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Sound Attenuation Performance of Fiber-reinforced Polymer Composite Circumaural Hearing Protection Devices

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by

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List of Abbreviations

3M	Minnesota Mining and Manufacturing Company
ABMA	Aviation Boatswain's Mate Association
ABS	Acrylonitrile Butadiene Styrene
ANSI	American National Standards Institute
ATF	Acoustical Test Fixture
CAHPD	Circumaural Hearing Protective Device, Circumaural Hearing Protection Device
dB	Decibel
FDC	Flight Deck Crewmen
FRPC	Fiber-reinforced thermoset Polymer Composite
HDPE	High Density Polyethylene
HPD	Hearing Protective Device
JOLENE	Dangerous Decibels® Test Manikin
KEMAR	Knowles Electronics Manikin for Acoustic Research
LSO	Landing Signal Officer
MIRE	Microphone in Real Ear
NASA	National Aeronautics and Space Administration
NIHL	Noise Induced Hearing Loss
NRR	Noise Reduction Rating
OE	Original Equipment
REAT	Real Ear at Threshold

SD	Standard Deviation
SLM	Sound Level Meter
SPL	Sound Pressure Level
USN	United States Navy

Abstract

Personnel who work on the flight deck of an aircraft carrier are exposed to extreme levels of jet engine noise often in excess of 140 decibels (dB). The current circumaural hearing protective devices (CAHPD) employed by flight deck crewmen are inadequate for the level of protection required for these extreme levels of noise. Fiber-reinforced thermoset polymer composite (FRPC) materials such as aramid fibers used in body armor, have high theoretical values of acoustic impedance due to a fundamentally high modulus of elasticity and may offer a superior level of hearing protection over original equipment (OE) thermoplastic CAHPDs. The objective of this project was to measure and evaluate the attenuation of CAHPD's constructed from FRPC materials. FRPC CAHPD ear cups were paired with OE thermoplastic CAHPD ear cups of equal shape and thickness, and the protected and unprotected A-weighted sound pressure level (SPL) was measured in continuous and impulse noise environments >80 dBA using a JOLENE manikin. These data were evaluated for paired differences between the protected and unprotected mean SPL, and OE protected and FRPC protected mean SPL and indicates that OE thermoplastic CAHPDs provide greater sound attenuation of continuous noise >80 dBA and aramid FRPC CAHPDs provide greater sound attenuation of impulse noise >80 dBA.

Introduction

Background

The United States Navy (USN) flight deck crewmen (FDC) are exposed to extreme noise levels from the launching and arrestment of jet aircraft from the deck of an aircraft carrier at sea (see Figure 1). The circumaural hearing protection devices (CAHPD) issued to flight deck crewmen provide inadequate protection from the noise, which can lead to noise induced hearing loss. The flight deck noise level can reach levels above 140 dB requiring the use of double hearing protection. Double hearing protection can attenuate up to 30 dB of noise if worn correctly but insufficient when the noise level can approach short bursts of 150 dB during intermittent launching and arrestment events to include impulse noise from catapult water-brakes.

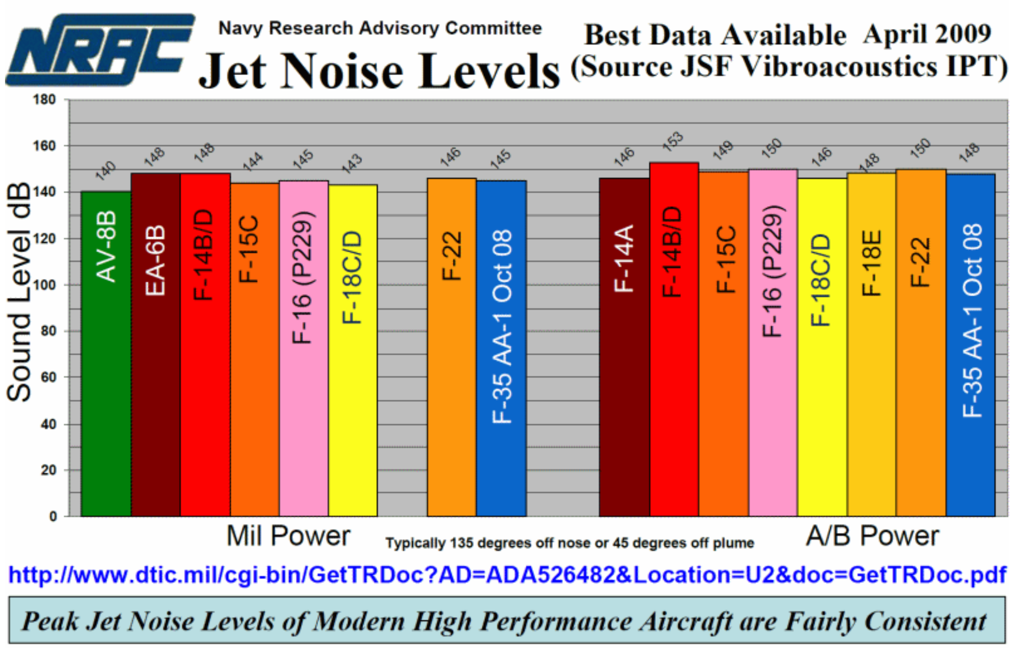

Figure 1 - Flight Deck Noise from Launching Aircraft

Flight deck crewmen can spend upwards of 8-16 hours a day in this environment and are consistently in danger of exceeding their maximum noise dose. Dangers from rotating prop arcs, jet intakes and taxiing aircraft in close quarters, reduced situational awareness and difficulty using helmet mounted communication devices often lead to the decision to decline the use of double hearing protection.

The current CAHPD employed by flight deck crewmen is constructed of polyurethane foam lined high density polyethylene (HDPE) ear cups with removable foam filled ear seals. This FDC CAHPD and its sound powered variant were determined to have reached the limits of their usefulness by the USN Aviation Boatswain's Mates Association (ABMA) and an improved replacement is the number one priority of the ABMA due to major hearing loss trends and compromised safety of flight issues from degraded communications (ABMA, 2014).

Composites are becoming more popular sound absorbing materials and CAHPDs constructed from Fiber-reinforced thermoset Polymer Composite (FRPC) materials may provide an advantage over conventional original equipment (OE) thermoplastic CAHPDs at attenuating extreme noise due to their high modulus of elasticity and distinct energy absorption properties observed in other applications such as body armor. Commercially available CAHPD's are constructed from blow-molded and injection-molded thermoplastics and are easy to manufacture and low cost. There is zero availability of FRPC constructed CAHPDs due to the complexity of manufacturing and high cost so the attenuation performance of FRPC constructed CAHPDs is not fully understood.

Purpose

The purpose of this research effort was to evaluate the sound attenuation performance of FRPC constructed CAHPDs and determine whether they offer an improved level of hearing protection when compared to OE thermoplastic CAHPDs. The research questions are:

a. For impulse noise above 80 dBA, do FRPC CAHPDs better attenuate sound than CAHPDs made from thermoplastic materials of equal shape and thickness?

b. For continuous noise above 80 dBA, do FRPC CAHPDs better attenuate sound than CAHPDs made from thermoplastic materials of equal shape and thickness?

Discovery of a measurable sound attenuation advantage from FRPC CAHPDs may lead to future innovations of CAHPD design and consideration of composite materials in their construction for the benefit of servicemen and women exposed to extreme noise such as flight deck operations.

Literature Review

Flight Deck Exposures

Early research on flight deck noise exposure includes a characterization of USN Landing Signal Officer (LSO) flight deck noise exposure (Robertson, Maxwell, & Williams, 1979). LSOs enter the flight deck without protective gear and only disposable ear plugs – often in a signal ear – because they must communicate with the pilots on approach from a platform on the starboard side of the aircraft carrier (see Figure 3). A forward platform shield provides some protection from flying debris but hearing protection is limited to foam plugs or a single plug if on phone talker duty. A 1979 study of LSO noise exposure confirmed the potential for noised induced hearing loss under current conditions and due to the situational awareness required of LSO's to perform their duties, CAHPD's adaptable to other in use communications equipment which enable the LSO to retain the essential auditory cues is the only feasible alternative but not commercially available (Robertson, Maxwell, & Williams, 1979).

Other personnel on the flight deck, even with the required CAHPD's, are also at risk of noise induced hearing loss. A case control study of USN flight deck crewmen, engineering crewmen and administrative crewmen occupational noise exposure found flight deck crewmen exposure to be higher than administrative and engineering personnel at 109 dBA time weighted average over 11.5 hours with increased prevalence of permanent threshold shifts (Rovig, Bohnker, & Page, 2004). This study also found that 29% of flight deck personnel experienced a temporary threshold shift after their shift largely due to them not wearing double hearing protection.

Figure 2 - LSO Flight Deck Operations

In 2005, the USN conducted a study to evaluate the level of protection offered by the current hearing protection in use on the flight deck and the level of compliance with hearing conservation program requirements. This study found that 79% of flight deck personnel received little to no protection from ear plugs due to not being inserted correctly or not worn at all. Several other conditions were found to contribute to a reduction in attenuation including leaks under ear cup seals, improperly sized helmets, poorly maintained helmets, missing foam inserts, eyewear, and other head gear interfering with the ear cup seal (Bjorn, Albery, Shilling, & McKinley, 2005).

Situational Awareness

Reduced situational awareness and degraded communications are legitimate threats to the safety of flight for flight deck crewmen. The effects of protective equipment on situational awareness has been examined in a 1999 study which explored the impact of hearing protection and protective headgear on human subjects ability to localize sound (Vause & Grantham, 1999). Localization error was present in all directions from all combinations of protective gear worn when compared to a bare head condition indicating the test subjects had difficulty discriminating between front-to-back or left-to-right sound sources. These findings are significant in any environment where the physical hazards require protective headgear, hearing protection and localization of sound such as the carrier flight deck. Commercially available CAHPDs may exist as passive or active devices and manufacturers of active or electronic CAHPDs often claim the end user retains lost sound localization through an internal amplifier that shuts off when a threshold of noise is exceeded. A sound localization study in 2007 examined electronic hearing protectors and found they did not preserve localization under most conditions (Carmichel, Harris, & Story, 2007).

HPD Attenuation Evaluation Methods

There are several methods for determining the attenuation rating of HPDs. The gold standard method is the subjective real ear at threshold method (REAT) where the noise reduction rating (NRR) is determined based on subjective responses from test subjects under protected and unprotected conditions. This method was benchmarked by the U.S. Environmental Protection Agency in part 211 of title 40 Code of Federal Regulations adopting the American National Standards Institute 1957 (ANSI Z24.22), 1974 (ANSI S3.19), 1984 and revised 1997 (ANSI

S12.6) REAT standards as the federally mandated method for determining HPD attenuation (USEPA, 1979). These laboratory determined NRRs are not always representative of real world attenuation and the Occupational Safety and Health Administration (OSHA) requires a 7 dB subtraction from the NRR when calculating a worker's A-weighted time weighted average noise dose (U.S. Department of Labor, 2015).

Two other objective methods to measure HPD attenuation include the microphone in real ear (MIRE) and acoustical test fixture (ATF) methods. The MIRE and ATF methods were adopted in ANSI standard S12.42 to test HPD attenuation which employs an inner and outer ear microphone to measure the insertion loss using human subjects or manikins respectively.

All methods have inherent limitations and sources of error in capturing real-world performance of HPDs most notably is the loss of bone and tissue conduction pathways with MIRE and ATF as well as other static and dynamic factors affecting attenuation such as fit and wear differences between users, and disruptions in ear cup seals from jaw, head and torso movement or differences in hair length or interference from other protective gear.

