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# PRESTRESSED CARBON FIBER COMPOSITE OVERWRAPPED GUN TUBE


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ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
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A 120mm barrel has been manufactured using this process with IM7 fibers in a PEEK matrix and successfully test fired. This paper will present the design, manufacturing, test firing and fatigue testing of this barrel.

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## Abstract

The emphasis on lightweight large caliber weapons systems has placed the focus on the use of advanced composite materials. Using composite materials not only directly removes weight from the gun tube but, by better balancing the tube, allows the use of smaller drive systems, thus further enhancing the system weight loss. Additionally the use of high stiffness composites helps with pointing accuracy and to alleviate the dynamic strain phenomenon encountered with high velocity projectiles.

Traditionally there were two issues with composite jackets: the coefficient of thermal expansion mismatch between the steel substrate and the composite jacket causing a gap, and the lack of favorable prestress in the jacket. Dealing with these issues greatly complicated the manufacturing process to the point where mass-producing the barrels would have been problematic at best. By using a thermoplastic resin, a cure on the fly process and winding under tension the manufacturability of the barrels has been greatly improved, the gap has been eliminated, and a favorable prestress has been achieved.

A 120mm barrel has been manufactured using this process with IM7 fibers in a PEEK matrix and successfully test fired. This paper will present the design, manufacturing, test firing and fatigue testing of this barrel.


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# Introduction

Previous composite wrapped gun tube efforts have been undertaken by Benét Laboratories during the late 1980's and early 1990's. These efforts led to the fabrication and test of several 105mm and 120mm gun tubes. An outcome of this work was the need to prevent or eliminate the formation of a gap, on the order of 0.1 mm (0.004 in), between the composite overwrap and gun steel liner during the composite curing process. The gap formed due to the coefficient of thermal expansion (CTE) mismatch between steel and composite. This gap effectively prevented or reduced the load carrying capability of the composite. To overcome the problem, the gun tube was autofrettaged (method of achieving compressive residual stresses at the bore by plastic deformation) after the application of the composite. The autofrettage effectively closed the gap, and also imparted some favorable residual stresses to the gun tube structure. There were, however, two problems with this approach; first, the thermal soak treatment used to stabilize the residual stresses in the tube after autofrettage could not be conducted. The thermal soak is done at temperatures of 343 to 371 °C (650 to 700 $^{o}$F) which is well above the maximum use temperature of the composite. The second problem was that the tube could not be chrome plated since the process requires the tube to be immersed in chromic acid, which would destroy the composite and contaminate the plating bath.

One approach to solving these problems was the 105mm Multi-Role Armament and Ammunition System (MRAAS) Swing Chamber Launcher (Littlefield and Hyland, 2002). In this case the CTE mismatch was handled by tailoring the lay-up. A combination of fiberglass and graphite was used with the ply angles being adjusted such that the lay-up's CTE matched that of the steel. This resulted in no gap forming between the composite and the steel but the performance of the composite was not optimum.

The composites used on these efforts were all thermoset materials; therefore the curing process took place after composite wrapping. For the current Advanced Technology Demonstration (ATD) effort, thermoplastic composites will be used. The advantage of thermoplastics is that they do not need a cure cycle but can rather be melted and recrystalized / consolidated immediately after being placed on the gun tube. This results in a "cure in place" type fabrication technique. Heating of the composite is localized, minimizing heat input to the composite and gun tube. This process mitigates thermal expansion effects and effectively eliminates the gap problem. The composite can therefore be placed onto the gun tube after the autofrettage thermal soak and chrome plate application.

One of the challenges of the composite wrapped gun tube will be handling the dynamic loading environment of a gun tube. Firing data of gun tube strain have shown that the measured strains are typically higher than expected from static ballistic pressure alone. This increase in tube strain is attributed to both the loading condition, which is effectively a square wave, as well as high speed dynamic loading of the gun tube during projectile passage. In most cases, this strain is typically 8-10% above the statically predicted (open ended cylinder, Lame equations) values. In situations where thin walled gun tubes and high velocity projectiles are used, the strains can be significantly higher, on the order of 300-400%. This phenomenon is known as gun tube dynamic strain and has been an area of study for many years by Benét Laboratories (Simkins, 1987; Hasenbein et al., 1990; Hasenbein and Hyland, 1992). In the development of the Light Weight 120mm (LW120) cannon, this phenomenon will be of special interest since the LW120 will have a thinner tube wall than the current 120mm M256 cannon and thus it will be more prevalent.

