Nano-particles In Multi-scale Composites And Ballistic Applications

Jason Gibson
University of Central Florida
NANO-PARTICLES IN MULTI-SCALE COMPOSITES AND BALLISTIC APPLICATIONS

by

JASON GIBSON
B.S. The Ohio State University, 1994
M.S. The Ohio State University, 1996

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Mechanical and Aerospace Engineering in the College of Engineering and Computer Sciences at the University of Central Florida Orlando, Florida

Summer Term
2013

Major Professor: Jihua Gou
© 2013 Jason Gibson
ABSTRACT

Carbon nanotubes, graphene and nano sized core shell rubber particles have all been extensively researched for their capability to improve mechanical properties of thermoset resins. However, there has been a lack of research on their evaluation for energy absorption in high velocity impact scenarios, and the fundamental mechanics of their failure mechanisms during highly dynamic stress transfer through the matrix. This fundamental research is essential for laying the foundation for improvement in ballistic performance in composite armor. In hard armor applications, energy absorption is largely accomplished through delamination between plies of the composite laminate. This energy absorption is accomplished through two mechanisms. The first being the elongation of the fiber reinforcement contained in the resin matrix, and the second is the propagation of the crack in between the discreet fabric plies.

This research aims to fundamentally study the energy absorption characteristics of various nano-particles as reinforcements in thermoset resin for high velocity impact applications. Multiple morphologies will be evaluated through use of platelet, tubular and spherical shaped nano-particles. Evaluations of the effect on stress transfer through the matrix due to the combination of nano sized and micro scale particles of milled fiber is conducted. Three different nano-particles are utilized, specifically, multi-walled carbon nanotubes, graphene, and core shell rubber particles. The difference in surface area, aspect ratio and molecular structure between the tube, platelet and spherical nano-particles causes energy absorption through different failure mechanisms. This changes the impact performance of composite panels enhanced with the nano-particle fillers. Composite panels made through the use of dispersing the various nano-particles
in a non-contact planetary mixer, are evaluated through various dynamic and static testing, including unnotched cantilever beam impact, mixed mode fracture toughness, split-Hopkinson bar, and ballistic $V_{50}$ testing.

The unnotched cantilever beam testing showed that the addition of milled fiber degraded the impact resistance of the samples. Addition of graphene nano platelets unilaterally degraded impact resistance through the unnotched cantilever beam testing. 1.5% loading of MWCNT showed the greatest increase in impact resistance, with a 43% increase over baseline.

Determining the critical load for mixed mode interlaminar shear testing can be difficult for composite panels that bend without breaking. An iterative technique of optimizing the coefficient of determination, $R^2$, in linear regression is developed for objectively determining the point of non-linearity for critical load. This allows for a mathematical method of determination; thereby eliminating any subjective decision of choosing where the data becomes non-linear. The core shell rubber nano particles showed the greatest strain energy release rate with an exponential improvement over the baseline results.

Synergistic effects between nano and micro sized particles in the resin matrix during transfer of the stress wave were created and evaluated. Loadings of 1% milled carbon fiber enhanced the $V_{50}$ ballistic performance of both carbon nanotube and core shell rubber particles in the resin matrix. However, the addition of milled carbon fiber degrades the impact resistance of all nano-particle enhanced resin matrices. Therefore, benefits gained from the addition of micro-sized particles in combination with nano-sized particles, are only seen in high energy impact scenarios with micro second durations.
Loadings of 1% core shell rubber particles and 1% milled carbon fiber have an improvement of 8% in $V_{50}$ ballistic performance over the baseline epoxy sample for 44 mag single wad cutter gas check projectiles. Loadings of 1% multi-walled carbon nanotubes with 1% milled carbon fiber have an improvement of 7.3% in $V_{50}$ ballistic performance over the baseline epoxy sample.

The failure mechanism of the various nano-particle enhanced resin matrices during the ballistic event is discussed through the use of scanning electron microscope images and Raman spectroscopy of the panels after failure. The Raman spectroscopy data shows a Raman shift for the fibers that had an enhancement in the $V_{50}$ performance through the use of nano-particles. The Raman band for Kevlar® centered at 1,649 cm$^{-1}$ stemming from the stretching of the C==O bond of the fiber shows to be more sensitive to the residual axial strain, while the Raman band centered at 1,611 cm$^{-1}$ stemming from the C-C phenyl ring is minimally affected for the CSR enhanced panels due to the failure mechanism of the CSR particles during crack propagation.
I lovingly dedicate this to my wife Andrea and two children, Jacob and Lucas who supported me each step of the way. This research would not be possible without their support and willingness to allow me the time for this extensive process.
ACKNOWLEDGMENTS

I would like to acknowledge the financial support and guidance given by my employer, Composites One. This financial support and guidance from multiple individuals within the company are greatly appreciated. I would also like to acknowledge my appreciation for the guidance and support given by my advisor Dr. Jihua Gou. His consistent support and advice allowed the opportunity for me to push forward and expand my knowledge and experience in the exciting world of nano composites. I would like to express my gratitude to Dr. Seetha Raghavan, Dr. Yuanli Bai, and Dr. Lei Zhai for serving on my committee and investing in their time for evaluation of my dissertation. There have been many collaborative researchers at the University of Central Florida that have given valuable input. This includes, but not limited to James McKee and Don Lui for their help in the composites lab. They spent numerous hours helping me fabricate and test hundreds of composite samples for this research. Jinfeng Zhuge, Fei Liang and Xin Wang for their help with the various SEM images that were taken throughout the research. Steve Kraft for his help in setting up and utilizing the Instron machine and fixture for the mixed mode interlaminar shear testing. Dr. Seetha Raghavan, and her graduate assistants, Greg Freihofer, Albert Manero and Sanna Siddiqui were extremely helpful in developing the testing methods and data analysis for all of the Raman Spectroscopy data presented in this research. I want to thank Dr. Nikhil Gupta and Dr. Dung Luong with the Polytechnic Institute of New York University for graciously conducting all of the split-Hopkinson bar testing at their Composite Materials and Mechanics Laboratory while also serving as excellent hosts. Dr. Karl Chang at DuPont was instrumental in helping to define the unique differences between the grades of Kevlar.
Many companies graciously donated equipment and time for many of the ballistic and ASTM testing presented. Specifically, Zach McHale at P2SI in Moraine, OH donated use of the fixture for the mixed mode interlaminar shear testing. The \( V_{50} \) ballistic testing done in March, July and November of 2010 was conducted at High Com Security’s ballistic lab in Hilliard, OH by Chad Wright with help from Ben Raviv. The panels pressed with phenolic for the March 2010 ballistic test were processed at Iten Industries in Ashtabula, OH. John Frechette at Zyvex Technologies in Columbus, OH was instrumental in arranging for the processing of the panels for the ballistic shoots in July and November of 2010. Page McAndrew of Arkema was the point person for getting the Graphistrength®MWCNT material donated, and Bruce Duerringer at Kaneka arranged for the donation of the Core Shell Rubber nano-particles. Mike Bracey at BGF Industries in Greensboro, NC helped in getting the woven Kevlar material for all of the testing.
# TABLE OF CONTENTS