Both MIRE and ATF methods were evaluated in a 2010 study to determine HPD attenuation with respect to frequency (Zera & Mlynski, 2010). The investigators found that 1) frequency responses between test subjects could vary up to 10 dB, 2) MIRE was only a rough estimate of REAT, 3) resonances specific to the ear muffs being tested could be detected using MIRE, and 4) ATF testing resulted in strong dips and peaks in frequency response.

In a similar study in 2011 at the 3M Occupational Health and Safety Laboratory, an attempt to validate field-microphone in real ear (F-MIRE) as a viable method for measuring hearing protector attenuation was a primary objective. The investigators determined that measurement uncertainty of both REAT and MIRE were largely attributable to HPD fit variability but on average F-MIRE was a reliable indicator of REAT with some individual measurement variability of up to 10 dB at higher frequencies (Berger, Voix, Kieper, & Cocq, 2011). The implications of this study may suggest that due to uncertainty with both REAT and MIRE, neither method could be considered a more reliable measurement of real-world attenuation.

ATFs have been deployed successfully in the laboratory and the workplace to measure impulse noise but some conflicting evidence exists suggesting that measurement of attenuation using ATFs is an overestimation while other studies have observed large discrepancies between REAT and ATF only in the higher frequencies (Zera & Mlynski, 2007). A 2007 study investigating HPD attenuation of impulse noise using an ATF found that effective attenuation of impulse noise was dependent upon the impulse duration in addition to ear cup volume. This study also found that impulse rise time and duration increases between inner and outer HPD measurement. The investigators concluded that A-weighted time-weighted average criteria for estimating safe levels of exposure underestimates the risk for impulse noise without incorporating the change of impulse noise duration detected under the HPD (Zera & Mlynski, 2007).

The United States Army was interested in extreme noise exposures from free-field blast overpressures. Assessment of under ear muff exposure to impulse noise was conducted with human subjects to evaluate the safe exposure levels to noise from detonation of explosive materials. These investigators found that the Army's standard method for estimating the hazard to hearing in terms of safe exposure levels to impulse noise was over-estimated when applied to under-earmuff noise data (Patterson, Mozo, Gordon, Canales, & Johnson, 1997).

Velocity of Sound in a Medium

Sound can be reflected, transmitted, and absorbed upon transfer from one medium to another such as from air to a CAHPD. All three effects contribute to the overall attenuation of a sound wave and are important when selecting materials that are appropriate and effective. CAHPD ear cups should be constructed from materials with high sound reflection performance and the ear cup inner lining material should be constructed from materials with high sound absorption performance to dissipate the sound not reflected by the ear cup. Materials with the best sound reflection properties have a high acoustic impedance and a high elastic modulus.

The magnitude of sound reflected is proportional to the square of the ratio of the impedance (Z) between the two mediums (see Figure 3). Acoustic Impedance is the resistance of the transmission of sound through a medium and is directly proportional to the density (ρ) of the medium and the velocity (V) of sound through the medium (see Figure 3). The velocity of sound in a medium is inversely proportional to the square-root of the density and directly proportional to the square-root of the bulk modulus (β) for fluids, Young's modulus for solids with a small cross-section, and the sum of the bulk modulus and four-thirds the shear modulus (G) for solids with a large cross-section (see Figure 3).

The widely accepted method for measuring sound absorption properties of different materials over a wide range of frequencies is the two-microphone transfer function method which measures the fraction of sound wave energy traveling through or reflected by a material sample in an impedance tube. This coefficient of sound absorption can range from 0 – 1 where 1 is 100% absorption.

$$\text{Reflection (R)} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2$$

$$\text{Acoustic Impedance} = (Z) = \rho \text{ X } V$$

$$V_{\text{Fluids}} = \sqrt{\frac{\beta}{\rho}}, \quad V_{\text{Solids(SX)}} = \sqrt{\frac{E}{\rho}}, \quad V_{\text{Solids(LX)}} = \sqrt{\frac{\beta + \left(\frac{4}{3}\right)G}{\rho}}$$

Figure 3 - Acoustic Relationships (Crane & Rummel, 2002) *&* (Irvine, 2000)

<u>Composites in Sound Attenuation</u>

Among the largest differences in impedance from air are the FRPC materials (see Table I). Given these large theoretical values of acoustic impedance, FRPC constructed CAHPDs may offer a higher level of hearing protection than OE thermoplastic CAHPDs and the inherent energy absorption properties of aramid fibers seen in other ballistic applications may contribute to additional impulse sound attenuation resulting in a measureable advantage to incorporating aramid fibers in the construction of CAHPDs.

Table I - Material Acoustic Properties[1]

Material	Density (ρ) - (Kg/m^3)	Bulk Modulus (β) - (N/m^2) x10^9	Shear Modulus (G) - (N/m^2) x10^9	Young's Modulus (E) - (N/m^2) x10^9	Velocity (V) - (m/s)	Acoustic Impedance (Z) - kg/(m^2*s) x10^3
Air @ NTP	1.21	0.000143	N/A	N/A	344	0.416
HDPE	950	N/A	N/A	0.4-1.0	650 - 1025	618 - 974
ABS	1000	N/A	N/A	1.9 - 3.1	1378 - 1761	1509 - 1928
Aramid FRPC	1440	17	5	30	4564	6572
Glass FRPC	1900	14	4	25	3627	6891
Carbon FRPC	1600	29	5	70	6614	10582
Concrete	2400	14 - 41	18 - 23	29 - 86	3980 - 5465	9552 - 13115

Composite materials are becoming more popular alternatives for many other materials in industry due to their excellent strength to weight, heat and corrosion resistance, and energy absorption properties – including sound energy. Synthetic aramid fibers like Nomex™ and Kevlar™ were first introduced in the 60s and 70s by the DuPont company with excellent fire retardant and ballistic potential with a very good reputation for use in firefighting ensembles and military or law enforcement body armor and other protective equipment respectively (Du Pont, 2015). A 1979 NASA study concluded that Kevlar™ 29 was an efficient sound absorber even at low frequencies (Hersh & Walker, 1979).

Research pertaining to sound absorption properties of FRPC materials is primarily recycled and natural reinforcing materials for noise control applications. A 2010 article in *Sound*

[1] The values listed in Table I were obtained from a combination of literature sources (Howard & Angus, 2009) & (Irvine, 2000) and material product data sheets (INEOS, 2015) & (ACP Composites, 2014) and are included as reference information to illustrate the magnitude of the theoretical acoustic impedance only.

and Vibration identified porous materials that are either cellular, fibrous, or granular, as having the highest coefficients of sound absorption (Arenas & Crocker, 2010). A 2011 study of micro-perforated aramid materials found that sound absorption coefficients increased significantly with the addition of an aramid paper liner to an aramid felt and further improvement was observed with micro-perforated aramid paper and demonstrated that controlling the perforation ratio would translate to absorption improvements across different frequency ranges (Yifang, Yannian, Hongwei, & Xin, 2011).

Investigations into the sound absorption properties of reinforcing urethane foams and polypropylene thermoplastics with natural fibers such as kenaf and tea-leaf fibers produced mixed results with no measureable improvement using kenaf and improved sound absorption results for tea-leaf fibers with the added benefit of using waste material in the development of new environmentally friendly products (Jayamani & Hamdan, 2013) & (Ekici, Kentli, & Kucuk, 2012). A 2012 study investigating recycled wood and rubber composites as potential new sound control materials found that all samples of variable quantities of pine sawdust with recycled rubber in a polyurethane matrix exhibited good sound absorption across a wide range of frequencies (Borlea, Rusu, & Vasile, 2012).

FRPC CAHPDs are not commercially available likely due to the difficulty with manufacturing and mass production but considering the relatively large theoretical values of acoustic impedance of FRPC materials and proven energy absorption properties of aramid fibers observed in protective equipment like helmets and body armor, CAHPDs constructed from FRPC materials may have very good sound attenuation potential and should be explored.

Methods

JOLENE Manikin

Measuring HPD sound attenuation was conducted using an ATF to isolate attenuation provided by the HPD ear cups and measure sound attenuation from continuous and impulse noise >80 dBA. A commercially available ATF such as the KEMAR™ manikin was not in the USF inventory, and not feasible in terms of cost for this project. An alternative cost-effective HPD test fixture based on the JOLENE manikin concept developed for the Dangerous Decibels Project (OHSU, PSU, UNC, 2014) was constructed and deployed to collect attenuation data (see Figure 4). The Dangerous Decibels Project was a partnered public health campaign launched by Oregon Health and Science University, Portland State University and the University of Northern Colorado to lower Noise Induced Hearing Loss (NIHL) through public awareness. The JOLENE cookbook is available as a free download on the Dangerous decibels website and provides detailed instructions on construction of the manikin (OHSU, PSU, UNC, 2013). JOLENE was not designed to serve as a test fixture for measuring hearing protection attenuation so modifications to the original concept were necessary and include dual (left and right) Wensn type II data-logging Sound Level Meters (SLM) with a measuring range of 30 – 130 dBA, accuracy of +/- 1.5 dB, and a sample rate of two times per second; and installation of the SLM microphone posts into the silicone ear inserts to facilitate extension for calibration purposes (see Figure 5).

Figure 4 - JOLENE Test Fixture

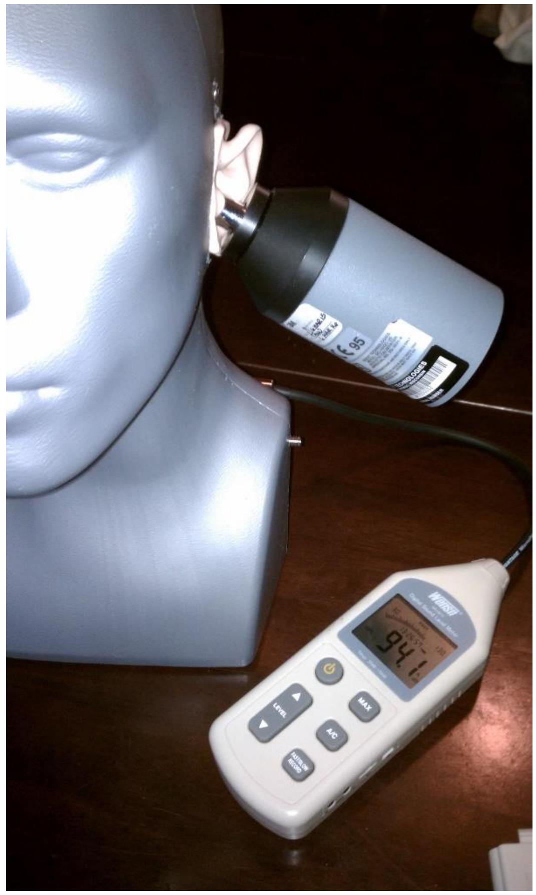

Figure 5 - JOLENE Calibration

<u>CAHPD Selection and Construction</u>

A pair of commercially available CAHPD's with removable ear seals were acquired from an online vendor based on the most popular or best-selling industry and recreational use passive CAHPDs (see Figure 6) in addition to standard military issue FDC CAHPDs (see Figure 7).

Figure 6 - 3M X1A Peltor (3M OE)

Figure 7 - David Clark MIL-A-23899 (FDC OE)

The foam liners were discarded to isolate the attenuation provided by the ear cups only. The 3M OE CAHPD has an NRR of 22 dB and is made from a blend of Acrylonitrile Butadiene Styrene (ABS) and Polyurethane thermoplastics. The FDC OE CAHPD has an NRR of 21 dB and is made from High Density Polyethylene (HDPE) thermoplastics.[2] These two CAHPDs will serve as the control group for this research effort. FRPC ear cups were constructed using one of the ear cups from each control CAHPD to construct a plaster mold and a common vacuum bagging technique (see Figure 8) of epoxy resin and reinforcing fiber to best replicate the geometry of the OE ear cup (Mallick, 2007).