The 120mm Line of Sight / Beyond Line of Sight (LOS/BLOS) ATD is tasked to design, develop & demonstrate new armament & ammunition technologies for use in the Army's Future Combat System (FCS). The specific role the ATD plays is to support the development of the main armament for the Mounted Combat System (MCS), which will be equipped with a 120mm main armament and will provide Line of Sight and Beyond Line of Sight firing capabilities.

One of the tasks assigned to the 120mm LOS/BLOS Gun Assembly Team was to provide a light weight 120mm gun assembly for the MCS vehicle. The focus of this report is the use of an organic composite overwrap to lighten the weight and reduce the imbalance of the gun tube. The ATD is scheduled to deliver two prototype composite wrapped gun tubes. The first tube, Serial No. ATD-1, was the first large caliber gun tube to be wrapped with thermoplastics and was reported on previously (Littlefield et al., 2006). The first tube to wrapped under tension and the second to use thermoplastics was Serial No. ATD-3 and was reported in previously (Littlefield et al., 2005). This report will focus on the 2$^{nd}$ tension wrapped tube, Serial No. ATD-5. This tube is identical in design to ATD-3 but was the first tube to be manufactured on a new fiber placement work cell designed specifically for high tension thermoplastic wrapping and utilizing automated substrate cooling. Additionally ATD-5 is the first composite tube to undergo fatigue testing after test firing.

## Design and Analysis

Initially a lightweight all steel 120mm gun tube was designed using traditional methods. The steel design had a weight of 889 kg and was 5460 mm in length. The goal of the composite design was to match or exceed the frequency of the first bending mode of the steel design as well as match the residual hoop stress distribution through the gun tube wall, while saving weight.

Thermoplastic composites were used instead of thermosets in order to take advantage of the "cure in place" fabrication technique. Additionally applying the composite under tension helped to build in a favorable prestress in the composite jacket. Besides this manufacturing consideration, the composite overwind had to be able to withstand the significant forces and heat fluctuations associated with firing the weapon.

IM7 fiber with a polyetheretherketone (PEEK) matrix was the material selected for this project for several reasons. The first is the superior strength (2.07 GPa (300 ksi) in the fiber direction), modulus (138 GPa (20 msi) in the fiber direction) and toughness of the composite when compared to the majority of thermoset and other thermoplastic materials. The second reason for the selection of this material was its high melt point (653 °F / 345 °C). The final reason for the selection of this material was its excellent chemical resistance; in particular, its resistance to petrochemical fluids that would be encountered in the day to day operation of a large machine. The cost of thermoplastics, while in general higher than thermoset counterparts (~20%), was offset by the fact that there would be no autoclave post cure required. With a shape as complex and large as this, bagging and autoclaving add significant expense (up to 20%) to thermoset processing, plus the capital investment in a large autoclave (approx $300,000 for one large enough to process this gun tube), making thermoplastics a competitive alternative.

The tube's natural frequency (especially the first bending mode) affects the gun aiming and stabilization system. Maintaining the same natural frequency as an all steel version of the gun tube minimizes changes to these systems. In addition, if the natural frequency gets too low, it may approach the natural frequency of the riding loads of the vehicle. Excitation of the natural frequency may then occur leading to a condition in which stabilization of the gun tube becomes impossible.

Large caliber gun tubes often use autofrettage to impart favorable residual stresses into the gun tube structure. Since we were replacing some of the steel with composites, it was vital that the composite provide the same residual stress distribution as the original steel. To accomplish this, the residual stress distribution through the tube wall, including autofrettage and the composite wrap were modeled.

Static, normal mode and dynamic analyses were all performed. For the dynamic analysis, a pressure load was moved down the bore of the tube to simulate a projectile. A graphical result of this analysis can be seen in **Error! Reference source not found.**.

