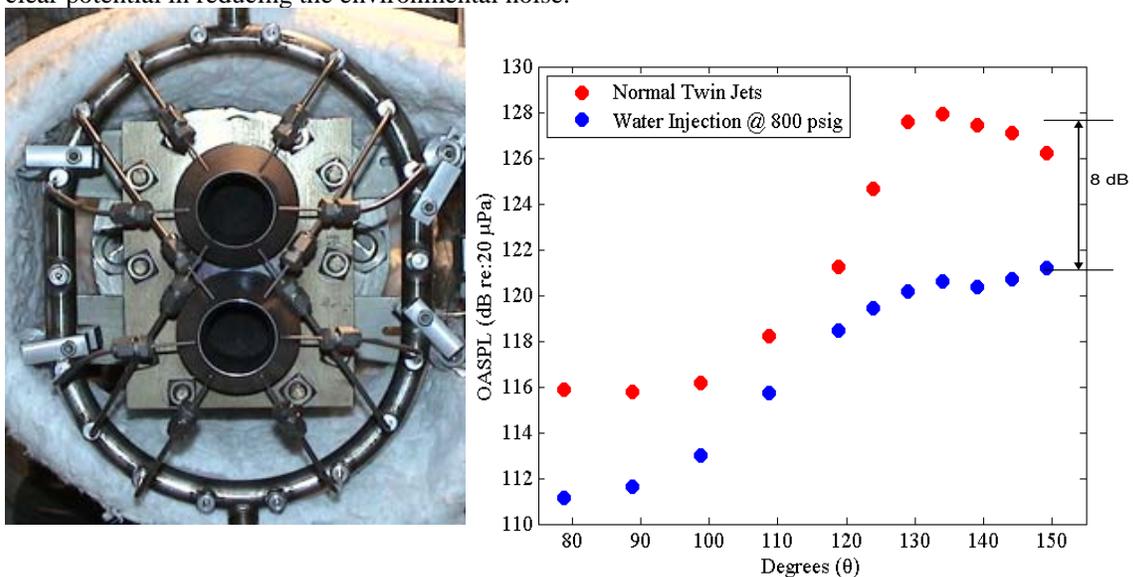


Figure 12 Far field noise directivity with twin nozzle configuration at Mil-Power with and without water injection at 800 psig.

3.12 Forward Flight Tests

The next step in determining the optimal methodology for jet noise reduction has been performed by a

Noise Issues Associated with Gas Turbine Powered Military Vehicles

series of forward flight tests at the Boeing LSAF test chamber in Seattle, Washington. Microjet injection, internal corrugations, bevelled nozzle and combinations were tested (scale models). Noise reductions with corrugations and with corrugations and water injection are shown for mil power and cut back power in figure 13 (a) and (b) (3). However, due to constraints in the availability of the test chamber and crew, the optimization was not done. From the tests it was evident that the microjet/internal corrugation provided better noise reduction than the bevelled nozzle/internal corrugation combination. Since carrying water on board will result in added weight, it was concluded that bevelled nozzle/ internal corrugation-a nozzle modification, and microjets as an external control will provide the maximum jet noise reduction. Figure 14 shows test results with internal seals and microjet combination (based on frequency spectrum).