[2] The terms "3M" and "FDC" will indicate the shape of the ear cup followed by an "OE" or "FRPC" to indicate if the material is original equipment thermoplastic construction or fiber-reinforced thermoset polymer composite construction respectively. Example: 3M OE refers to figure 6 above and 3M FRPC refers to figure 11 below.

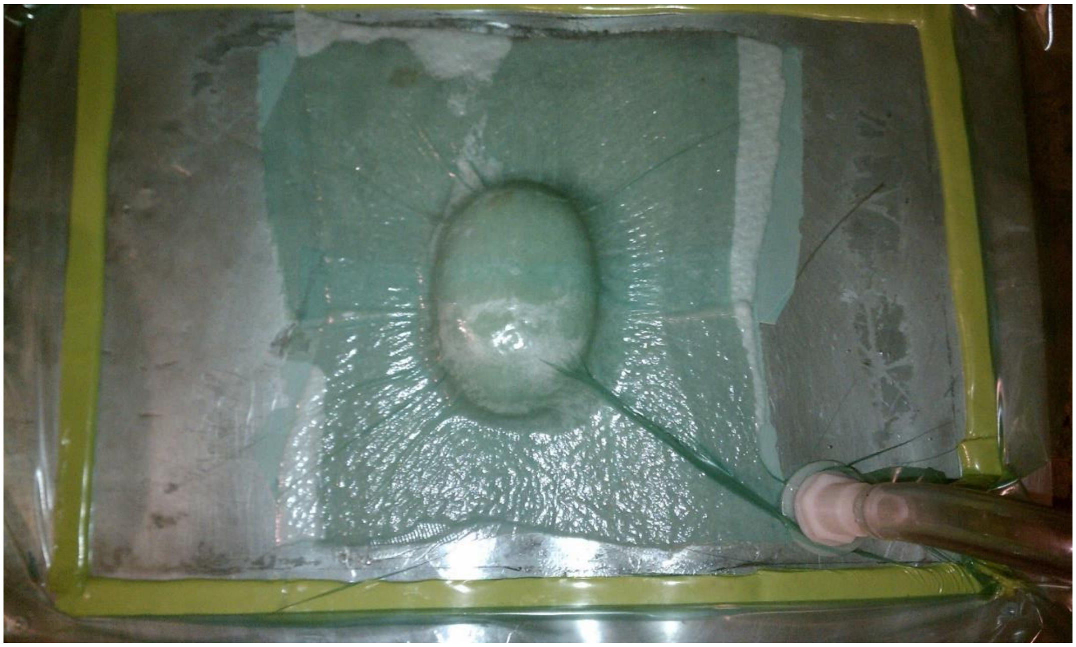

Figure 8 - FRPC Vacuum Bagging

To achieve equal material thickness, both the 3M OE and FDC OE ear cups were measured to be approximately 3mm thick and 12 layers of fabric was determined to equal 3mm based on a four layer laminate measurement of 1mm for a plain weave fabric. The epoxy resin mixing ratio (100:23 by weight per manufacturer's instructions) remained constant totaling 50 grams resin and 11.5 grams hardener for each FRPC ear cup resulting in sufficient volume for complete fiber impregnation. Fiber orientation (0°/90°) also remained constant for all FRPC ear cups. After curing for 24 hours, the composite ear cups were removed from the mold and excess laminate removed with a jigsaw and rotary tools until a good fit was achieved with the OE ear seals. This finishing step proved to be more difficult for the 3M FRPC ear cups due to the snap fit of the 3M OE ear seals and an alternative ear seal was employed in this test set. Small machine screws were installed onto the composite ear cups with rubber seals to act as posts for mounting to the OE headband.

The variables include three types of reinforcing fibers (glass, carbon and aramid) with approximately the same thickness and geometry as its paired OE ear cup. The OE headbands were reassembled with OE ear cups and FRPC ear cups for a total of six combinations for testing and analysis of impact and continuous noise >80 dB (see Figures 9 thru 11). A-weighted sound pressure level (SPL) data for continuous and impulse noise was collected simultaneously for 10-20 minutes of each ear cup combination using the JOLENE manikin inner ear SLM microphones in addition to an external SLM as the reference baseline to determine the mean difference between the protected and unprotected SPL and if any difference between ear cups is observed based on a paired difference T-test.

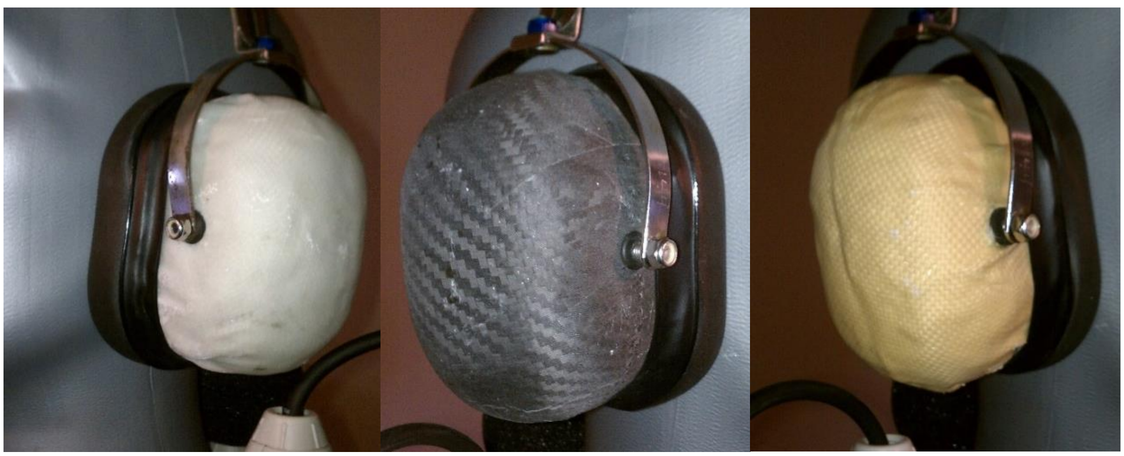

Figure 9 - FDC FRPC Ear Cups (left to right: Glass, Carbon, Aramid)

Figure 10 - OE Ear cups (left to right: FDC and 3M)

Figure 11 - 3M FRPC Ear Cups (left to right: Glass, Carbon, Aramid)

Data Collection

12 and 20 gauge shotgun impulse noise data were collected during a Tampa Sport Clay Shooting Tournament on March 21st, 2015. The temperature was 69°F, the atmospheric pressure was 30.1 inHg, and the relative humidity was 65%. There were approximately 200 shooters on three different outdoor courses located in a wooded area. The test manikin was set-up approximately 5 meters from Station 1 (see Figure 12) and collected data on 5 of the 6 combinations of ear cups – laptop battery life prevented data collection on the 6th test set. All three SLMs were set to collect noise data simultaneously using the following parameters: A-weighting, fast response, and 30 – 130 dB range. Each test run lasted between 5-15 minutes with sound levels ranging from 55 – 120 dBA. Some technical difficulties were experienced such as data-logging interruptions and screen timeouts, which resulted in some shorter duration test intervals than desired. Following the shoot, the internal and external data were paired by time

and filtered in excel by external values >80dBA. All three SLMs were pre-and-post calibrated at 94 dBA and 1000 Hz using a Quest QC-20 calibrator and within +/- 0.5 dBA.

Figure 12 - Sport Clay Shoot

Continuous noise data collection was conducted at a plasma spray industrial process on May 6th, 2015. The temperature was 66°F, the atmospheric pressure was 30.1 inHg, and the relative humidity was 66%. Plasma spray operations involve the high temperature application of surface coatings using inert gases and high voltage which emitted continuous noise between 100-120 dB depending upon equipment settings. The spray nozzle and work area were confined in a

12’ x 12’ indoor space and separated from the equipment controls making this an ideal location to collect noise data as the machinery was able to be switched off remotely to facilitate earmuff changes. The test manikin was set-up approximately 3 meters from the spray nozzle and noise data collected on all six test combinations (see Figure 13). All three SLMs were set to collect noise data simultaneously using the following parameters: A-weighting, fast response, and 30 – 130 dB range. Each test run was 15-20 minutes and all three SLMs were pre-and-post calibrated at 94 dBA and 1000 Hz using a Quest QC-20 calibrator and within +/- 1.7 dBA.

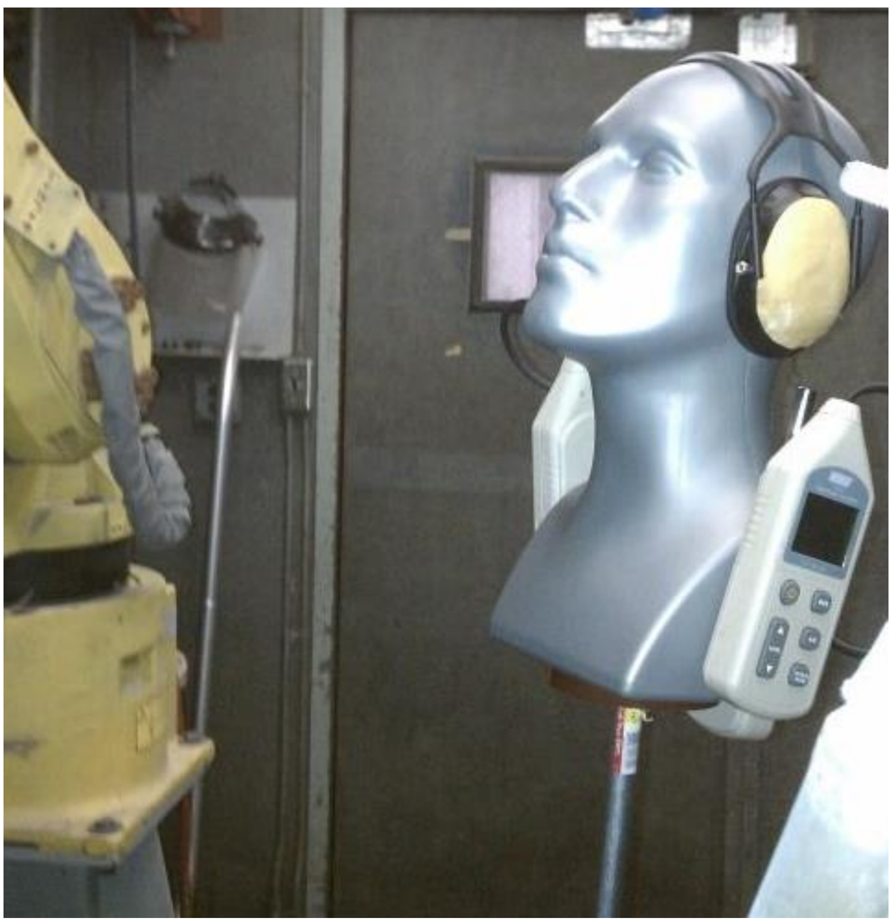

Figure 13 - Plasma Spray

Results

Impulse Noise: Clay Sport Shooting Data is shown in Tables II thru VII and Figures 14 thru 19