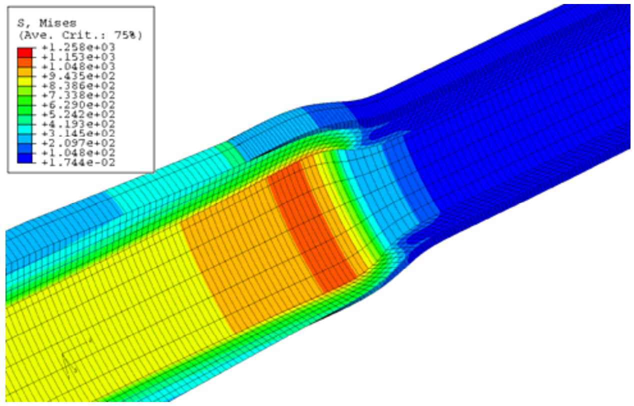


**Figure 1: Dynamic FEA analysis of a steel tube with a composite jacket - Mises stress, 100x magnification**

These analyses were repeated until a lay-up was arrived at that met or exceeded all of the metrics. The final lay up consisted of a mixture of hoop and axial plies. The hoop plies were to be wound under tension to match the residual stress distribution of the original all steel design. Two ±45 degree layers of S2/PEEK were added on the outside to protect the carbon fiber layers. This lay-up resulted in 113.4 kg (250 lbs) of steel being removed and 20.4 kg (45 lbs) of composite being added for a net weight savings of 93 kg (205 lbs).

## Manufacture

The steel portion of the gun barrel was manufactured according to the normal process, except that an area was undercut for the composite.

The composite was applied utilizing a robotic fiber placement process to precisely place and consolidate strips of thermoplastic prepreg tape. The process uses a hot gas torch (HGT) to melt the prepreg and then consolidates it with a pressure roller. Throughout the process the tape is held under tension and upon cooling this tension is locked in; inducing a residual stress into the part.

There were three major issues that needed to be overcome in order to fabricate the overwind:

- Tightness of fit between overwrap and barrel
- Galvanic corrosion between overwrap and barrel
- Maintaining the desired outside diameter (OD)

Winding under tension helps to ensure a tight fit between the overwrap and barrel but beyond this it was decided to cool the barrel, thus causing it to shrink during processing. Upon returning to room temperature the barrel attempts to grow in size but is constrained by the composite. In this way we are using the CTE mismatch to help form a tighter fit between the steel and composite instead of a gap, as was the case in older thermoset overwrapped gun tubes. This cooling process was found to induce level of residual stress equivalent to approximately 133 N (30 lbs) of winding tension.

Additionally the cooling helps to remove the heat generated from the fiber placement process. Without cooling the barrel temperature would have quickly heated to between 60 and 65 °C (140 to 150 °F). The exact temperature the barrel was cooled to can not be released but it was within the operational temperature of the gun system so it will not adversely affect the mechanical properties of the steel. The temperature was monitored at the coolant inlet, the breech, and muzzle. These three values were then used to control the amount of coolant introduced into the tube to maintain the desired substrate temperature.

If carbon fiber is brought into direct contact with steel, galvanic corrosion would take place. To avoid this two layers of S2 fiberglass / PEEK were placed between the steel and the carbon fiber. This thin layer is enough to act as an insulator but thin enough to not effect the performance of the overwrap.

Due to some standard variation in raw material thickness (specification for the material allows a +/-0.0127 mm variation in tape thickness), close attention was paid to the OD during fabrication. Modifications to ply lengths and locations were made to maintain the desired final OD.

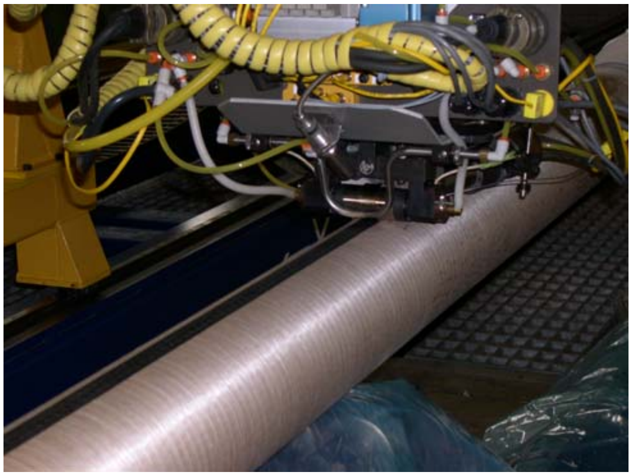

**Figure 2: An axial ply being applied to the gun barrel**

**Error! Reference source not found.** shows an axial ply being applied to the gun barrel. The white area is frost that develops on the part due to the chilling of the barrel. The hot gas torch vaporizes this as it applies the tape, so that none of the moisture finds it way into the part.