LIST OF FIGURES .................................................................................................................. xiii

LIST OF TABLES ...................................................................................................................... xvi

LIST OF ACRONYMS (or) ABBREVIATIONS ........................................................................ xvii

CHAPTER 1: INTRODUCTION ............................................................................................... 1

1.1 Current Problems/Challenges ......................................................................................... 2

1.2 Our Technical Approach ................................................................................................. 3

CHAPTER 2: LITERATURE REVIEW ..................................................................................... 6

CHAPTER 3: METHODOLOGY ............................................................................................... 10

3.1 Materials ......................................................................................................................... 10

3.1.1 Multi Walled Carbon Nanotubes (MWCNT) .............................................................. 10

3.1.2 Core Shell Rubber Particles (CSR) ........................................................................... 10

3.1.3 Graphene .................................................................................................................... 10

3.1.4 Milled Carbon Fiber .................................................................................................. 11

3.1.5 S-2 Glass Fiber .......................................................................................................... 11

3.1.6 Aramid Fiber ............................................................................................................. 11

3.1.7 Epoxy Resin ............................................................................................................. 12

3.1.8 Phenolic Resin ......................................................................................................... 12

3.2 Processing of Materials ................................................................................................ 12
3.2.1 Preparation of carbon nano paper sheet for interleaving............................... 12
3.2.2 Preparation of Interleaving Carbon Nano Paper Sheets.............................. 13
3.2.3 Preparation of Zyvex MWCNTs Dispersed in Epoxy Matrix......................... 13
3.2.4 Dispersion of Nano Particles for Non Functionalized MWCNT’s .................. 14
3.2.5 Impregnation of Kevlar® fabric with Nano-Particle Enhanced Resin............. 15
3.2.6 Unnotched Cantilever Beam Impact and Split Hopkinson Bar Samples ...... 15
3.2.7 Cure of Samples for Mixed Mode Shear Testing and V50 Ballistic Testing . 16
3.3 Testing and Evaluation Methods...................................................................... 16
3.3.1 Unnotched Cantilever Beam Impact Testing (ASTM D4812-11) .............. 16
3.3.2 Mixed Mode I – Mode II Interlaminar Fracture Toughness ....................... 17
3.3.3 Split Hopkinson Bar Testing......................................................................... 25
3.3.4 V50 Ballistic Testing.................................................................................... 26
3.4 Micro Testing.................................................................................................... 27
3.4.1 Raman Spectroscopy................................................................................... 27
3.4.2 Scanning Electron Microscope..................................................................... 30

CHAPTER 4: FINDINGS............................................................................................. 31
4.1 Unnotched Cantilever Beam Impact Testing (ASTM D4812-11) ................. 31
4.2 Mixed Mode I-Mode II Interlaminar Fracture Toughness (ASTM D6671-06) .. 37
4.3 Split-Hopkinson Bar Results............................................................................ 39
4.4  \( V_{50} \) Ballistic Testing Results ................................................................. 52

4.4.1 Phenolic Panels with MWCNT Paper Interleaved .............................. 52

4.4.2 Zyvex MWCNT in Epoxy Resin Prepreg ............................................... 54

4.4.3 Zyvex MWCNT and Milled Fiber Prepreg ............................................. 54

4.4.4 Nano Particle and Milled Fiber Epoxy Panels ........................................ 55

4.4.5 SEM Imaging of Ballistic Panels .......................................................... 59

4.4.6 Raman Spectroscopy for Evaluation of Residual Strain in Kevlar®29 .... 65

CONCLUSION ........................................................................................................ 77

4.5 Unnotched Cantilever Beam Impact Testing (ASTM D4812-11) ............. 77

4.6 Mixed Mode I-Mode II Interlaminar Fracture Toughness (ASTM D6671-06) .. 79

4.7 Split-Hopkinson Bar Testing ...................................................................... 80

4.8  \( V_{50} \) Ballistic Testing .................................................................................. 81

4.9 Raman Spectroscopy ................................................................................... 83

4.10 Summary ..................................................................................................... 84

4.11 Future Work ............................................................................................... 87

APPENDIX ........................................................................................................... 89

4.12 OBL Test Report – 4/16/13 Shoot ............................................................... 90

4.13 High Com Test Report – 11/02/2010 Shoot ............................................. 117

4.15 High Com Test Report – 3/04/2010 Shoot ................................. 123

4.16 Raman Fitted Peak Data for Baseline-1,611 cm⁻¹ Band–4/16/13 Shoot ....... 128

4.17 Raman Fitted Peak Data for CNT 1-1 - 1,611 cm⁻¹ Band – 4/16/13 Shoot... 164

4.18 Raman Fitted Peak Data for CSR 1-1 - 1,611 cm⁻¹ Band – 4/16/13 Shoot ... 172

4.19 Raman Fitted Peak Data for Baseline-1,651 cm⁻¹ Band – 4/16/13 Shoot ..... 185

4.20 Raman Fitted Peak Data for CNT 1-1 - 1,651 cm⁻¹ Band-4/16/13 Shoot ..... 221

4.21 Raman Fitted Peak Data for CSR 1-1 – 1,651 cm⁻¹ Band-4/16/13 Shoot ..... 229

REFERENCES .......................................................................................................................... 242
LIST OF FIGURES