Table II - Impulse Noise CAHPD Attenuation

Clay Sport Shooting Noise Summary Data Sheet (80 dBA cut-off)					
FDC OE vs Carbon FRPC (Time: 0949 - 1001)					
	Min (dBA)	Max (dBA)	Mean (dBA)	SD (dBA)	Mean Attenuation (dBA)
Unprotected	80.1	118.8	90.0	11.3	N/A
OE Left	65.7	101.4	71.8	6.1	18.2
FRPC Right	65	105	71.5	7.9	18.5
3M OE vs Glass FRPC (Time: 1013 - 1020)					
	Min (dBA)	Max (dBA)	Mean (dBA)	SD (dBA)	Mean Attenuation (dBA)
Unprotected	80.8	117.6	93.6	12.2	N/A
OE Left	64.0	78.1	68.7	4.0	24.9
FRPC Right	64.2	79.1	68.6	4.3	25.0
FDC OE vs Aramid FRPC (Time: 1036 - 1046)					
	Min (dBA)	Max (dBA)	Mean (dBA)	SD (dBA)	Mean Attenuation (dBA)
Unprotected	80.1	118.5	90.5	12.2	N/A
OE Left	65.2	101.3	71.4	6.7	19.1
FRPC Right	54.6	82.5	61.8	7.9	28.8
3M OE vs Aramid FRPC (Time: 1049 - 1058)					
	Min (dBA)	Max (dBA)	Mean (dBA)	SD (dBA)	Mean Attenuation (dBA)
Unprotected	80.0	121.3	89.4	11.7	N/A
OE Left	64.8	80.7	69.4	3.9	20.0
FRPC Right	64.3	89.4	70.8	5.7	18.6
FDC OE vs Glass FRPC (Time: 1100 - 1116)					
	Min (dBA)	Max (dBA)	Mean (dBA)	SD (dBA)	Mean Attenuation (dBA)
Unprotected	80	120.2	88.8	12.0	N/A
OE Left	63.1	104.2	69.3	7.1	19.5
FRPC Right	64.6	104.8	70.6	6.0	18.2

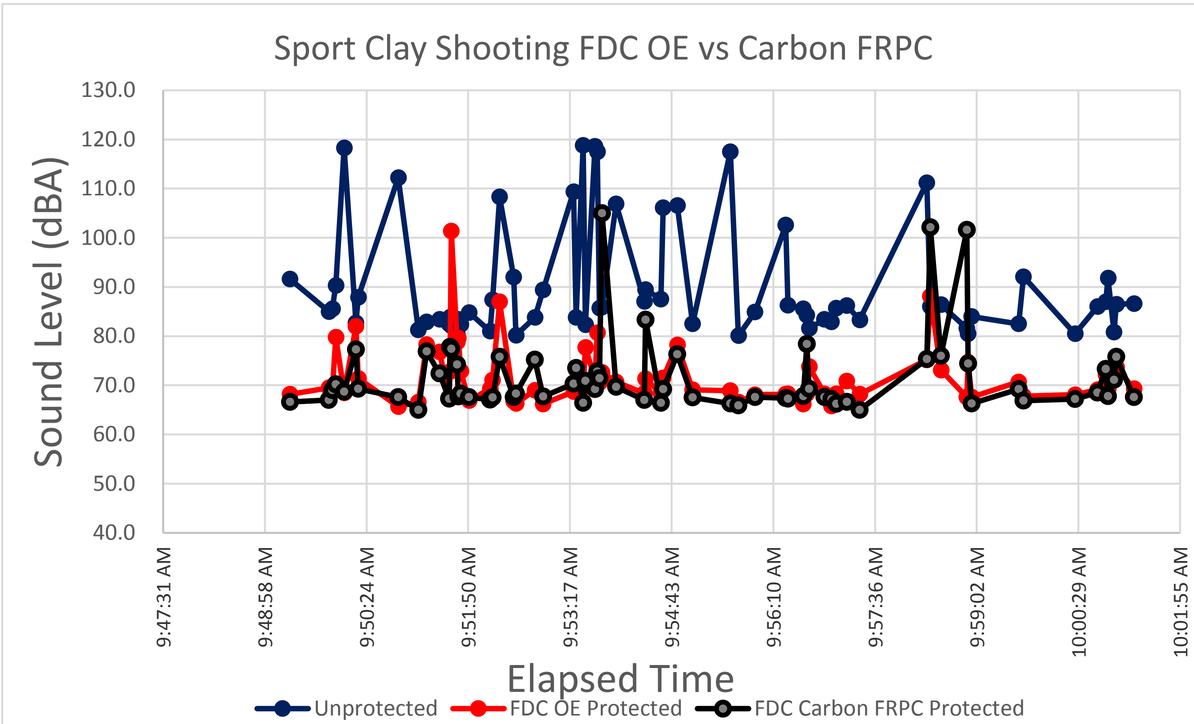

Figure 14 – Impulse Attenuation FDC OE vs Carbon FRPC

Table III - Impulse FDC OE vs Carbon FRPC Paired Difference T-test

		Paired Differences					t	df	Sig. (2-tailed)[3]
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	UPCARBONVSFDC - LEFTFDCOE1	18.21	12.76	1.55	15.12	21.30	11.76	67	.000
Pair 2	UPCARBONVSFDC - RIGHTCARBONFDC	18.45	14.39	1.74	14.97	21.94	10.58	67	.000
Pair 3	LEFTFDCOE1 - RIGHTCARBONFDC	.24	7.74	.94	-1.63	2.12	.26	67	.796

[3] For α = 0.05 and 67 degrees of freedom, the critical value is +/-1.996. The paired difference T-test shows the mean difference between the protected and unprotected was statistically significant and the mean difference from left to right was not statistically significant.

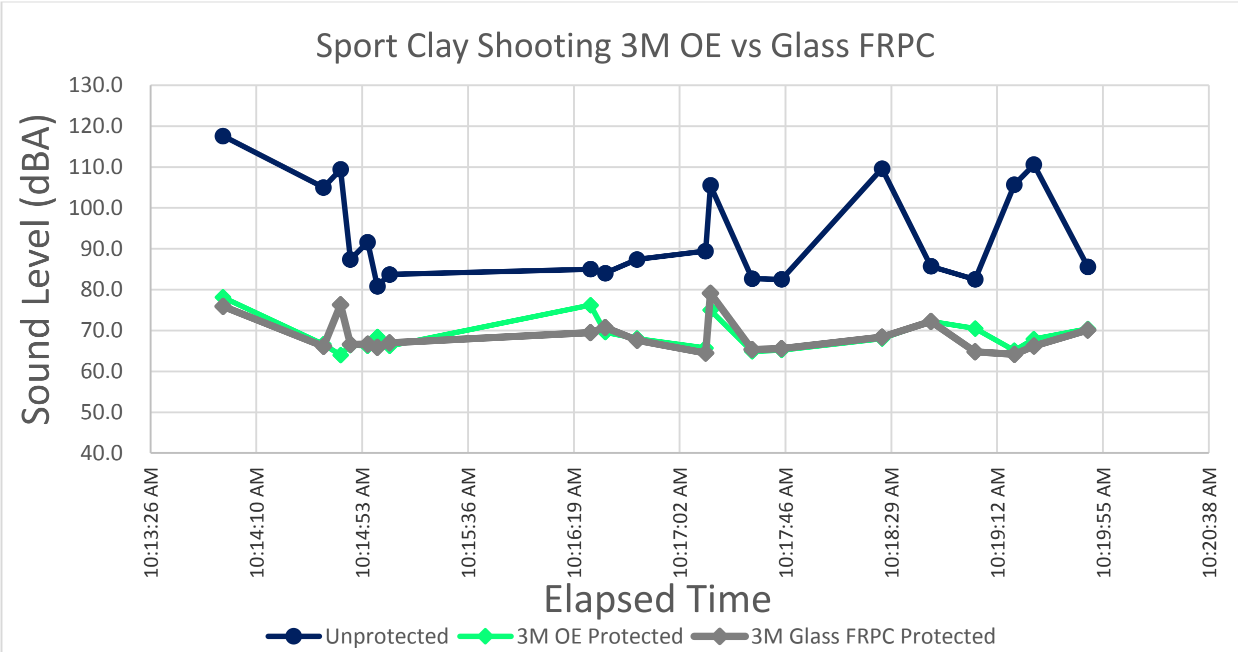

Figure 15 - Impulse Attenuation 3M OE vs Glass FRPC

Table IV - Impulse 3M OE vs Glass FRPC Paired Difference T-test

		Paired Differences					t	df	Sig. (2-tailed)[4]
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	UPGLASSVS3M - LEFT3MOE1	24.86	12.17	2.72	19.16	30.55	9.13	19	.000
Pair 2	UPGLASSVS3M - RIGHTGLASS3M	24.95	10.98	2.46	19.81	30.09	10.16	19	.000
Pair 3	LEFT3MOE1 - RIGHTGLASS3M	.10	3.73	.83	-1.65	1.84	.11	19	.911

[4] For α = 0.05 and 19 degrees of freedom, the critical value is +/-2.093. The paired difference T-test shows the mean difference between the protected and unprotected was statistically significant and the mean difference from left to right was not statistically significant.

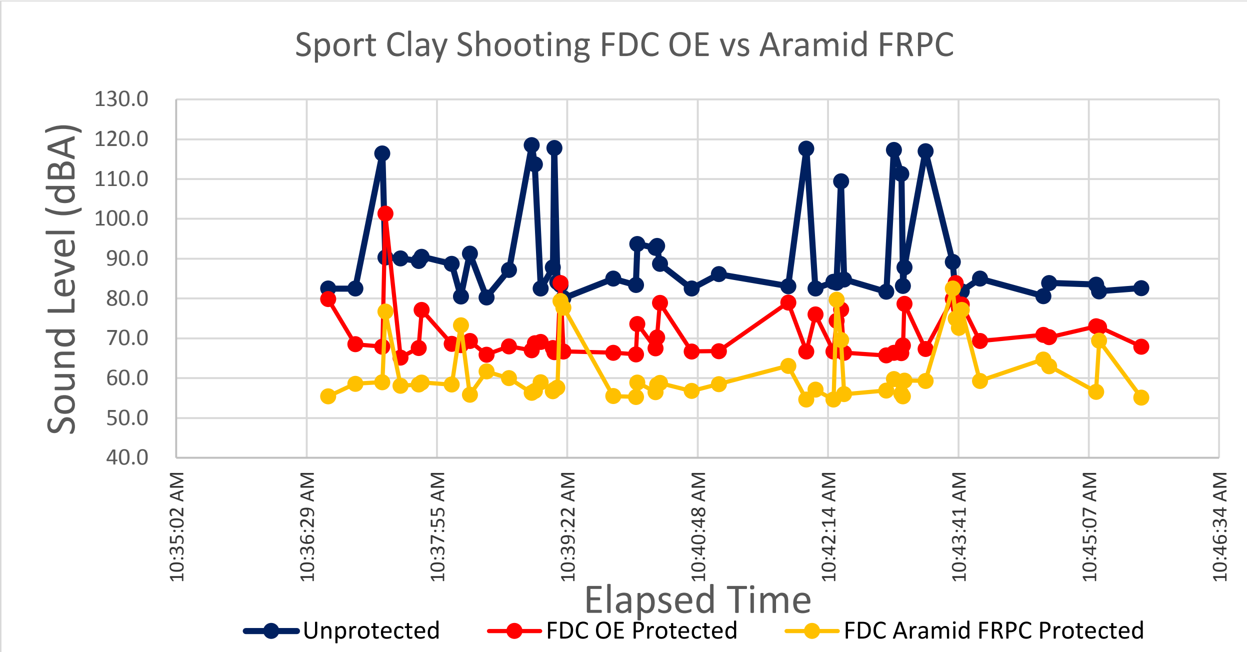

Figure 16 - Impulse Attenuation FDC OE vs Aramid FRPC

Table V - Impulse FDC OE vs Aramid FRPC Paired Difference T-test

		Paired Differences					t	df	Sig. (2-tailed)[5]
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	UPARAMIDVSFDC - LEFTFDCOE2	19.10	15.10	2.11	14.85	23.34	9.03	50	.000
Pair 2	UPARAMIDVSFDC - RIGHTARAMIDFDC	28.75	16.14	2.26	24.21	33.29	12.72	50	.000
Pair 3	LEFTFDCOE2 - RIGHTARAMIDFDC	9.66	6.68	.93	7.78	11.53	10.33	50	.000

[5] For α = 0.05 and 50 degrees of freedom, the critical value is +/-2.009. The paired difference T-test shows the mean difference between the protected and unprotected was statistically significant and the mean difference from left to right was also statistically significant.