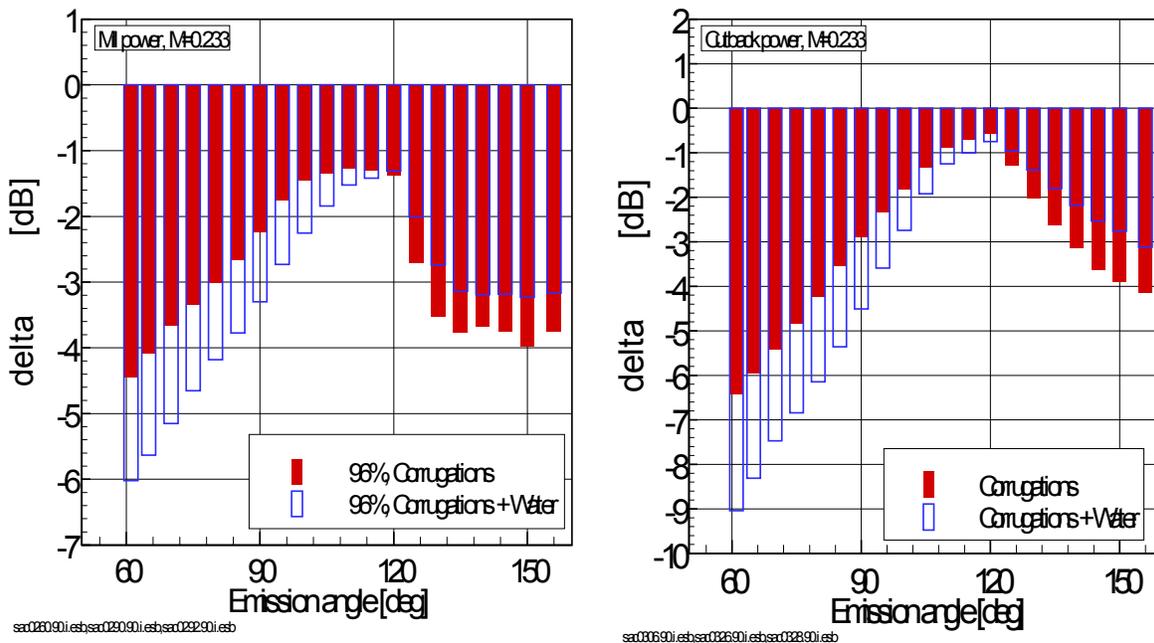


Figure 13 Noise reduction with corrugations and corrugation/water injection combinations (a) at Mil power (b) at Cutback power

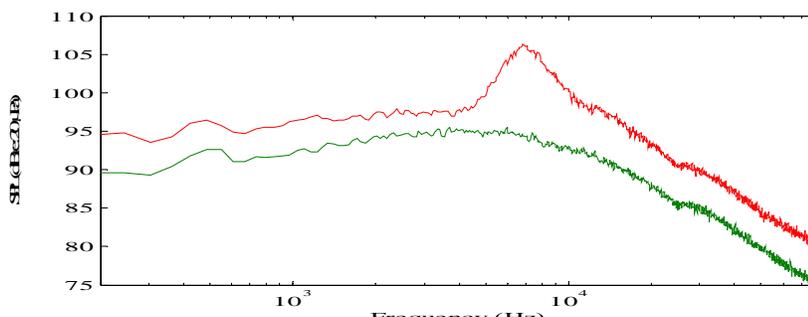


Figure 14 Internal seals & water injection

3.13 Computational Effort

Testing various concepts under varying operating conditions in wind tunnels and anechoic chambers is expensive and time consuming. To alleviate this problem, codes were written and validated with bench mark experiments. By controlling the similarity parameters in sub-scale testing, it is possible to mimic actual operating conditions. Combining this with the computational efforts, it was possible to tailor experiments and help in optimization. Computational model used and verified with model scales were extended to predict performance at larger scales. Tests indicated that the performance agreed with prediction. This gave the confidence to extend the predictions to full scale, and eliminate configurations that did not indicate desirable benefits. Computational studies included jets into still air with corrugated nozzles, bevelled nozzles, chevrons, microjets and varied combinations. Mean flow, turbulence characteristics, and thrust implications were calculated. A typical multi-element unstructured grid for internal corrugations (lobes) is shown in figure 15, and the TKE contours are shown earlier in figure 7. These studies were repeated for jets with external streams and verified with LSAF tests. Full-span model aero effects also were calculated.

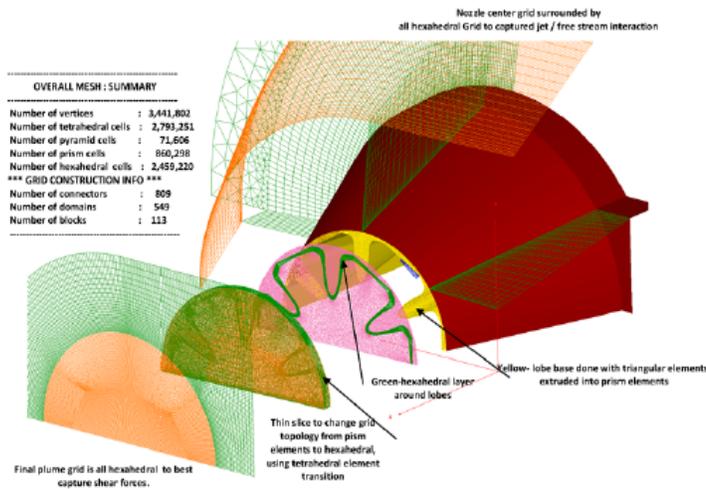


Figure 15 Multi-element Unstructured Grid for Nozzle with 6 Lobes

3.14 Flight Tests

Once the optimized configuration is determined from forward flight tests, the full scale configuration can be designed with confidence. Flight tests with optimal configurations installed will determine the actual noise reductions at various modes of operation (idle, take-off etc.) of the aircraft.