## Non-Destructive Evaluation

Modal impact, pressure, and acoustic emission (AE) testing were all performed to assess the state of the composite overwrap. The tests were to be conducted both before and after firing however there was not enough time between the conclusion of test firing and the commencement of fatigue testing to perform the post firing tests. Ultrasonic inspection was planned if any of the tests uncovered possible areas of damage.

Modal impact testing was performed both prior to and after applying the composite to determine the effect of the overwrap on tube stiffness. In all cases the tube was hung from springs to simulate free-free boundary conditions. This setup can be seen in **Error! Reference source not found.**.

Accelerometers were placed at the muzzle and every foot (304.8 mm) down the length of the composite. The tube was then impacted 219 mm from the muzzle and the response of the accelerometers was recorded. After this, all but the muzzle accelerometer were removed and the tube was then impacted at each previous accelerometer location.

The results of this testing for the first three modes can be seen in Table 1. The composite wrap slightly increased the stiffness of the gun. These results were compared to the FEA analysis and were found to be in good agreement. Not only did this result help to validate the FEA models but also ensured that energy was being transferred from the composite to the steel and vice versa.

**Table 1- Modal Impact Testing Results**

| | Mode (Hz) | | |
|---|---|---|---|
| | First | Second | Third |
| Before Wrap | 26.00 | 89.25 | 169.75 |
| After Wrap | 28.25 | 83.50 | 173.75 |

The pressure and AE tests were conducted at the same time as they both required pressurizing the gun tube. The pressure test helps to ensure that there is no gap between the steel and the overwrap. If a gap exists then there would be a delay in the composite picking up the pressure load applied to the bore. For the AE test the tube is pressurized twice. The first time there will be some fiber and matrix cracking as any defects need to work themselves out. The second loading should be quiet. If the second loading produces any noise events they could be an indication of damage and need to be investigated.


**Figure 3: Modal testing setup**

Standard rosette strain gages were placed at two axial locations along the length of the composite. At each location a gage was placed at the 12, 3, 6 and 9 O'clock positions. The gauges were oriented to record both hoop and axial strain. These same gauges were later used in the firing test. The tube was pressure tested to a peak pressure of 68.9 MPa (10 ksi). The strain readings were recorded every 6.89 MPa (1000 psi) up to peak pressure.

Eight Physical Acoustics R-151 acoustic emission sensors were set up in an F-array so that the location of any suspected damage could be located. The strain data collected, during the pressure test, was in good agreement with predictions and within 3% of the FEA analysis.

## Firing Results

The gun was taken to Aberdeen Proving Ground (APG), MD for test firing from 21 February till 15 Jun 2006. The gun was fired in direct and indirect fire modes for a total of 250 rounds though strain data was collected for only the first 68 direct fire shots. During these shots a series of two round types were fired at both ambient and hot conditions. **Error! Reference source not found.** is a photo of a direct fire shot.

**Figure 4: Test firing at APG**

The test instrumentation used was standard rosette strain gauges. Gauges were placed at two axial locations along the composite area of the tube. At each axial location a gage was placed at the 12, 3, 6 and 9 O'clock positions. Measurements of axial and circumferential (hoop) strain were recorded throughout the first 68 rounds of the test.

**Table** 2- Experimental and Theoretical Hoop Strains

| | Ambient | Hot |
|---|---|---|
| Location 1<br>Experimental | Mean<br>1724<br>Std Dev<br>95 | Mean<br>1758<br>Std Dev<br>99 |
| Location 1<br>Theoretical | 1721 | 1796 |
| Location 2<br>Experimental | Mean<br>1690<br>Std Dev<br>127 | Mean<br>1771<br>Std Dev<br>101 |
| Location 2<br>Theoretical | 1766 | 1926 |

gives both the theoretical and experimental strains for the round types fired. Looking at the table it can be seen that there is good qualitative and quantitative agreement between theoretical and measured strain levels. The response for the hot rounds was higher than expected but this is believed to be due to higher than expected pressures generated by the round. The results for round type 2 ambient were excellent with test results at location 1 being within 1% of theoretical and location 2 being within 5%.