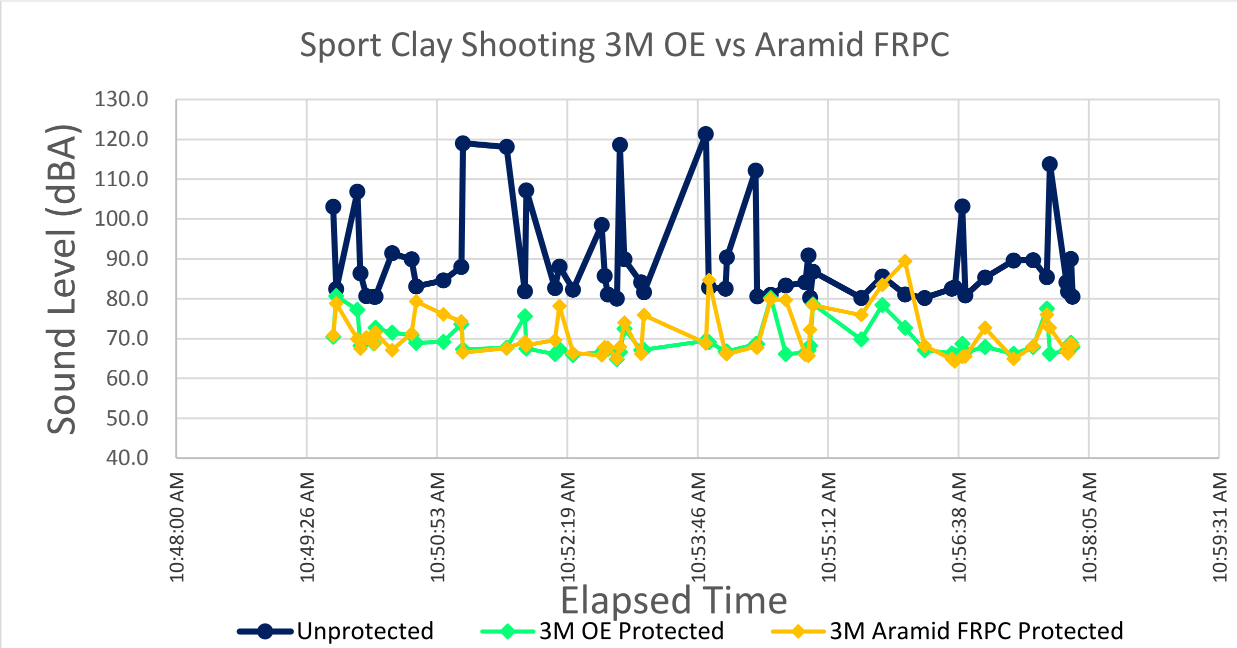

Figure 17 - Impulse Attenuation 3M OE vs Aramid FRPC

Table VI - Impulse 3M OE vs Aramid FRPC Paired Difference T-test

	Paired Differences					t	df	Sig. (2-tailed)[6]
	Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
Pair 1 UPARAMIDVS3M - LEFT3MOE2	20.03	12.66	1.69	16.64	23.42	11.84	55	.000
Pair 2 UPARAMIDVS3M - RIGHTARAMID3M	18.61	14.11	1.89	14.84	22.39	9.87	55	.000
Pair 3 LEFT3MOE2 - RIGHTARAMID3M	-1.42	4.78	.64	-2.70	-.14	-2.22	55	.030

[6] For α = 0.05 and 55 degrees of freedom, the critical value is +/-2.004. The paired difference T-test shows the mean difference between the protected and unprotected was statistically significant and the mean difference from left to right was also statistically significant.

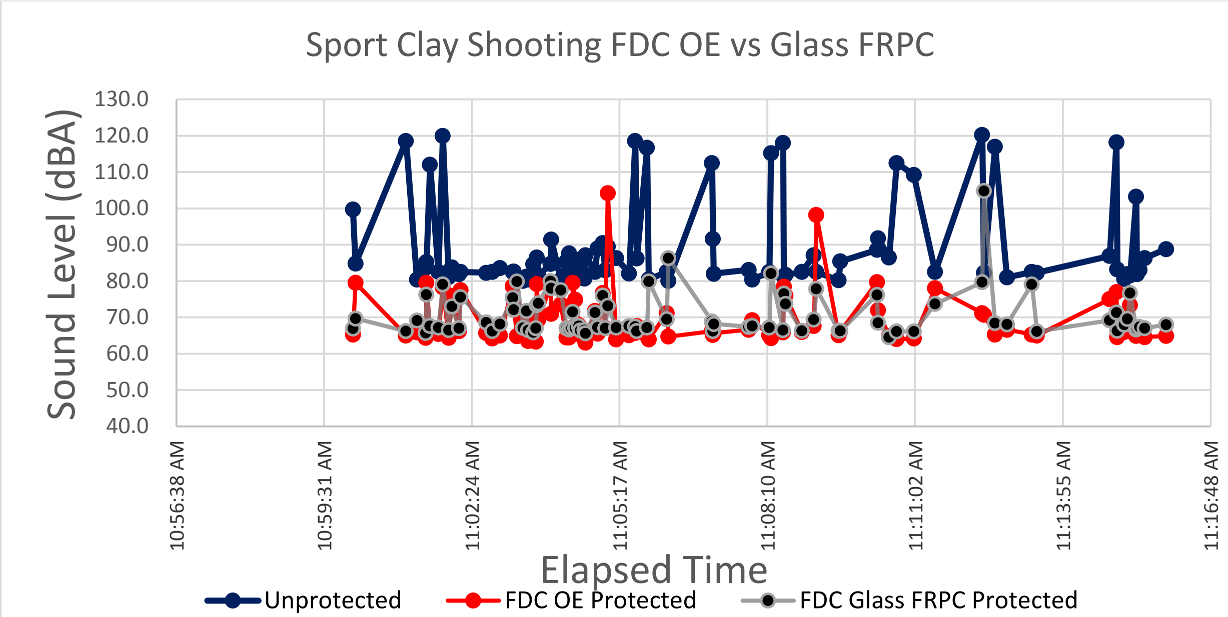

Figure 18 – Impulse Attenuation FDC OE vs Glass FRPC

Table VII - Impulse FDC OE vs Glass FPC Paired Difference T-test

	Paired Differences					t	df	Sig. (2-tailed)[7]
	Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
Pair 1 UPGLASSVSFDC - LEFTFDCOE3	19.49	14.29	1.51	16.48	22.51	12.86	88	.000
Pair 2 UPGLASSVSFDC - RIGHTGLASSFDC	18.23	13.61	1.44	15.36	21.10	12.63	88	.000
Pair 3 LEFTFDCOE3 - RIGHTGLASSFDC	-1.26	7.27	.77	-2.79	.27	-1.63	88	.105

[7] For α = 0.05 and 88 degrees of freedom, the critical value is +/-1.987. The paired difference T-test shows the mean difference between the protected and unprotected was statistically significant and the mean difference from left to right was not statistically significant.

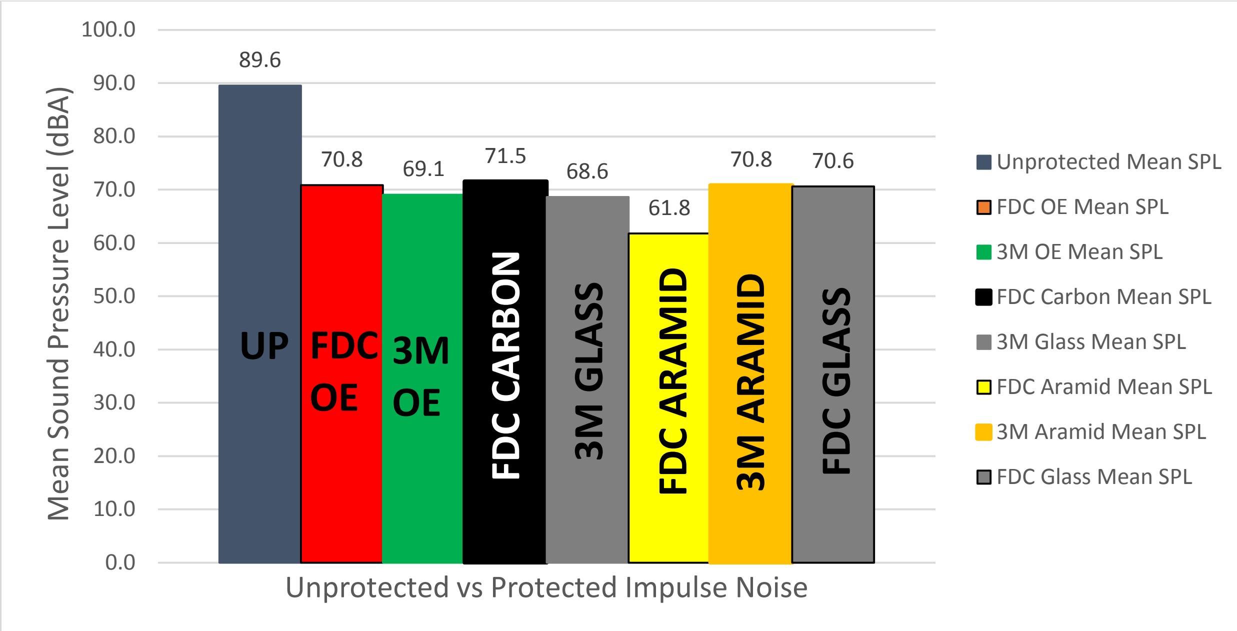

Figure 19 - Unprotected vs Protected Mean Impulse SPL

Continuous Noise: Plasma Spray Data is shown in Tables VIII thru XIV and Figures 20 thru 26

Table VIII - Continuous Noise CAHPD Attenuation

Plasma Spray Noise Summary Data Sheet 6MAY2015					
3M OE vs Carbon FRPC (Time: 0848 - 0902)					
	Min (dBA)	Max (dBA)	Mean (dBA)	SD (dBA)	Mean Attenuation (dBA)
Unprotected	104.9	110.5	108.8	0.6	N/A
OE Right	79	90.3	86.3	0.6	22.5
FRPC Left	91.9	104.5	102.5	0.8	6.2
FDC OE vs Carbon FRPC (Time: 0908 - 0921)					
	Min (dBA)	Max (dBA)	Mean (dBA)	SD (dBA)	Mean Attenuation (dBA)
Unprotected	106.3	111	108.0	0.6	N/A
OE Right	90.8	95.2	92.5	0.5	15.5
FRPC Left	91.4	94.7	93.0	0.5	15.0

Table VIII - Continuous Noise CAHPD Attenuation – cont.