3.15 Measurement and Diagnostics

Sound or noise cannot be measured in absolute units like length or weight. Further the sound generated or received should be translated in terms of the effect perceived by the individual hearing the sound. Sound pressure level (SPL) is expressed in dB defined as a function of the measured pressure of the sound wave. Sound power level (PWL) has also the units of dB defined as a function of the measured power of the sound wave. The audible range for the human in ear is from 20Hz to 20KHz, and it filters more of the lower frequencies. The resulting SPL spectra is commonly A-weighted in order to account for the fact that the human ear is more sensitive to higher frequencies. The A-weighted results are presented in dBA and

Noise Issues Associated with Gas Turbine Powered Military Vehicles

covers the range of 20 to 20kHz. Laboratory scale measurements are A-weighted through the Strouhal number (St). $St=f D/u$, where f is the frequency, D is the nozzle diameter and u is the jet velocity. Further units such as PNdB, EPNdB are used for FAA licensing purposes. In order to make comparisons, and show the effectiveness of noise reduction, one has to be careful about the units.

Very carefully executed bench mark noise measurements taken at strategic locations of normal flyover, and with noise mitigation employed in aircrafts is necessary for comparison. Further measurements should be taken under identical flying conditions, and trajectories, weather conditions (wind, humidity, temperature), or should be carefully extrapolated.

With the advent of micro sensors, robust compact lasers and fast algorithms for in-situ data reduction, it is now possible to study in detail the jet structure, mixing scenario and the penetration of the noise control devices in the exhaust plume, and their effect in controlling the jet structure and to effect noise reduction. In particular, durable diode laser absorption, laser-induced fluorescence, and three-dimensional particle velocimetry offer valuable insight in to the jet mitigation process.

4.0 COMBUSTION FLOW GENERATED NOISE

The energy conversion process in the gas turbine engine (fuel to thrust) itself is a source of noise. Turbulence, vortex-droplet-interactions, unsteady heat release, the break-up of vortical structures into small-scale turbulence etc result in combustion pressure oscillations. Undesirable combustion instabilities develop when Rayleigh's criterion occurs. Various methodologies have been tried (both passive and active) to produce a uniform combustion and combustion flow.

4.1 Distributed Combustion:

In-order to achieve desirable pattern factors (resulting in uniform temperature distribution in the combustion chamber), reduce emissions (elimination of hot spots generating NO_x) and noise (from pressure fluctuations), distributed combustion, often called flameless combustion or high temperature air combustion has been a subject of worldwide research (4). Figure 16 shows three modes of combustion. In the distributed high temperature air combustion (flameless) mode, the flame becomes colorless, and produces the best pattern factor, minimal noise emission and reduced noise. Figure 17 shows the temperature distribution in the flameless mode compared with several other cases. As can be seen, in case 6, where the best distributed combustion mode is obtained, the temperature is uniform over the entire combustor length with minimum fluctuations and below NO_x formation levels. The situation is conducive for minimum noise.



Figure 16 Different Modes of Combustion

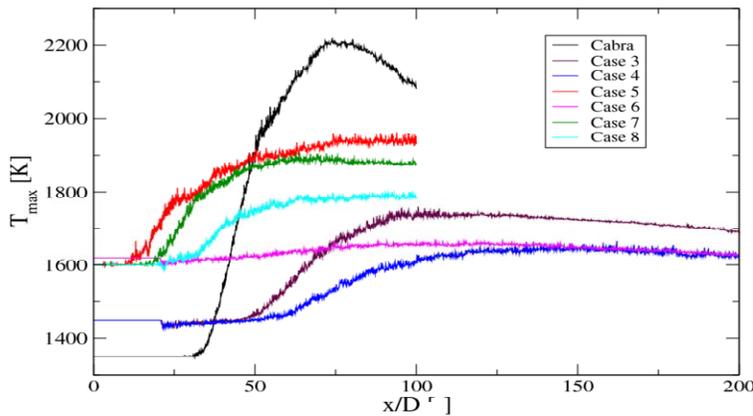


Figure 17 Temperature Profile comparison (conventional-flameless)