**Table 2- Experimental and Theoretical Hoop Strains**

| | Ambient | Hot |
|---|---|---|
| Location 1<br>Experimental | Mean<br>1724<br>Std Dev<br>95 | Mean<br>1758<br>Std Dev<br>99 |
| Location 1<br>Theoretical | 1721 | 1796 |

| | | |
|---|---|---|
| Location 2<br>Experimental | Mean<br>1690<br>Std Dev<br>127 | Mean<br>1771<br>Std Dev<br>101 |
| Location 2<br>Theoretical | 1766 | 1926 |

**Error! Reference source not found.** and **Error! Reference source not found.** show the experimental and theoretical strains vs. time at both axial locations for both round type 1 ambient. Looking at the figures it can be seen again that there is good agreement between theoretical and experimental results.

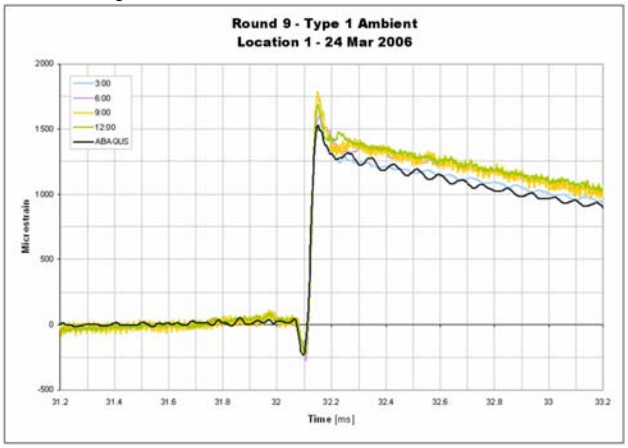


**Figure 5: Experimental & Theoretical Strain vs. Time**

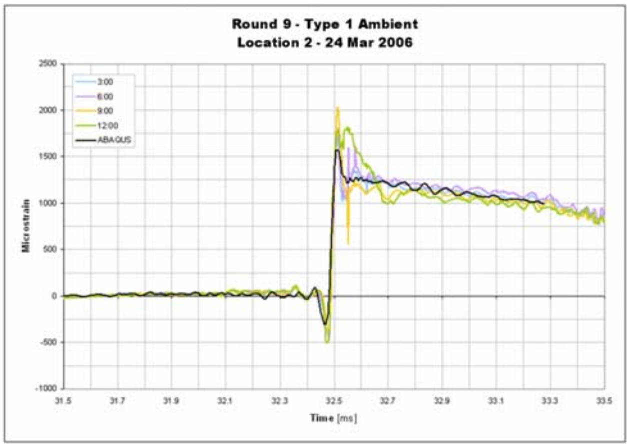


**Figure 6: Experimental & Theoretical Strain vs. Time**

## Fatigue Testing

Before a new cannon system can be fielded it must undergo fatigue testing to establish its safe service life. To generate an interim safe service life (ISFL) two gun tubes must be tested. For the final safe service life (FSFL) an additional four tubes are required. The safe fatigue life testing follows the International Test and Operating Procedure (ITOP) 3-2-829 and the NATO Standardization Agreements (STANAG) 4385. The ITOP establishes the test procedure and the FSFL mathematical calculations. The STANAG defines the cannon and ammunition pressure terms.

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Though this fatigue test was run according to the ITOP and STANAGs the goal was not to generate an ISFL or FSFL. That will be left for future gun tubes. The goals for this test were three fold:

1. To determine the Safe Maximum Pressure (SMP) of a composite section of the tube
2. To verify that the composite wrapped section of the tube will not be the fatigue critical area.
3. To get an idea of how tolerant the composite section is to firing damage.

To determine the SMP the tube section was cycled to increasingly higher pressures until plastic deformation of the bore takes place. This verifies the analysis used to establish the Safe Maximum Pressure (SMP) of the gun tube. The piece test was a composite wrapped autofrettaged section, with the same goals.