Figure 1 Mixed Mode Fixture [5] ........................................................................................................... 18
Figure 2 $R^2=0.956$ – Analyzed Data Points = 8,000 ................................................................. 24
Figure 3 $R^2 = 0.998$ – Analyzed Data Points = 1,621 ................................................................. 24
Figure 4 – Split Hopkinson Bar Setup ................................................................................................ 25
Figure 5 – Raman spectrum for Kevlar [36] ................................................................................ 28
Figure 6 – Impact Resistance .............................................................................................................. 32
Figure 7 – Milled fiber fracture with MWCNT – CNT 1-1.5 ............................................................ 33
Figure 8 – Milled fiber fracture with CSR – CSR 1-1 ................................................................. 33
Figure 9 – Graphene Impact Resistance Results ............................................................................... 34
Figure 10 – MWCNT Impact Resistance Results ................................................................................. 35
Figure 11 – CSR Impact Resistance Results .................................................................................... 35
Figure 12 – CNT 0-1.5 fracture surface ............................................................................................ 36
Figure 13 – CSR 0-1 fracture surface ............................................................................................... 36
Figure 14 – Graphene 0-3 fracture surface ....................................................................................... 37
Figure 15 – Mixed Mode strain Energy Release Rate ....................................................................... 38
Figure 16 – Critical Load and Critical Total Strain Energy Release Rate ......................................... 39
Figure 17 – Strain signals from Split Hopkinson Bar ......................................................................... 40
Figure 18 – Energy Loss for Baseline Sample 8 ............................................................................... 42
Figure 19 – Energy Loss for CSR 2-1 Sample 2 ............................................................................. 43
Figure 20 – Energy Loss for Split Hopkinson Bar ............................................................................ 45
Figure 21 – Baseline Sample 10 at 23X ...................................................................................... 46
Figure 22 – CNT 1-1.5 Sample 7 at 23X .................................................. 47
Figure 23 – CSR 2-1 Sample 2 at 23X .................................................. 47
Figure 24 – Baseline Sample 10 at 375X............................................. 48
Figure 25 – CNT 1-1.5 Sample 7 at 375X............................................. 48
Figure 26 – CNT 1-1.5 Sample 7 at 374X – Fractured Surface .................. 49
Figure 27 – CSR 2-1 Sample 2 at 375X .................................................. 49
Figure 28 – Baseline Sample 10 at 22.80 KX......................................... 50
Figure 29 – CNT 1-1.5 Sample 7 at 22.82 KX ........................................ 51
Figure 30 – CSR 2-1 Sample 2 at 22.80 KX .......................................... 51
Figure 31 - Diagram of Overlaps of Interleaved MWCNT Enhanced Paper ........... 53
Figure 32 - V₅₀ Ballistic Results Varying Morphology Nano Particles.................. 58
Figure 33 – Back Face Deformation Comparison .................................... 59
Figure 34 – Elongation of Kevlar® fiber at location of pass through of projectile .......... 60
Figure 35 – SEM image showing brittle fracture of baseline epoxy .................... 61
Figure 36 – SEM image at 1.08 KX magnification of CNT enhanced epoxy ............ 62
Figure 37 – SEM image of 86.02 KX magnification showing MWCNT in resin matrix........ 63
Figure 38 – Milled Fiber Surrounded by MWCNT’s .................................. 64
Figure 39 - Milled Fiber Surrounded by CSR’s...................................... 64
Figure 40 – Raman Spectroscopy Data.................................................... 66
Figure 41 – Raman Spectroscopy data for CNT only and CNT and Milled Fiber Panels........ 67
Figure 42 – View of Fiber Orientation for Polarization Effect .......................... 68
Figure 43 – Effect of Polarization on Raman Spectroscopy data ........................ 68
Figure 44 – Raman Spectroscopy Data on Copper from Bullet ............................................. 69
Figure 45 – Raman Spectroscopy Data on Lead from Bullet .................................................. 69
Figure 46 - Raman Shift Peaks for Kevlar®29 of Baseline at 1,611 cm\(^{-1}\) band.................. 71
Figure 47 - Raman Shift Peaks for Kevlar®29 of Baseline at 1,651 cm\(^{-1}\) band.................. 72
Figure 48- Raman Shift Peaks for Kevlar®29 of CNT 1-1 at 1,611 cm\(^{-1}\) band................. 73
Figure 49 - Raman Shift Peaks for Kevlar®29 of CNT 1-1 at 1,651 cm\(^{-1}\) band.................. 74
Figure 50 - Raman Shift Peaks for Kevlar®29 of CSR 1-1 at 1,611 cm\(^{-1}\) band.................. 75
Figure 51 - Raman Shift Peaks for Kevlar®29 of CSR 1-1 at 1,651 cm\(^{-1}\) band.................. 76
LIST OF TABLES

Table 1 – Theoretical and Experimental Raman Peaks for Kevlar ....................................................... 29
Table 2 – Energy Loss for Split Hopkinson Bar ...................................................................................... 44
Table 3 – $V_{50}$ Ballistic Results for Interleaved CNT Paper ................................................................. 52
Table 4 – $V_{50}$ Ballistic Results for Zyvex Functionalized MWCNT Epoxy Panels ......................... 54
Table 5 – $V_{50}$ Ballistic Results for Zyvex Functionalized MWCNT with Milled Fiber ............... 55
Table 6 – $V_{50}$ Ballistic Results for Various Loadings of Nano Particles and Milled Fiber ........ 57
# LIST OF ACRONYMS (or) ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM</td>
<td>American Society of Testing Materials</td>
</tr>
<tr>
<td>CNT</td>
<td>Carbon Nanotube</td>
</tr>
<tr>
<td>CSR</td>
<td>Core Shell Rubber particles</td>
</tr>
<tr>
<td>CVD</td>
<td>Chemical Vapor Deposition</td>
</tr>
<tr>
<td>DWNT</td>
<td>Double Walled Carbon Nanotube</td>
</tr>
<tr>
<td>EPS</td>
<td>Electron Spectroscopy</td>
</tr>
<tr>
<td>FMJ</td>
<td>Full Metal Jacket (type of bullet)</td>
</tr>
<tr>
<td>FSP</td>
<td>Fragment Simulated Projectile</td>
</tr>
<tr>
<td>HNT</td>
<td>Halloysite Nanotubes</td>
</tr>
<tr>
<td>NGP</td>
<td>Nano-Graphene Platelet</td>
</tr>
<tr>
<td>MCF</td>
<td>Milled Carbon Fiber</td>
</tr>
<tr>
<td>MCNT</td>
<td>Multi Walled Carbon Nanotubes</td>
</tr>
<tr>
<td>MWCNT</td>
<td>Multi Walled Carbon Nanotubes</td>
</tr>
<tr>
<td>PMER</td>
<td>Possible Maximum Energy Release</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>SWCGC</td>
<td>Semi-Wad Cutter Gas Check (type of bullet)</td>
</tr>
<tr>
<td>SWNT</td>
<td>Single Walled Carbon NanoTube</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>$V_{50}$</td>
<td>Ballistic performance attribute as defined by MIL-DTL-662F [1]</td>
</tr>
</tbody>
</table>
CHAPTER 1: INTRODUCTION

Composites are materials that contain two or more constituent materials, that when combined create significantly elevated physical properties. Composites are generally made of two different categories of materials: the matrix and reinforcement. The history of composites began with use of natural resins that were derived from plants and animals as the source of binder and glue. But the creation of plastics in the early 1900s, such as vinyl, polystyrene, phenolic and polyester, allowed for physical properties beyond what was available with natural resins. Glass fiber that was originally introduced by Owens Corning in 1935, allowed for incredibly strong structures that were increasingly light weight when combined with these plastic based resin matrices. The following demands of World War II propagated its use in aircraft structures and radomes, due to these high strength, low weight ratios, along with the capability to be molded into complex shapes.

Composite materials are now widely utilized in industries as varied as automotive, aerospace, marine, recreational, sports, medical, and many others. Their high strength and durability, coupled with low densities, make them attractive alternatives to metals. In many of these fields, impact resistance is critical to the survivability of the composite structure; however, typically composites do not have high fracture toughness when compared to metals.