4.2 Porous Inserts

It has been shown experimentally and computationally that porous inserts in the combustion chamber, similar to one in a gas turbine engine, can influence the emission characteristics and temperature distribution (5,6), and preliminary investigations concluded that the noise also will be reduced. In a later study (7) high temperature HfC/SiC foam was placed in several locations within the reaction zone of the combustor. Experiments were conducted for a range of flame temperatures, foam thicknesses, and foam locations within the reaction zone. These tests identified a specific foam location that provided the greatest noise reduction. Testing showed that the noise reduction increased with increasing foam thickness, and the results are shown in Figure 18. The combustor generated 124 dB without the open-cell foam, and 113 dB with the optimal thickness, indicating a remarkable improvement of 11 dB over the baseline. Optimization of pore density can provide more noise reduction. The rings stayed in tact after testing (figure 19).

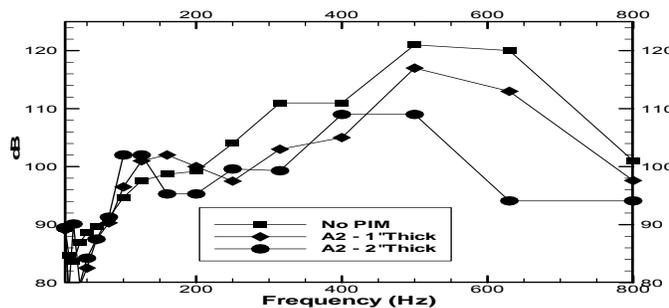


Figure 18 Variation of dB level in octave frequency bands ($\Phi = 0.85$) (Total noise with no PM:124 dB; A2 with 1" thick PM :119 dB; A2 with 2" thick PM :109 dB)

Noise Issues Associated with Gas Turbine Powered Military Vehicles

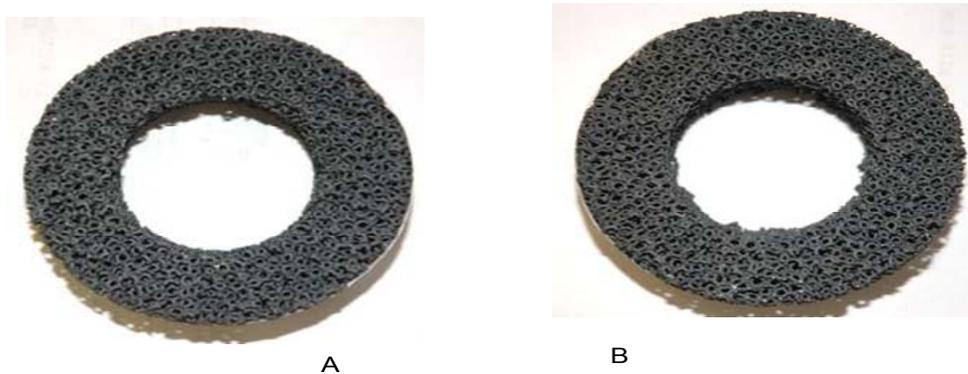


Figure 19: 1.0" thick ring placed in corner of recirculation zone fabricated from 20-ppi HfC/SiC-coated foam before (A) and after (B) hot-fire testing at 1800°C

Visual image of the flame are shown in figure 20 and 21 for two configurations. In figure 20, the left image shows a swirl-stabilized, lean premixed methane flame. A geometrically shaped foam structure placed at the combustor inlet (right image) reduced the combustion noise by 11 dB. In figure 21, a swirl-stabilized, lean premixed methane flame is shown on the left image. The open-cell foam disk placed downstream of the flame, shown in the right image reduced the combustion noise by 10dB (8).



Figure 20 Noise Reduction by a geometrically shaped foam structure.