As part of the ITOP procedure the chamber section and other high risk sections must be fatigue tested. Ideally one would like the chamber to be the only high risk section that way only the chamber sections must be fatigue tested. Simulations suggested that the composite wrapped section would not be a high risk section but, since composite wrapped gun tubes are new, two pieces of the composite section were tested. The first section was taken from the autofrettaged zone of the tube; the second section from the non-autofrettaged zone. These sections were cycled to 10,000 cycles or failure, whichever came first.

There has been some concern that a composite wrapped tube would be more susceptible to small arms fire than an all steel gun tube. To test this, a section of the tube would be shot with a small caliber round, causing a glancing blow, damaging the composite but not the steel. The section would then be cycled 100 times.

The fatigue test is conducted under quasi-static loading conditions so crack initiation must have occurred prior to test commencement. The 250 round firing test discussed in section five was used to establish the required heat checking and crack initiation. Previous work (Racicot et al., 1973) has shown that if heat checking and crack initiation is present then one cycle in the lab is equivalent to one round fired in the field.

After the gun tube was received it was cut into test sections and seal pockets were machined into the ends of the sections. Strain gages were mounted to the outside of the sections to monitor the hoop strains generated. A filler bar was placed inside the section to minimize the amount of oil that must be pressurized. An end closure with seal assembly was installed in the both end seal pockets, covering the entire circumference of the seal pocket. The entire assembly was then placed into the press.

The composite section SMP and fatigue tests were performed in our 13.3 MN (3000 kip) press. High pressure fluid was introduced from the pre-load reservoir (for initial seal seating) and from a high pressure intensifier, into the test specimen, through ports in the end closures. There is a calibrated pressure sensor placed in the high pressure piping, close to the test specimen for monitoring the test pressure. A digital readout is connected to the pressure transducer and viewed by the system operator during testing. For the SMP test pressure was applied to the specimens in steps, held for a few seconds in order to collect all strain reading. For fatigue testing the pressure was cycled from a low to high setting until the desired number of cycles was reached of the specimen failed. The time for one pressure cycle was approximately ten seconds. **Error! Reference source not found.** shows a composite section in the press.

The composite SMP test produced the expected results. The autofrettaged composite test section failed at a much lower cycle count then expected. However in reviewing the test data it was determined that it was cycled at a much higher pressure then it should have been. When this was taken into account the result matched with predictions and indicates that it will not be a fatigue critical portion of the tube. The non-autofrettaged section survived all 10000 fatigue cycles without failure.

For the damage tolerance test, the non-autofrettaged composite section was shot with a 7.62mm armor piercing round. This was done at a glancing angle to cause damage in only the composite and not the steel. The section was then placed in the press and cycled 200 times without failure. This indicates that the composite has come degree of damage tolerance and that the gun tube has the potential to continue firing even after sustaining minor battle damage.

**Figure 7: Composite Section in Press**

Overall these initial fatigue test results are very promising though there are still some unanswered questions. A degree of damage tolerance has been demonstrated, but further work in this area should be conducted. No major issues with the composite wrapped sections and fatigue life were uncovered. This bodes well for future composite wrapped tubes to achieve an FSFL in line with requirements.

## Conclusion

A lightweight composite wrapped 120mm gun tube was successfully designed, manufactured, test fired and fatigue tested. A thermoplastic matrix was used, allowing for cure in place fabrication. This avoided the manufacturing complications due to coefficient of thermal expansion mismatch encountered in previous attempts at composite wrapped gun tubes. The prepreg was applied under tension resulting in a favorable prestress in the composite jacket. The design resulted in a gun tube that was 93 kg (205 lbs) lighter than its all steel counterpart while maintaining the same first bending mode and cross sectional profile.

Finite element models were used to help predict the response of the gun tube to firing loads. These models were validated through non-destructive testing and later shown to be in good agreement with the firing results. The composite jacket survived the firing with no apparent damage. The fatigue tests were conducted and the results did not uncover any major issues. The preliminary fatigue results bode well for future composite wrapped tubes to achieve an FSFL in line with requirements.

Overall, this effort was very successful and the data collected will be very useful in the design of future composite wrapped gun tubes.

## Acknowledgments

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