Plasma Spray Noise Summary Data Sheet 6MAY2015					
FDC OE vs Glass FRPC (Time: 0926 - 0940)					
	Min (dBA)	Max (dBA)	Mean (dBA)	SD (dBA)	Mean Attenuation (dBA)
Unprotected	105.5	110.4	107.5	0.6	N/A
OE Right	83.1	93.6	91.4	0.8	16.0
FRPC Left	92.7	96	94.6	0.5	12.9
3M OE vs Glass FRPC (Time: 0944 - 0958)					
	Min (dBA)	Max (dBA)	Mean (dBA)	SD (dBA)	Mean Attenuation (dBA)
Unprotected	105.3	109.7	107.2	0.7	N/A
OE Right	82	90	85.6	0.6	21.5
FRPC Left	98.8	102.7	100.6	0.7	6.6
FDC OE vs Aramid FRPC (Time: 1002 - 1015)					
	Min (dBA)	Max (dBA)	Mean (dBA)	SD (dBA)	Mean Attenuation (dBA)
Unprotected	103.7	109.4	106.9	0.6	N/A
OE Right	82.7	98.1	95.7	0.8	11.3
FRPC Left	95.6	99.8	97.7	0.8	9.2
3M OE vs Aramid FRPC (Time: 1019 - 1032)					
	Min (dBA)	Max (dBA)	Mean (dBA)	SD (dBA)	Mean Attenuation (dBA)
Unprotected	104.3	109	107.1	0.5	N/A
OE Right	87.1	94.9	92.8	0.8	14.3
FRPC Left	95.8	99.8	97.8	0.6	9.3

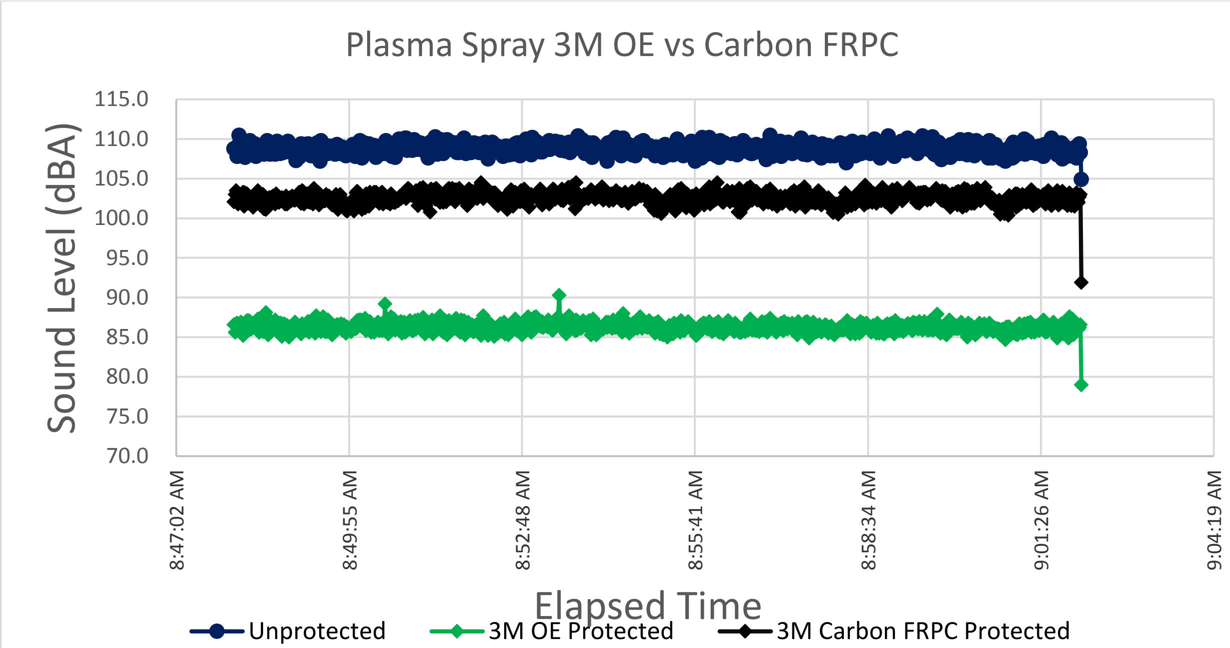

Figure 20 - Continuous Attenuation 3M OE vs Carbon FRPC

Table IX - Continuous 3M OE vs Carbon FRPC Paired Difference T-test

		Paired Differences					t	df	Sig. (2-tailed)[8]
		Mean	Std. Dev	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	UPCARBONVS3M - RIGHT3MOE1	22.51	.71	.02	22.47	22.56	911.08	847	.000
Pair 2	UPCARBONVS3M - LEFTCARBON3M	6.24	.84	.03	6.19	6.30	216.23	847	.000
Pair 3	RIGHT3MOE1 - LEFTCARBON3M	-16.26	.81	.03	-16.32	-16.21	-580.76	847	.000

[8] For α = 0.05 and 847 degrees of freedom, the critical value is +/-1.96. The paired difference T-test shows the mean difference between the protected and unprotected was statistically significant and the mean difference from left to right was also statistically significant.

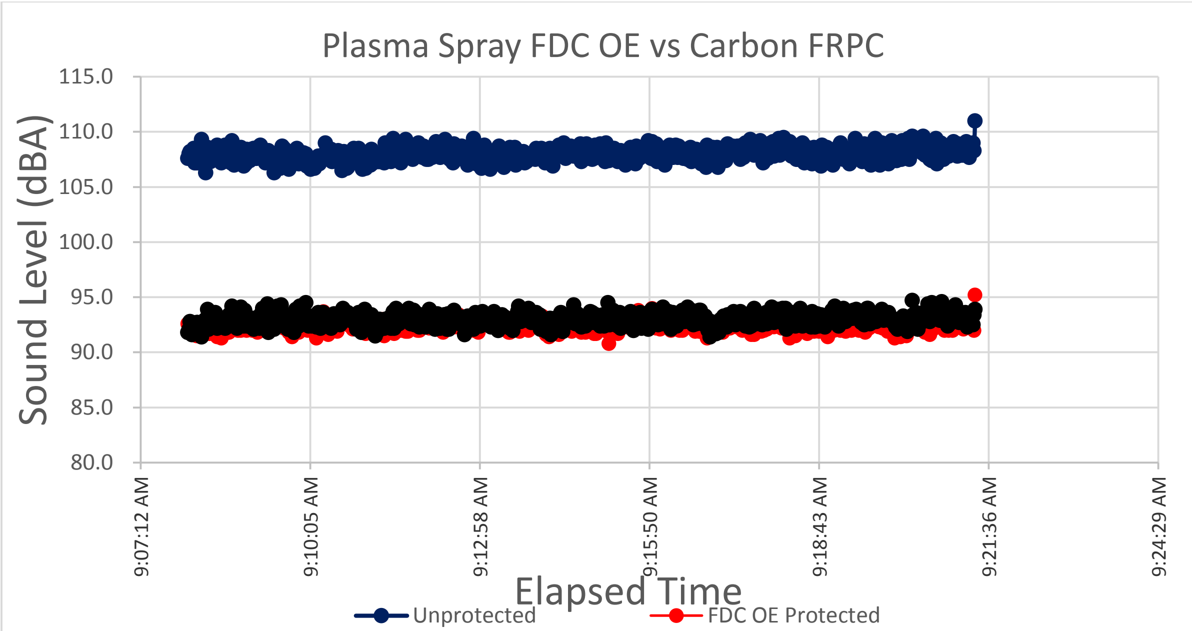

Figure 21 - Continuous Attenuation FDC OE vs Carbon FRPC

Table X - Continuous FDC OE vs Carbon FRPC Paired Difference T-test

	Paired Differences					t	df	Sig. (2-tailed)[9]
	Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
Pair 1 UPCARBONVSFDC - RIGHTFDCOE1	15.48	.75	.03	15.43	15.53	581.99	802	.000
Pair 2 UPCARBONVSFDC - LEFTCARBONFDC	15.02	.77	.03	14.97	15.08	554.92	802	.000
Pair 3 RIGHTFDCOE1 - LEFTCARBONFDC	-.45	.64	.02	-.50	-.41	-20.30	802	.000

[9] For α = 0.05 and 802 degrees of freedom, the critical value is +/-1.96. The paired difference T-test shows the mean difference between the protected and unprotected was statistically significant and the mean difference from left to right was also statistically significant.

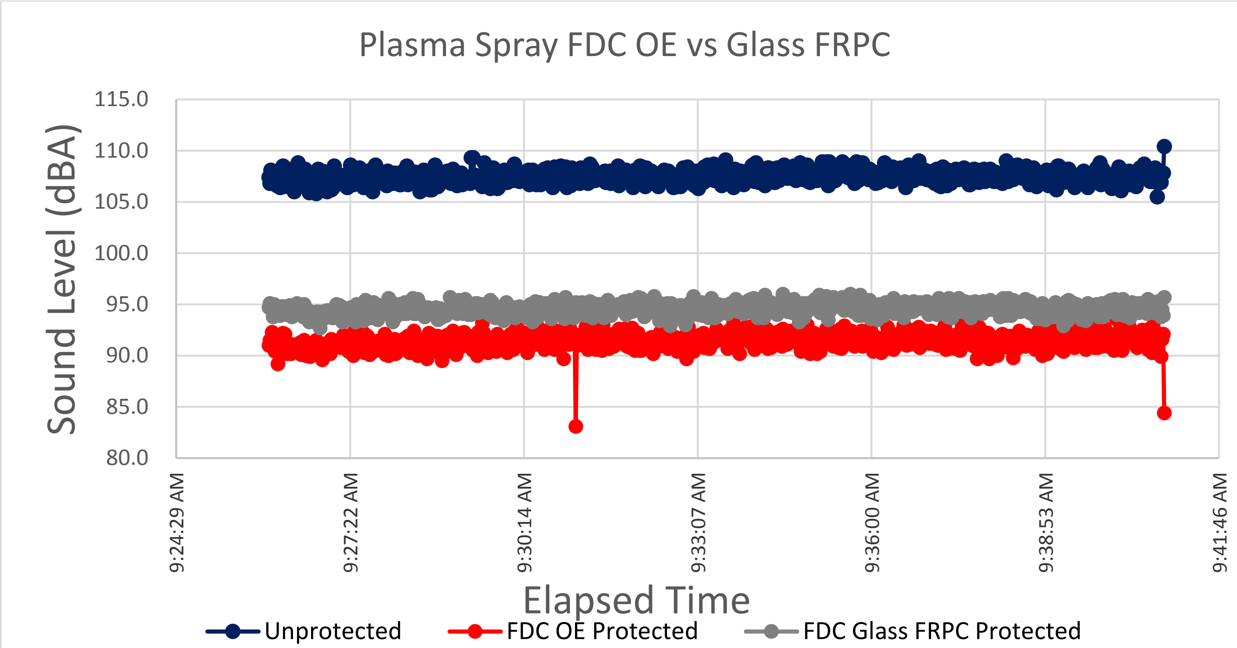

Figure 22 - Continuous Attenuation FDC OE vs Glass FRPC

Table XI - Continuous FDC OE vs Glass FRPC Paired Difference T-test

		Paired Differences					t	df	Sig. (2- tailed)[10]
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	UPGLASSVSFDC - RIGHTFDCOE2	16.03	.9431	.03	15.97	16.09	507.41	890	.000
Pair 2	UPGLASSVSFDC - LEFTGLASSFDC	12.89	.7348	.02	12.84	12.94	523.60	890	.000
Pair 3	RIGHTFDCOE2 - LEFTGLASSFDC	-3.14	.9193	.03	-3.20	-3.08	-102.02	890	.000

[10] For α = 0.05 and 890 degrees of freedom, the critical value is +/-1.96. The paired difference T-test shows the mean difference between the protected and unprotected was statistically significant and the mean difference from left to right was also statistically significant.