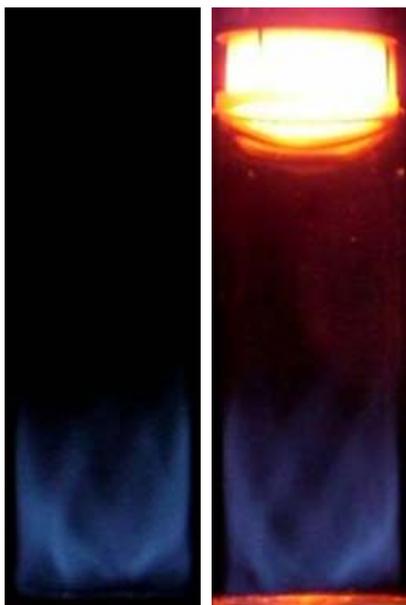


Figure 21 Noise Reduction with an open-cell foam disk

4.3 Combustion Control:

Both passive and active combustion control have been investigated over the past two decades to reduce combustor pressure oscillations and instability, thereby improve performance and extend life of the combustor. Important among these studies are non axi-symmetrical nozzles-square, rectangular, and elliptical cross section, where axis switching phenomenon and simultaneous formation of large and small scale structures resulted in reduced pressure oscillation; convoluted splitter, counter currents steer layer etc (9).

Recent efforts focussed on developing new generation fuel injector that can produce precisely the required droplet-size and distribution (11), as well as different methods for fuel air mixing enhancement (12). In the former study, the large strain and high coupling properties of piezoelectric single crystals are used to replace the currently used piezo ceramic actuators. This results in greater stoke and force, with faster response time allowing for more effective electronic control of fuel injection. In the latter study thin wedge-shaped fin that guides transverse penetration of fuel jet is examined for improved fuel air mixing yielding better supersonic combustion, and reduced pressure oscillations and consequent noise.

5.0 AEROACOUSTICS AND PSYCHOACOUSTICS:

The impact of noise generated by military aircraft cannot be assessed from a through understanding of the noise phenomenon alone. The advances made recently in understanding the noise sources and generation of noise, its propagation and control has made it possible to a great extent, though not sufficient extent, to reduce the level of noise exposure and its physiological effects. However, different individuals' response to the same noise level may be different and the psycho acoustic phenomena need to be understood. A certain sound level can be just an annoyance to one, where as it may be a real problem for another since each person's reaction to noise depends on his or her tolerance level. This depends not only on the physiological and psychological aspect, but also can depend upon the attitude of the person. As in any physiological or medical research, the scientific basis of aeracoustics is not sufficient input data. The perception of noise has to be studied with various individuals and a statistical/scientific criteria need to be developed. The individuals who could be subjected to these extreme noise levels should be made aware of (through education, communication and direct interaction), the different noise pattern from different aircrafts, the dB levels and impact and be prepared and avoid any psychological shock. To this extent

Noise Issues Associated with Gas Turbine Powered Military Vehicles

systematic studies have been conducted and training is available in controlled simulation chambers (13).

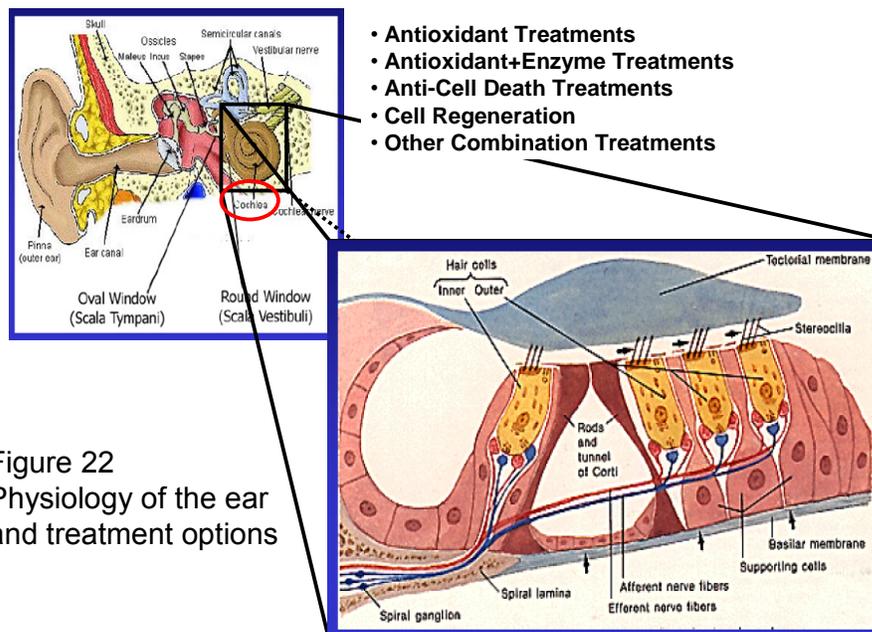


Figure 22
Physiology of the ear
and treatment options

6.0 EAR PROTECTION, HEARING LOSS PREVENTION AND RESTORATION

Having done all that is practically possible, any individual subjected to the high noise levels should be protected by simple ear plugs to sophisticated state-of-the-art custom-made personal protection Equipment (PPE) according to the noise environment. Active-noise cancellation technology utilization in the PPE will also improve communications.