There is a large field of research pertaining to impact resistance in composite structures. However, very little research has been conducted on nano particle enhancement in the energy dissipation of composite laminates during high velocity impact. This research will focus primarily on the high impact range of damage tolerance utilizing various nano particles and their
synergistic effects with micro sized particles of milled fiber while dispersed in a resin matrix of a fiber reinforced composite laminate. Specifically composite materials used in ballistic or high velocity impact scenarios where the damage and response of the material is highly dynamic with durations in milliseconds.

1.1 **Current Problems/Challenges**

Composite armor is widely used in both civilian and military applications in order to achieve high levels of ballistic protection while minimizing the amount of weight required. Composite armor has a history dating back to the 1950’s when the US Army developed a composite of fused silica glass between rolled homogenous steel plates for the experimental T95 tank.

There is a wide range of fibers and resins employed in order to optimize against particular threat levels and maintain flame, smoke and toxicity standards. In hard armor applications, energy absorption is largely accomplished through delamination between plies of the composite laminate.

As mentioned earlier, the energy absorption in ballistic events for composite hard armor applications is largely through crack propagation during the delamination of plies. Some research in the recent past has pertained to use of fibers in tow or yarn form, placed in the z direction through 3D-braiding, weaving, sticking, and z-pinning [1]. However, this can have a negative impact on in-plane performance [1] [2]. Another possible solution is through the enhancement of the interlaminar fracture toughness of the composite through the use of nano-particles.
Because "the C-C bond in graphite is the strongest bond in nature" [3], carbon nanotubes theoretically have the capacity to drastically improve energy absorption in ballistic events. The fracture of the thermoset resin during a ballistic event, involves a multiscale activity from the microscopic interaction of the MWCNT’s amongst themselves, through “sword-in-sheath” type fracture mechanism, or their interaction with the resin matrix through their surface bond. Up to a larger scale where crack propagation is mitigated through placement of the MWCNT’s in the matrix. Because of this complex interaction, the theoretical strength and resiliency of the MWCNT’s can have an impact on the energy absorption of the laminate, but is limited by the bond strength between the resin and MWCNT. Assuming that the bond strength is not negligible, the fracture toughness of the brittle epoxy polymer matrix will increase with the addition of the MWCNT’s.

1.2 **Our Technical Approach**

For purposes of this research, nano-particle enhancements will focus on improving the performance of the composite through enhanced energy absorption characteristics of the matrix. Specifically through increased performance in crack propagation. This will be accomplished through dispersion of nano-particles in the resin matrix, as well as evaluations of their interactions with micro sized particles, specifically, milled carbon fiber.

Improvements will be measured through multiple methods. On the micro-scale, we will use Raman Spectroscopy to evaluate the composite panels capacity for stress absorption, as well as Scanning Electron Microscope imaging to evaluate damage mechanisms in the evaluated panels.
At the macro-scale, we will measure the impact toughness of the resin matrices through the use of the unnotched cantilever beam impact test, ASTM D4812 [4]. These results will give guidance on refining the amount of panels needed to test further in interlaminar shear, split Hopkinson Bar and V\textsubscript{50} ballistic testing. During a ballistic event, delamination between the discrete plies of fabric happens in both peel and shear mechanisms. Therefore, both the Mode I and II interlaminar fracture toughness for evaluation of crack propagation in the composite panels through the use of ASTM D6671 [5] is utilized. Analysis of the nano-particle reinforcement in dynamic compression testing is critical to understanding ballistic performance; therefore, split Hopkinson bar testing is utilized. The energy levels for the split Hopkinson bar and unnotched cantilever beam testing are both in the range of 300 Joules. But each test is crucial to the research, because the split Hopkinson bar tests with compression stress waves, while the unnotched cantilever beam testing is focused on the shear mechanisms. For macro testing of the entire composite laminate, we will utilize V\textsubscript{50} ballistic testing as defined in MIL-DTL-662 F [6]. The energy levels of the ballistic testing is exponentially higher than all previous testing, and is in the range of 37,000 Joules. Distributing large amplitude stress waves into the nano-scale particles for energy absorption with microsecond time durations becomes challenging. Ballistic testing will evaluate the effectiveness of micro-sized particles to enhance the transfer of energy from the macro-scaled fiber reinforcement down to the nano-scale.

Nano-materials have three distinct morphologies. The first is essentially a two dimensional structure in platelet form. This can include nano clay (Montmorillonite), or Nano graphene platelet (NGP), where the thickness is on the nano-scale, but length and width are on the micro-scale. Another classification of geometry for nano particles is in the form of fibers
where diameters are on the nano-scale with lengths in the micro-scale. This group can include carbon nano fiber, carbon nanotubes (SWNT, DWNT, or MWNT), Halloysite nanotubes (HNT), or silicon carbide whiskers. For use of nano-particles with three distinct geometries, you must consider particulate nano-particles. Specifically, silica, POSS®, alumina or core-shell rubber (CSR) nanospheres. It has been shown that aspect ratio of the nano-particles can have an effect on mode I and II fracture toughness [7]. Therefore, it is of interest for this research to look at all three geometry types of nano-particles in order to investigate the effect of geometry on the response of composite laminates for high velocity impacts. Specifically, we will utilize nano graphene platelets (NGP), multi walled carbon nanotubes (MWCNT), and core-shell rubber (CSR) nano spheres. Therefore impact of various morphologies of the nano-particles can also be discussed.
CHAPTER 2: LITERATURE REVIEW

Carbon nanotubes have been shown to “elastically sustain loads at large deflection angles” [8]. Demczyk et al has shown measured tensile strengths of 0.15 TPa [8] and Young’s modulus of 0.9 TPa [8] for carbon nanotubes.

Analytically, it has been predicted that significant increases in toughness of the laminate through alignment of the MWCNT’s in the z direction of the polymer matrix can be obtained as the diameter of the vertically aligned pins approach nanometer dimensions [9].

Through-thickness reinforcement or ‘z-pins’ have been shown to improve delamination properties; however, experiments and numerical simulations show that these ‘z-pins’ can decrease the tensile strength of the composite by 27%, and the compressive strength by 30% [2]. Instead of using micro-diameter filaments in the z-direction that can have these negative effects, it has been shown analytically that Mode I interlaminar toughness can increase through the use of aligned carbon nanotubes [9]. It has also experimentally been shown to improve out-of-plane mechanical properties without detriment to the in-plane properties [10]. While they successfully enhanced the interlaminar shear strength by approximately 30% [10], it has required special processing whether through chemical vapor deposition (CVD) or electrophoresis.

Extensive research has been done to increase interlaminar shear strength properties through introduction of nano-sized particles onto the fiber or filament prior to addition of the resin matrix. Specifically, growing carbon nanotubes on the surface of the filaments [11], and growing carbon nanotubes on the surface of the tows [12].
Introduction of a carbon nanotube array at the surface of the fabric reinforcement has been shown to improve interlaminar properties to help with delamination issues in composite laminates [13].