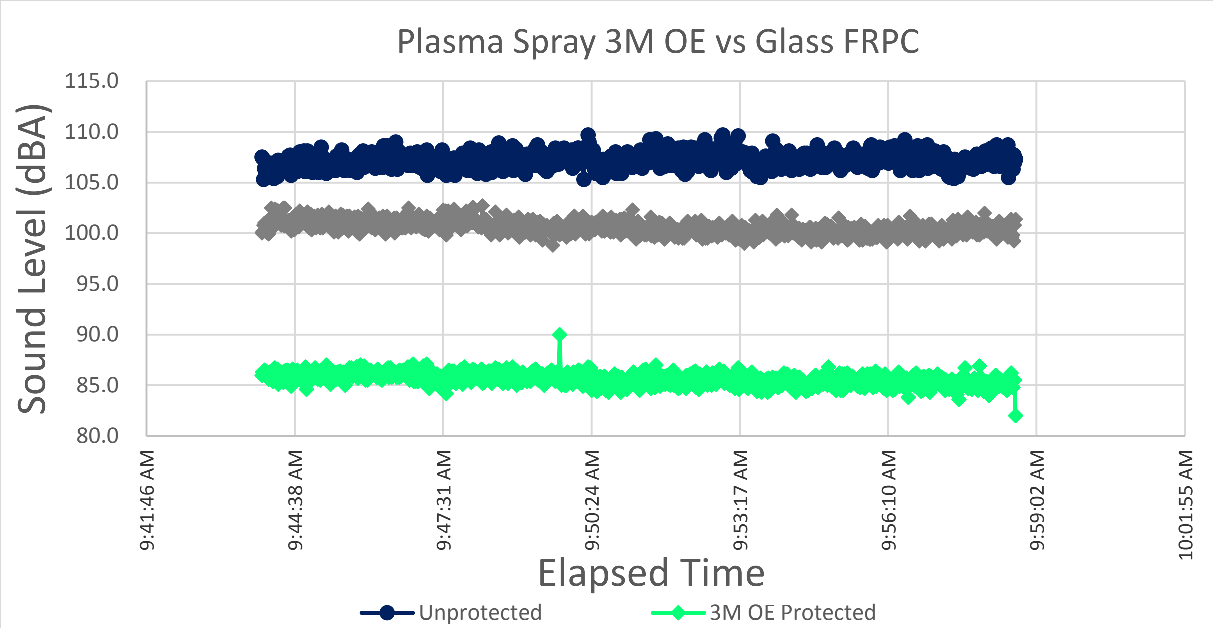

Figure 23 - Continuous Attenuation 3M OE vs Glass FRPC

Table XII - Continuous 3M OE vs Glass FRPC Paired Difference T-test

		Paired Differences					t	df	Sig. (2-tailed)[11]
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	UPGLASSVS3M - RIGHT3MOE2	21.54	.89	.03	21.48	21.59	717.40	878	.000
Pair 2	UPGLASSVS3M - LEFTGLASS3M	6.58	1.07	.04	6.51	6.65	183.03	878	.000
Pair 3	RIGHT3MOE2 - LEFTGLASS3M	-14.95	.81	.03	-15.00	-14.90	-545.76	878	.000

[11] For α = 0.05 and 55 degrees of freedom, the critical value is +/-2.004. The paired difference T-test shows the mean difference between the protected and unprotected was statistically significant and the mean difference from left to right was also statistically significant.

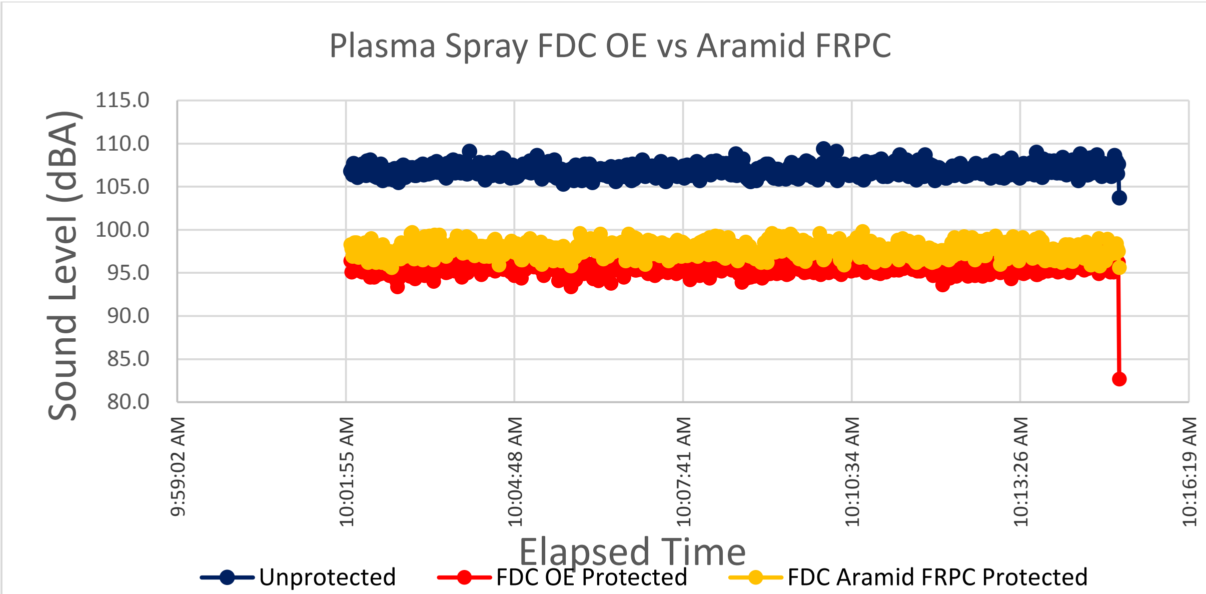

Figure 24 - Continuous Attenuation FDC OE vs Aramid FRPC

Table XIII - Continuous FDC OE vs Aramid FRPC Paired Difference T-test

		Paired Differences					t	df	Sig. (2-tailed)[12]
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	UPARAMIDVSFDC - RIGHTFDCOE3	11.25	.88	.03	11.19	11.32	359.41	788	.000
Pair 2	UPARAMIDVSFDC - LEFTARAMIDFDC	9.22	.97	.03	9.16	9.29	267.27	788	.000
Pair 3	RIGHTFDCOE3 - LEFTARAMIDFDC	-2.03	1.10	.04	-2.11	-1.95	-51.92	788	.000

[12] For $\alpha = 0.05$ and 788 degrees of freedom, the critical value is +/-1.96. The paired difference T-test shows the mean difference between the protected and unprotected was statistically significant and the mean difference from left to right was also statistically significant.

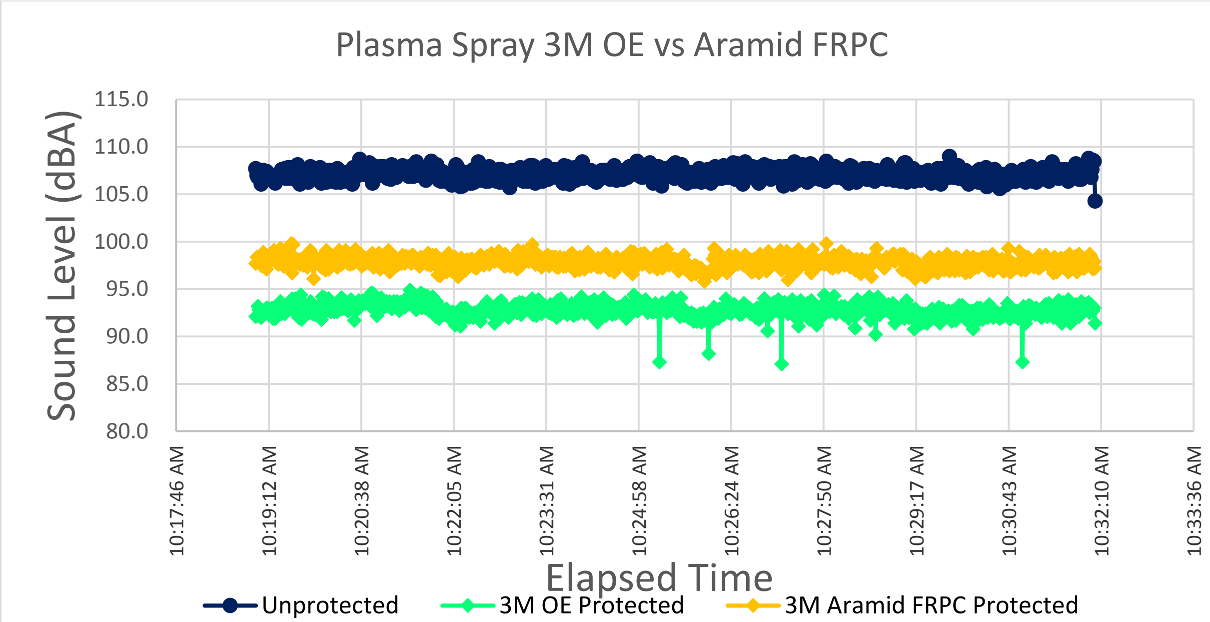

Figure 25 - Continuous Attenuation 3M OE vs Aramid FRPC

Table XIV - Continuous 3M OE vs Aramid FRPC Paired Difference T-test

		Paired Differences					t	df	Sig. (2-tailed)[13]
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	UPARAMIDVS3M - RIGHT3MOE3	14.34	.85	.03	14.28	14.40	473.71	784	.000
Pair 2	UPARAMIDVS3M - LEFTARAMID3M	9.28	.79	.03	9.23	9.34	329.88	784	.000
Pair 3	RIGHT3MOE3 - LEFTARAMID3M	-5.06	.87	.03	-5.12	-5.00	-162.51	784	.000

[13] For α = 0.05 and 784 degrees of freedom, the critical value is +/-1.96. The paired difference T-test shows the mean difference between the protected and unprotected was statistically significant and the mean difference from left to right was also statistically significant.