6.1 Ear Protection

The physiology of the human ear is very complicated (figure 22), and the physical dimensions and sensitivity can vary from person to person, which require production of custom-made PPEs, training to ensure proper wearing of the device, and also to make them comfortable to wear in terms of weight and fit. Extensive research is going on in these areas. Current earplugs, if properly worn, can reduce noise levels from a 100 dB environment, and double hearing protection from a 110 dB level. Noise reduction up to 45dB+ has been obtained by modern PPEs, and will improve with continued research. Customized ear plugs with dosimetry offer promise.

6.2 Hearing Preservation and Restoration

A successful mission depends upon the effective communications between the crews and to the pilots. In an extremely high noise environment such as a carrier deck, this often becomes a problem, and at times the human tendency is to remove the hearing protection device in spite of the training they had. Such exposures can induce acoustic trauma which results in damage to the cells and can often result in sensory-neural hearing loss. Another consequence of exposure to high levels of sound is tinnitus or ringing in the ears. Medical intervention will be required to deal with these conditions.

Research has been focussing on prevention of these impairments as well as on the restoration of the damage once it has occurred. Medical treatment included drugs with antidepressants (such as, sertraline, Trazodone, Paroxetine, Nortriptyline, etc) and without antidepressants (such as, Memantine, Acamprosate, Modafinil, Vardenafil etc). Treatments offering maximum efficacy and minimum side effects are expected

Noise Issues Associated with Gas Turbine Powered Military Vehicles

to be in the horizon.

Prevention of potential noise related medical problems is also getting increased attention, as a means to inhibit the adverse effects. Antioxidants and Glucocorticoids and a host of other medications are being investigated. On going studies also include anti-cell death treatments and cell regeneration, as well as combination of treatments.

It has been found that the physiological response to noise can be influenced (in the present case) by the type of fuel exhaust that generates the noise. Exhausts from combustion of fuels like JP-10 or JP-8 could be more detrimental (14). This leaves the research for alternative fuels with no such adverse effects wide open.

CONCLUSION

Focussed research during the past several years resulted in innovative noise reduction concepts. The most effective passive control appears to be on optimized combination utilizing internal corrugation and bevelling of the nozzle exit. This combination enables ideally expanded jet conditions during take-off manoeuvres, and did not exhibit any thrust penalty. Though microjet water injection or pulsed jet with reduced flow rate has the capability of reducing noise and in combination with others can considerably enhance noise reduction, it is not a viable option due to the excess weight of water to be carried on board aircrafts. However, this is an excellent option for external control, particularly during idle and take-off, and can be actively controlled.

Combustion-generated noise is also an issue. Turbulence vortex interaction, unsteady heat release and temperature fluctuations lead to combustion pressure oscillations (instability) and noise. Active combustion control, distributed combustion (often called flameless combustion) and porous inserts in the combustion chamber have shown to substantially suppress combustion instability and noise. The impact of this noise reduction in the overall audible noise needs to be determined systematically.

Future studies should include near-field jet noise characterization and reduction, strategic personnel placement (for carrier deck operation), carrier deck noise transmission reduction, jet impingement source noise reduction (VTOL), deck erosion mitigation (VTOL on carrier deck) etc. Other avenues include novel nozzle designs (non-axi symmetric nozzles, ejector systems, active flow control), and highly integrated propulsion system and airframes. Support studies should include high temperature flow diagnostics, high fidelity numerical simulations (LES, RANS, etc.), scaling, laws and system performance analysis.

The advancements made in the hearing protection devices scaling should be capitalized for use effectively (custom-fit), and research should focus on reducing weight, improve the noise reduction band and affordability. Pharmaceutical research is paving the way for prevention as well as restoration of noise related health predicaments. The psychological effect of noise should be addressed by community awareness and education programs, and knowledge of noise implications. The war on noise will be won if researchers and scientists from the disciplines involved join together and contribute, collaborate and communicate (the C³ formula). The sailors, marines and crew can come back home, mission after mission with the same hearing ability with which they started their military careers, and the community surrounding the bases can still say the aircraft noise is, “the sound of freedom”.

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Noise Issues Associated with Gas Turbine Powered Military Vehicles

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