Nano particles have been utilized in resin matrices to enhance electrical, thermal and mechanical properties with success [14] [15]. Most work has focused on the use with epoxy based resins, due to its popularity in the industry. Yasmin et al. [15] obtained a 60% increase in elastic modulus with decrease in tensile strength for addition of nano-clay. Liu et al. [16] added nanoclay into the bisphenol A side of the epoxy mixture, and had an increase in elastic modulus, decrease in glass transition temperature, and about an 80% increase of stress intensity factor. They also found an increase of impact strength (Charpy impact tests) from 32.1 to 38.1 kJ/m² with 3 wt% of nano-clay.

Zhao and Hoa [17] look thoroughly at the effect of particle dispersion, size and volume fraction on the effect of toughness in epoxy resin. They outline a few key features for this research:

1. Particle size in the resin system can be reduced to lessen stress concentration, up to a particular limit.

2. 2D/3D analytical cell models of fracture are proposed to give correlation of parameters to toughness. They find that the addition of 5% volume fraction of spherical silicate can improve the toughness of epoxy up to 18 times. They also theorize that greater improvements are possible for particles of larger aspect ratios.
3. Particle volume fraction $V_p$ has an inverse relation to the possible maximum energy release (PMER); however, increasing $V_p$ beyond a specified limit does not enhance the PMER significantly.

Theoretical understanding regarding toughening mechanisms in resin systems has been evaluated through several reviews [18] [19]. A few of these aspects are summarized below:

Crack-pinning mechanism [20] states that the crack front bows out between filler particles and remains pinned at the particles as it propagates through the resin.

Toughness increases can be found by incorporation of rubber into polymers [21] [22]. The micro cracks are caused by the presence of rubber particles, and cause tensile yielding, which subsequently allows for large tensile deformation. The voids that are created when the micro cracks open, permit large strains. This debonding or micro cracking lowers the modulus in the frontal zone around the crack tip, and thereby locally reduces the stress intensity.

Dilatational deformation of the matrix and cavitations of the rubber particles, due to the triaxial stresses at the crack tip, in addition to shear yielding between the voids formed by the cavitated rubber particles, allows for the major energy absorption mechanism to be the plastic deformation of the matrix. The crack tip is blunted by the plastic deformation, thereby reducing the local stress concentration and increasing the allowed load prior to failure [23] [24].

Sigl et al. [25] proposes that particles play two roles: (1) The particle acts as particle bridging, resulting in compressive traction along the crack wake and (2) A ductile particle deforms plastically around the crack tip, reducing crack spreading. However, the particle bridging is responsible for the majority of the improvement in toughness.
Bugarin has shown that stress concentration values at the interface of spherical particles and resin matrices are significantly influenced by particle aspect ratio, excitation frequency and the degree of elastic mismatch between the particle and matrix [26]. Therefore, under this finite element model, the stiffer the particle in relation to the resin matrix, the higher the stress concentration, and earlier onset of crack propagation.

While all of the afore mentioned research pertains to improving specific mechanical properties that should theoretically have an improvement in ballistic performance, there has been minimal research pertaining to ballistic testing of composite armor panels utilizing nano-particles. Ma et al. [27], has shown better impact resistance and a 43% reduction in deflection on composite armor panels utilizing 5% nano-clay in an epoxy matrix. Grujicic et al. [28], has shown through computer simulation that a 6% improvement in $V_{50}$ ballistic performance with 30 caliber fragment simulated projectiles can theoretically be obtained with the addition of either 30% by volume multi-walled carbon nanotube mat or 0.498% by volume multi-walled carbon nanotube doped matrix.
CHAPTER 3: METHODOLOGY

3.1 Materials

3.1.1 Multi Walled Carbon Nanotubes (MWCNT)

Multi-walled carbon nanotubes (MWCNT) as supplied by Arkema were utilized for experimentation. The Graphistrength® CS1-25 MWCNT for epoxy dispersion in masterbatch form at 25% concentration was utilized. These MWCNT’s have diameters up to 100 nanometers, and lengths up to 100 microns. They have a specific gravity of 2.90 g/cm$^3$, and an apparent density of 0.15 g/cm$^3$. They have a surface area between 100 and 250 m$^2$/g, and a tensile modulus on the scale of 10$^3$ GPa.

3.1.2 Core Shell Rubber Particles (CSR)

Kane Ace® MX 153 manufactured by Kaneka was utilized throughout experimentation, and is a 33% concentrate core shell rubber (CSR) toughening agent in unmodified liquid epoxy resin based on Bisphenol-A. The diameters of the CSR particles are approximately 100 nanometers.

3.1.3 Graphene

Graphene nanoplatelets manufactured by XG Sciences were utilized for experimentation. Graphene nanoplatelets have a “platelet” morphology, where they have a very thin but wide aspect ratio. These nanoparticles are made of short stacks of graphene sheets having a platelet shape. Specifically, the xGnP-M-5 was utilized, which have an average thickness of approximately 6 nanometers and a typical surface area of 120-150 m$^2$/g with an average particle diameter of 5 microns. The bulk density is 0.03 to 0.1 g/cc with an oxygen content less than 1
percent, and carbon content greater than 99.5 percent. The tensile properties parallel to the surface are 1,000 Gpa for modulus and 5 Gpa for strength. The electrical conductivity is $10^7$ siemens/meter.

3.1.4 Milled Carbon Fiber

The milled carbon fiber was manufactured by Kureha in Tokyo, Japan. It is their Kureha KRECA KGF 200 M-201F milled fiber. It has an average diameter of 12.5 µm and an average length of 0.15 µm. The KRECA line of carbon products are petroleum pitch based carbon products, and due to their high affinity for resins, no sizing agent was required for good bonding characteristics with the Bisphenol-A based epoxy resins.

3.1.5 S-2 Glass Fiber

The S-2 glass fiber is a high tensile strength fiberglass meeting the requirements as specified in Appendix A of MIL-DTL-64154B [29]. This fiber was manufactured and supplied by AGY in Aiken, SC. It was woven by BGF Industries out of Greensboro, NC into a plain weave with the construction of 5 ±0.5 ends in the warp and 5.2 ±0.9 ends in the fill with a nominal weight of 24 ounces/square yard ±5%. This fabric was in accordance with Class A of MIL-DTL-64154B [29].