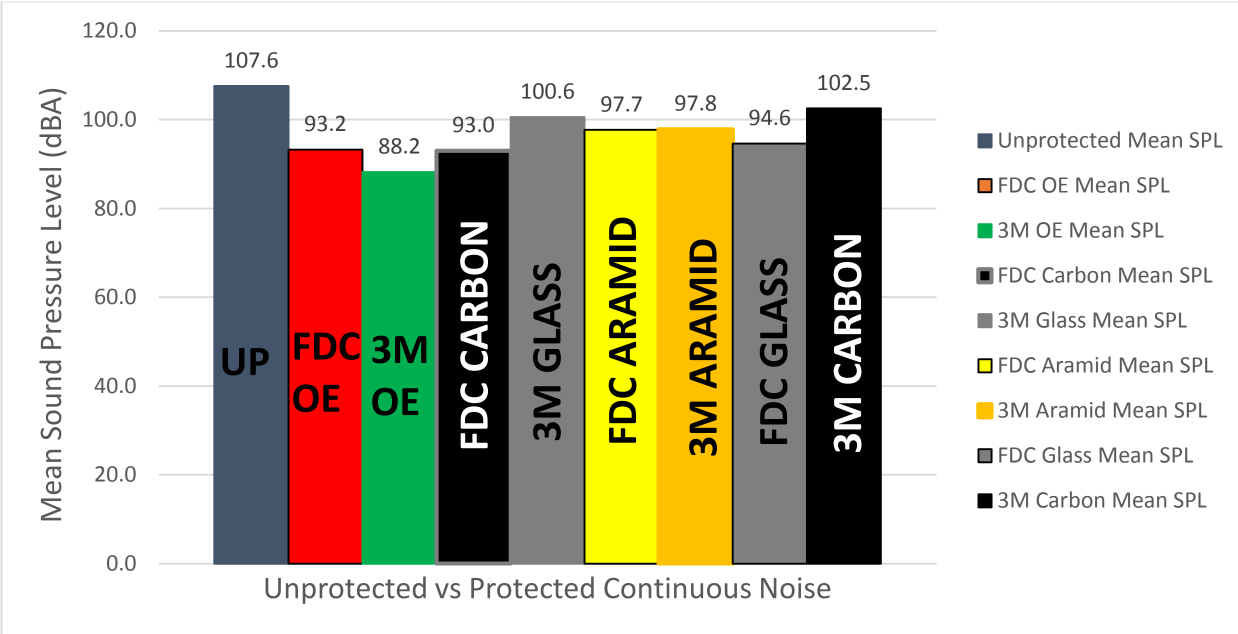

Figure 26 - Unprotected vs Protected Mean Continuous SPL

Discussion

The NRR of the FDC OE and 3M OE HPDs are 21 dB and 22 respectively. The NRR is the subjective REAT laboratory mean attenuation of HPDs, less two standard deviations measured across one-third octave band frequencies of continuous noise and, although not a direct comparison, the overall difference between the protected and unprotected 3M OE and FDC OE SPLs was relatively consistent from test-to-test and a close approximation of their respective NRRs. The difference between the protected and unprotected mean SPLs was statistically significant at $\alpha = 0.05$ for all OE and FRPC ear cups indicating that their measured sound attenuation was unlikely due to chance.

Impulse Noise

The difference between the protected and unprotected mean SPL was 18.2 – 19.5 dBA for FDC OE ear cups and 20.0 – 24.9 dBA for 3M OE ear cups. The largest observed difference from the unprotected mean SPL was the aramid FDC FRPC ear cup (28.8 dBA) and an additional 9.7 dBA more sound attenuation than the paired FDC OE ear cup. This test was the only statistically significant positive finding amongst all the left to right pairs using a paired difference T-test suggesting that an aramid FRPC HPD may offer additional protection from impulse noise when compared to a thermoplastic HPD. This trend was not repeated in the 3M OE vs aramid 3M FRPC pairing with only a 1.4 dBA difference between them and, albeit statistically significant, less than the measurement accuracy of the Wensn type II SLM of +/- 1.5 dB. There were no other statistically significant impulse noise findings indicating there is no sound attenuation advantage or disadvantage from carbon or glass FRPC constructed HPDs.

Continuous Noise

The type II SLM was more capable of capturing continuous noise and provided data with a smaller variance than the impulse noise. The difference between the protected and unprotected mean SPL was 11.3 – 16.0 dBA for the FDC OE ear cups and 14.3 – 22.5 dBA for 3M OE ear cups. The final two aramid FDC and 3M pairings produced some abnormal continuous noise data and the difference between the protected and unprotected mean SPL was 11.3 dBA for the FDC OE ear cups and 14.3 dBA for the 3M OE ear cups. These values did not align with the previous measurement trend of 15 – 19 dBA and 20 – 25 dBA observed for both impulse and continuous noise respectively.

The largest observed difference from the unprotected mean SPL was the 3M OE ear cup (22.5 dBA) and both the 3M OE and FDC OE ear cups attenuated more continuous noise than all paired FRPC ear cups. The 3M OE ear cup sound attenuation was 5-16 dBA more than the paired 3M FRPC ear cups and the FDC OE ear cup sound attenuation was 0.5-3 dBA more than the paired FDC FRPC ear cups. All paired difference tests were statistically significant at $\alpha = 0.05$ indicating that all paired differences from the unprotected mean and paired differences between OE and FRPC ear cups (left/right) were unlikely due to chance. The relatively large continuous noise sample size ($n > 700$) did increase the power to detect statistically significant differences between left and right pairings as small as 0.5 dBA and although significant, are outside the limits of instrument accuracy (+/- 1.5 dBA).

Conclusions

The purpose of this research was to evaluate the sound attenuation performance of FRPC constructed CAHPDs and measure whether these offer a superior level of hearing protection when compared to thermoplastic OE CAHPDs. For impulse noise above 80 dBA, only the aramid FDC FRPC ear cup attenuated more sound than its paired thermoplastic OE ear cup of equal shape and thickness. For continuous noise above 80 dBA, the thermoplastic OE ear cups better attenuated sound than all paired FRPC ear cups of equal shape and thickness. These findings suggest the combination of increased surface area from the larger FDC geometry and the characteristic energy dissipation properties of aramid fibers may be responsible for the measured increase in impulse sound attenuation and further investigation is needed to determine if aramid FRPC CAHPDs can provide better protection from impulse noise than conventional thermoplastic CAHPDs.

On multiple occasions the FRPC ear cups mirrored the sound attenuation provided by the OE thermoplastic ear cups indicating that the geometry of ear cup or the integrity of the CAHPD-to-head fit are the driving factors behind maximum sound attenuation and perhaps there is a limit to the attenuation attained based on differences in impedance. On close examination, the continuous noise data shows the 3M OE ear cups attenuated more sound than the FDC OE ear cups; however, amongst the FRPC ear cups, the larger FDC FRPC ear cups attenuated more sound than the 3M FRPC ear cups further reinforcing that shape and fit differences may be influencing the results. These findings validate the need and more recent trend of fit-testing and individual protected and unprotected field dosimetry as well as both subjective (REAT) and objective (MIRE and ATF) methods to monitor both noise exposure and effectiveness of PPE in order to select the best HPD that fits the person and the job.

Limitations

Measuring the sound attenuation of the HPDs using A-weighting is a good approximation but without knowing the behavior of the sound waves incident on the manikin head; the SPL across a range of frequencies, since sound attenuation is frequency dependent in solid materials; the fraction of bone and tissue sound conduction; potential fit differences between users; and if any resonant frequencies are present contributing to decreased, or even zero attenuation; quantifying real-world HPD sound attenuation will remain an estimation with appropriately applied safety factors.

This study is limited in scope with only two sources of noise, only two types of thermoplastic CAHPDs and only three types of FRPC materials. Additional trials are needed with advanced instrumentation more capable of measuring impulse noise and the sound across a range of frequencies to properly characterize the noise and quantify HPD attenuation. Introduction of the alternative ear cup seal in the 3M FRPC pairings and improper earmuff to manikin head seals may have introduced undetectable biases in addition to non-uniform thickness of the FRPC materials due to fabric overlap and wrinkles in the fabric during vacuum bagging. With sampling rate limits of 2 times per second, the type two SLM is limited in its capability to capture and data log shotgun impulse noise lasting only a few milliseconds; however, the construction and deployment of the test manikin and the FRPC ear cups were designed to ensure the experimental test conditions remained the same for both left and right microphones so most experimental error will be systematic but may include:

Noise infiltration from inside the hollow manikin or through the holes drilled in the FRPC ear cups to house the mounting posts, and vibrations transmitted through the manikin test stand. This noise infiltration may have been more prevalent in the relatively confined space of the plasma spray room due to reverberation and the relatively equivalent protected mean SPL observed in the impulse data may represent sound attenuation provided by the manikin head and not the HPDs. Also, underestimation of the unprotected SPL due to max range limits of the Wensn type II SLM or interference from the position of the SLM behind the manikin head are possible sources of error.

Future Research

The results of this study indicate aramid fibers should be investigated further as a potential material for construction of CAHPDs designed to protect the human ear from impulse noise. The results also imply the David Clark CAHPD worn by flight deck crewmen is outdated and may not be offering the highest level of protection as it consistently attenuated less sound than the 3M CAHPD during this study. Field testing a replacement CAHPD could be considered a viable intervention strategy as a better performing replacement may be available off the shelf.

Additional acoustics and hearing protection research is needed to understand the sound attenuation properties of the almost limitless fiber-matrix combinations that make up FRPC materials and potential applications in hearing protection. Materials studies using an impedance tube to evaluate how changing the ratio of fiber to matrix as well as fiber orientation, tow, weave and weight can affect the sound attenuation properties across a wide range of frequencies. A better understanding of any dominant frequencies present with jet engine noise as well as HPD sound localization studies may offer valuable information in identifying and matching the right HPD to the noise. Experimentation with different natural and synthetic fibers, plant and petrochemical derived resins, and hybrid thermoplastic composite materials is needed to identify a matrix material with excellent sound attenuation properties. Also, evaluation of different combinations of micro-perforated felts, polyurethane foam, and other ear cup lining materials is necessary to discover a material with superior attenuation potential.

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Appendices

Appendix I: Equipment List

JOLENE

Male Mannequin Head
Part #: B00CB05TXU
Qty: 1

Wensn Sound Level Meter (Left/Right)
Part #: WS1361C
Qty: 2

Wensn Sound Level Meter (External)
Part #: SL1361
Qty: 1

Westone Silicone Ear
Part #: 20221
Qty: 2

Quest SLM Calibrator
Part #: QC-20
Serial #: QF7050032
Cal Date: 6MAR15/6MAR16

Lowe's 3.5" Diameter 1/2" Deep Round Electrical Box
Part #: 72470
Qty: 2

8/32 1" Long Machine Screws
Part #: 605511
Qty: 12

1/4" Mono Phone Plug
Part #: B00CZIC5S0
Qty: 2

1/4" Mono Phone Jack
Part#: B0008JFHAQ
Qty: 2

Microphone Cable
Part #: B00AAK52BC
Qty: 6ft

FRPC Materials

Stretchlon 200 Bagging Film
Part #: 1678C
Qty: 5yds

Breather Cloth
Part#: 579-A
Qty: 5yds

Nylon Release Peel Ply
Part #: 582A
Qty: 5yds

Vacuum Coupling
Part #: 891-A
Qty: 1

Perfect Line Tape
Part #: 1735-A
Qty: 1 roll

Vacuum Tubing
Part #: 893
Qty: 5ft

Yellow Sealant Tape
Part #: 580-A
Qty: 2 rolls

Partall Paste Wax
Part #: 1016-A
Qty: 1

PVA Release Film
Part #: 0013-A
Qty: 1

System 2000 Epoxy Resin
Part #: 2000-A
Qty: 1

2020 Epoxy Hardener
Part #: 2020-A
Qty: 1

Kevlar® Plain Weave Fabric
Part #: 2469-A
Qty: 1 yd

Carbon Plain Weave Fabric
Part #: 530-A
Qty: 1yd

Fiberglass Plain Weave Fabric
Part #: 244-F
Qty: 1yd

OE CAHPDs

USN Flight Deck Crewman Hearing Protector
Part #: MIL-A-23899
Serial #: 4240-00-759-3290
Qty: 1

3M Peltor X1A-series
Part #: B00CPCH658
Qty: 1

Tools and Other Materials

Muscle shears
Part #: 1732-A

1" Paint Brush
Part #: 34-A
Qty: 6

Shooters Ear Protection
Browning Evader II
Part #: 12689
Qty: 1

TMS Vacuum Pump
Part #: B00BXMRP4I
Qty: 1

Black and Decker Matrix
Drill/Saw Combo Power Tool
Qty: 1

Safety Glasses

Soldering Iron with Find Point Tip and Electrical Solder

Needle Nose Pliers

Small Phillips Screwdriver

Wire Stripper

1/4" Hole Punch

Hammer

Heat Torch

Heat Shrink Tubing

Flat Metal File or Sandpaper

Round Metal File

Medium Phillips Screwdriver

Medium Flat Screwdriver

Tape Measure

Workbench Vise