3.1.6 Aramid Fiber

Kevlar® 29 fiber was provided by DuPont industries in Richmond, VA. It is a 3,000 denier fiber that was woven by BGF industries out of Greensboro, NC, into their 5745 style 17 x 17 pick count plain weave of 14 oz/yd², as defined in MIL-DTL-62474F [30].
3.1.7 Epoxy Resin

Epoxy resins are high molecular weight polymers containing two epoxide groups. The epoxy resin utilized for this research included a bisphenol A reacting with a modified cycloaliphatic amine hardener. Rhino Epoxy 1403 bisphenol-A based resin with Rhino 4120 hardener was utilized for experimentation. The 1403 resin is a medium viscosity, undiluted, extended pot life epoxy resin. The neat resin viscosity is 7,300 cps. The 4120 hardener is a modified cycloaliphatic amine hardener. It provides greater than 7-hour gel time at room temperature. Rhino 4120 is solvent free, and has a mix ratio of 35 parts per 100 of resin.

3.1.8 Phenolic Resin

Phenolic resins are synthetic polymers obtained by the reaction of phenol with formaldehyde. The Phenolic resin utilized for this research was supplied by Iten Corporation in Ashtabula, OH, and was in accordance with the requirements specified in Appendix B of MIL-DTL-64154B [29].

3.2 Processing of Materials

3.2.1 Preparation of carbon nano paper sheet for interleaving

Raw MWCNTs not in masterbatch form from Arkema were transferred into a solvent of ethanol to form a suspension. The suspension was sonicated using a high intensity sonicator for 20 minutes with a power of 30-50 watts. After sonication, both the suspension and probe were cooled down to room temperature. Two drops of concentrated HCl were added and the suspension was sonicated again for another 20 minutes under the same conditions. This suspension of MWCNTs was left overnight, and was capable of staying in suspension. The suspension was then filtrated through a 0.45 μm teflon filter with the aid of vacuum to fabricate
the carbon nano-paper sheets. After the filtration, a filter and heavy plate were put on top of the nano-paper sheet to allow for drying flat. The preparation was complete after the sheets were further dried through a 2 hour cycle in a 120°C vacuum oven.

3.2.2 Preparation of Interleaving Carbon Nano Paper Sheets

The panels utilizing the plain weave S2 glass and phenolic resin were prepared at Iten Industries in Ashtabula, OH, and were pressed to the specifications of MIL-DTL-64154B [29], with the carbon nano-paper sheet placed between the first and second ply of woven S2 glass. The panel was constructed to 18” x 18”; however, the carbon nano-paper was limited to a 12” x 12” size. Therefore, 4 plies of paper were placed such that there was a six inch overlap on the horizontal and vertical center of the panel, and a six inch square in the center of the panel with an overlap of all four plies of the carbon nano-paper sheets. These panels were pressed to achieve an aerial density of 0.97 lb/ft³. These panels are defined as Panel Group A.

3.2.3 Preparation of Zyvex MWCNTs Dispersed in Epoxy Matrix

The panels utilizing the plain weave Kevlar®29 and epoxy resin were prepared by Zyvex Performance Materials out of Columbus, OH. The MWCNTs were dispersed in their epoxy resin through shear mixing, and subsequently impregnated onto the woven Kevlar®29 at either 30% (Panel Group B) or 18% (Panel Group C) resin content by weight. This material was subsequently processed in autoclave at 120 psi for the appropriate heating cycle as defined by Zyvex’s Arovex prepreg line. The panels were limited to 12” x 12”, and two panels were constructed for each V50 ballistic test to allow for accurate values of V50 ballistic performance. A total of four baseline panels without MWCNTs and four panels enhanced with MWCNTs were produced to allow for testing with both 30 caliber fragment simulated projectiles and 44 mag soft
point bullets. The loading of MWCNTs was 0.5% for panels without additional milled fiber (Panel Group B), and was 1.65% for the panels made in combination with 1.65% milled fiber (Panel Group C).

3.2.4 Dispersion of Nano Particles for Non Functionalized MWCNT’s

The Thinky ARE-310 planetary centrifugal mixer was utilized for dispersion of the nanoparticles in the resin systems. Thinky planetary centrifugal mixers are useful for their simultaneous processing of mixing, dispersion, and deaeration of high-viscosity materials. The centrifugal force of over 400G enables thorough mixing, and subsequent deaeration removes any bubbles formed during the mixing process. Mixing cycles were run at 2,000 rpm, and deaeration cycles were run at 2,200 rpm.

Dispersion of the Arkema Graphistrength® MWCNT’s was done by measuring the appropriate amount of MWCNT’s in pellet form and placing in the appropriate amount of Rhino epoxy 1403 resin. This mixture was then inserted in an oven at 100 °C for at least 12 hours prior to mixing. The heated mixture was then placed in the Thinky planetary centrifugal mixer for a total of ten minutes of mixing with subsequent two minutes of deaeration.

Dispersion of the Kaneka CSR particles and XG Sciences Graphene particles was done by measuring the appropriate amount of nano-particles, placing them in the appropriate amount of Rhino epoxy 1403, and running through a single cycle of five minute mixing and subsequent one minute deaeration.
3.2.5 Impregnation of Kevlar® fabric with Nano-Particle Enhanced Resin

Impregnation of the BGF 5745 woven Kevlar® was done through use of a Binks 18” impregnation machine. The gap on the pinch rollers were set to 0.010”, which controls the amount of resin content on the finished product. Each ply of material in the finished part was individually impregnated, and was weighed prior to and after wet-out to have measurements on resin content prior to cure in the autoclave. Average resin content of samples for the mixed mode interlaminar shear testing was 19.6% with a standard deviation of 3.5%. Average resin content for the V\textsubscript{50} ballistic testing was 18.75% with a standard deviation of 0.89%

3.2.6 Unnotched Cantilever Beam Impact and Split Hopkinson Bar Samples

An aluminum mold with specimen dimensions of 1” x 3” x 0.125” deep was used to mold the pieces for the Unnotched Cantilever Beam Impact Testing (ASTM D4812-11) [4]. The split Hopkinson bar samples were made in a different aluminum mold as discreet sheets. The molds with mixed epoxy resin were put into an ASC Econoclave EC2x4 autoclave and run through a cure cycle. The cure cycle heats up to 250 °F at a rate of 5 °F per minute under a pressure of 5 psi. Once temperature reaches 250 °F, it holds for 2 hours, with subsequent cool down happening at a rate of 5 °F per minute. The pieces are placed back into the autoclave for a post-cure at 350 °F for twelve hours. Split Hopkinson bar samples were subsequently milled to control thickness and ensure surfaces were parallel. They were then drilled out with the use of a diamond bit hold saw.
3.2.7 Cure of Samples for Mixed Mode Shear Testing and $V_{50}$ Ballistic Testing

A flat aluminum mold with a reusable silicone bag was used to mold the composite samples under vacuum pressure for the Mixed Mode Interlaminar Shear Testing (ASTM D6671/D6671M-06) [5] and $V_{50}$ ballistic testing [6]. The impregnated fabrics were placed in the mold and pulled under 1 atm of vacuum. The mold was placed in the autoclave for the cure cycle. The cure cycle starts with a pressure ramp up to 50 psi, and is held at this pressure for 15 minutes with subsequent heating up to 250 °F at a rate of 5 °F per minute under the pressure of 50 psi. Once temperature reaches 250 °F, it holds for 2 hours, with subsequent cool down happening at a rate of 5 °F per minute. The pieces are demolded, and placed back into the autoclave for a post-cure at 350 °F for twelve hours with a ramp up and cool down no greater than 5 °F per minute.

For the Mixed Mode Interlaminar Shear Testing panels, stainless steel hinges were bonded to the composite samples through the use of epoxy paste adhesive. Hysol EA9394 was utilized because its bond strength to both the metal hinge and epoxy composite specimens was great enough to hold together throughout testing. This adhesive was cured at 250 °F for 12 hours.

3.3 Testing and Evaluation Methods

3.3.1 Unnotched Cantilever Beam Impact Testing (ASTM D4812-11)

A Baldwin Impact Tester with a capacity of 16 ft-lbs. and a weight set of 4 lb. manufactured by Baldwin-Lima-Hamilton Corporation out of Waltham, MA was utilized for this testing. The post-cured unnotched resin samples were placed in the clamp of the equipment with $1.25 \pm 0.010$ in. of the specimen projecting above the top surface of the vise as per section 6.3.1
in ASTM D4812-11 [4]. Multiple loadings from 0% to 5% by weight of milled carbon fiber and various nano-particles were tested, resulting in an evaluation of 72 batches of material. Seven samples were tested for each batch, with the averages compared across batches. Therefore, 504 unique specimens were tested, and averaged across batches for a total of 72 results.

Windage and friction were accounted for by performing the procedure described in section A2 of ASTM D4812-11 [4] prior to every specimen tested. This allowed for calculation of the energy correction, including both pendulum windage and dial friction, \( E_A \). The total correction energy, \( E_{TC} \), was then calculated using \( E_A \). The impact resistance was then determined by taking the difference in dial reading breaking energy for a specimen, \( E_S \), and the total correction energy, \( E_{TC} \), and subsequently dividing by the thickness of the specimen, \( t \), as shown in equation (1):

\[
I_S = \frac{E_S - E_{TC}}{t}
\]  

(1)

3.3.2 Mixed Mode I – Mode II Interlaminar Fracture Toughness

A Mixed-Mode Bending Fixture manufactured by Wyoming Test Fixtures was utilized for this testing. See Figure 1 for schematic of the fixture. An Instron 3300 electromechanical table top with 50 kN capacity, utilizing the Merlin control software was used for the loading and recording of data. All testing was completed in accordance with ASTM D6671 [5].
The composite specimens were processed with eight plies of the impregnated Kevlar®29, woven in BGF style 5745, with an insert of PTFE skived film at 0.0005” thick. The samples were approximately 1 in. x 7 in. x 0.162 in. thick. At least five samples of each batch were produced for testing. The displacement rate of the crosshead was conducted at 0.02 (in/min). The mode mixture, $G_{II}/G$ was chosen to be 0.937, resulting in a lever length of 0.8664 (in.), as shown in equations (2)–(6):

Lever length of the MMB test apparatus:

$$c = \frac{12\beta^2 + 3\alpha + 8\beta \sqrt{3\alpha}}{36\beta^2 - 3\alpha} L$$

(2)

Where:

Mode mixture transformation parameter for setting lever length:
\[ \alpha = \frac{\frac{g_{II}}{g}}{\frac{g_{II}}{g}} \]  

(3)

Non-dimensional crack length correction for mode mixture:

\[ \beta = \frac{a + \chi h}{a + 0.42 \chi h} \]  

(4)

Crack length correction parameter:

\[ \chi = \sqrt{\frac{E_{II}}{11G_{13}} \left( 3 - 2 \left( \frac{\Gamma}{1+\Gamma} \right)^2 \right) } \]  

(5)

Transverse modulus correction parameter:

\[ \Gamma \equiv 1.18 \sqrt{\frac{E_{11}E_{22}}{G_{13}}} \]  

(6)

and

\[ E_{11} = \text{longitudinal modulus of elasticity measured in tension} \]

\[ E_{22} = \text{transverse modulus of elasticity} \]

\[ G_{13} = \text{shear modulus out of plane} \]

Aluminum 6061 T6511 was utilized for the calibration specimen, in order to calculate compliance of the calibration specimen, \( C_{\text{cal}} \). This in turn allows for calculation of the compliance of the Mixed Mode Bending test system, \( C_{\text{sys}} \) as shown in equations (7) and (8):

Compliance of calibration specimen:
System compliance:

\[ C_{sys} = \frac{1}{m_{cal}} - C_{cal} \]  \hspace{1cm} (8)

Where:

L = half-span length of the MMB test apparatus = 1.9680 (in.)

t = thickness of the calibration specimen = 0.375 (in.)

\[ E_{cal} = \text{modulus of the calibration bar -- published value for AL 6061 T6511 = 10 Msi} \]

\[ b_{cal} = \text{width of calibration specimen = 1.0 (in.)} \]

\[ m_{cal} = \text{slope of calibration curve} = 3.9728955 \times 10^3 \left( \frac{lbf}{in} \right) \]

For calculating \( G_1 \) and \( G_{II} \), the critical load, \( P_c \) must be determined through one of three options:

\( P_{nl} \) = Point of load-displacement curve where data becomes non-linear

\( P_{5\%\text{max}} \) = critical load at 5% of maximum point of loading curve

\( P_{vis} \) = critical load when delamination is observed to grow

Option 1, the non-linear value, has benefit in having been shown by micro-focus radiography to correspond to crack initiation at the specimen center in some materials [31]. The
second option, a 5% offset value, corresponds to a crack that has already advanced in the specimen, and is a compromise between trying to detect the exact moment of first crack advance and the lack of a quantitative measurement. The third option, which is based on observation of the specimen edge is subjective.

The ASTM (American Society for Testing and Materials) D30 group specifies the lowest initiation value of the three measured during the test as the most conservative value [32]. In most cases, this was the non-linear value, or option 1. Due to the nature of the Kevlar® composite, many of the specimens never reached a maximum load during deflection, and simply continued to bend until the fixture deflected to the bottom of the testing bed. Due to this fact, and the subjective nature of observing the crack growth in option 3, critical load, \( P_c \), is determined using option one with the critical load being at the point where non-linearity of the data begins. However, as mentioned by Davies [33], “it is difficult to determine changes in slope accurately, and without a quantitative criterion for the degree of non-linearity its identification may be quite subjective.” Therefore, in order to quantitatively determine the point of non-linearity, use of an iterative refinement of linear regression analysis is utilized to determine the point of non-linearity initiation.

This iterative technique utilizes the coefficient of determination, \( R^2 \) value for optimization. The coefficient of determination is the square of the sample correlation coefficient between the measured experimental value and the predicted value from the regression analysis, as shown in equations (9) – (12).

21
Residual Sum of Squares:

\[ SS_{err} = \sum_i (y_i - f_i)^2 \]  

(9)

Total Sum of Squares:

\[ SS_{tot} = \sum_i (y_i - \bar{y})^2 \]  

(10)

Mean of the Observed Data:

\[ \bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i \]  

(11)

Coefficient of Determination:

\[ R^2 \equiv 1 - \frac{SS_{err}}{SS_{tot}} \]  

(12)

Using the method of minimizing the sum of square errors, any set of n data points in the form \((x_i, y_i)\), allows for calculation of the slope and y-intercept of the fitted linear equation, when equations (13) and (14) are satisfied:

\[ m \sum_{i=1}^{n} x_i + bn = \sum_{i=1}^{n} y_i \]  

(13)

\[ m \sum_{i=1}^{n} x_i^2 + b \sum_{i=1}^{n} x_i = \sum_{i=1}^{n} x_i y_i \]  

(14)

From equations (13) and (14), the slope and y-intercept of the linear equation \(y=mx+b\) are found to be:

\[ m = \frac{n \sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n \sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2} \]  

(15)
\[ b = \frac{\sum_{i=1}^{n} y_i - m \sum_{i=1}^{n} x_i}{n} \quad (16) \]

This iterative technique of optimization of the coefficient of determination is a quantitative measurement for fit of the line to the experimental data. For each data set of load and displacement, a linear regression was done for a given amount of the data set, starting at the initiation of the data. When the entire data set was included in the linear regression, the \( R^2 \) value was low, because the entire data set is partially parabolic in nature, as shown in an example in Figure 2. However, iteratively continuing to do the linear regression with progressively smaller data sets, continuously improves the fit of the linear projection of the red line, until you get an optimum \( R^2 \) value, thereby quantitatively determining the point of non-linearity. Taking the load value at the maximum displacement of the optimized data set, as being the \( P_{nl} \) or \( P_c \). As shown in Figure 3, the fitted linear relationship matches well to the linear aspect of the data set. This method of linear regression iteration for optimizing \( R^2 \), allows for a quantitative determination of \( P_{nl} \), and can be repeated without concern for subjective input.
Figure 2 $R^2 = 0.956$ – Analyzed Data Points = 8,000

Figure 3 $R^2 = 0.998$ – Analyzed Data Points = 1,621
3.3.3 Split Hopkinson Bar Testing

The Hopkinson Pressure Bar was first established by Bertram Hopkinson in 1914. He designed it to measure stress wave propagation in metal bars. In 1949, H. Kolsky redesigned this test into what is now known as the split-Hopkinson bar, which measures stress, strain and strain rate.

![Figure 4 – Split Hopkinson Bar Setup](image)

Figure 4 shows the details of the test setup utilized. There are three bars made of Inconel, all are at ½” diameter. The Young’s modulus and density of the Inconel bars are 195 GPa and 8,190 kg/m³ respectively. The elastic wave velocity for the Inconel bars at room temperature is 4,879 m/s. The specimens were sandwiched between the two 1.27 m long incident and transmitter bars. The striker bar is launched through the use of compressed gas, and shoots forward to impact a brass pulse shaper that is applied on the face of the incident bar. The purpose of the pulse shaper is to optimize a constant rise time and strain plateau in the incident pulse. Selection of the pulse shaper is based on calibration studies. This impact creates a stress pulse that propagates into the incident bar, defined as the incident stress pulse. At the interface of the incident bar and the test specimen, the incident stress pulse wave splits into two parts, defined as the transmitted and reflected waves. The amplitude of each specific wave is a function of the impedance mismatch between the tested specimen and the incident bar. This same impedance mismatch impacts the two stress waves at the interface of the specimen and
transmitter bar. Therefore, you have three stress pulses. The incident stress pulse that initially travels away from the striker bar through the incident bar. The reflected stress pulse that reflects back into the incident bar in the direction of the striker bar. And the transmitted stress pulse which travels through the transmitter bar away from the test specimen. These three stress pulses are measured via two strain gauges placed on the incident and transmitter bars as shown in Figure 4. The strain gauges used for this experimentation were of the type CEA-13-240UZ-120 (Vishay Precision Group, Melvern, PA). The signals were recorded by an oscilloscope Tektronix TDS 2014B (Beaverton, OR). The data was then processed through a MatLab code developed by Luong et al [34]. The test specimens were all nominally 3 mm thick and 7.5 mm in diameter. Testing was done at three different levels of gas pressure on the striker bar, specifically 600, 800 and 1,000 psi. Three samples were evaluated at each pressure level for all nano-particle ratios.

3.3.4 V50 Ballistic Testing

Thirteen panels of approximately 18” x 18” x 0.310” of 16 distinct plies of 5745 Kevlar® impregnated with epoxy at an average resin content of 18.75% with 0.89% standard deviation were sent to Oregon Ballistics Lab in Salem, OR for V50 ballistic testing as per Military Specification MIL-DTL-662 F [6].

The samples were tested in an indoor range with the muzzle of the test barrel mounted 16.5 feet away from the target panel and positioned to produce 0 degree obliquity impacts. Four Oehler Model 57 infrared light screens, in conjunction with time-based frequency counters, were positioned such that bullet velocity was measured 8.25 feet from the target. Penetrations were
determined by examination of a piece of 0.020 inch 2024-T3 aluminum mounted 6 inches behind and parallel to the test sample.

All panels were tested utilizing a .44 Mag 240 grain SWCGC (Semi-Wadcutter Gas Check) bullet, fired from a universal barrel holder utilizing a 10” 1:20 .44 Mag barrel.

3.4 Micro Testing

3.4.1 Raman Spectroscopy

Raman spectroscopy is a technique used to study vibrational, rotational, and other low-frequency modes in a system [35]. It utilizes inelastic scattering or Raman scattering, of monochromatic light, from a laser. The frequency of photons in monochromatic light changes upon interaction with the sample. The photons from the laser are absorbed and subsequently reemitted by the sample. The interaction of the laser light with molecular vibrations or phonons, results in a shift of the energy of the laser photons, which is then measured for information about the vibrational modes in the system. This frequency difference of the reemitted photons from its original state is called the Raman effect.

The laser light that impinges upon a molecule and interacts with the electron cloud and its molecular bonds, creates the Raman effect. The photon from the laser excites the molecule into a virtual energy state, from its original ground state. A photon is then emitted as the molecule relaxes to a different rotational or vibrational state. A shift in the emitted photon’s frequency can be measured as the energy difference between the original state and the newly relaxed state.

A Renishaw RM-1000 Ramascope was utilized throughout this research for Raman shift peak measurements on the Kevlar®29 post shoot. Single point measurements were completed
using a 50x Nikon objective with 532 nm laser excitation. Multiple point or mapping measurements were completed using a 10x Mitutoyo objective with a numerical aperture of 0.28 and a 532 nm laser excitation. The monochromatic light source probe was mounted on a fixture that allowed for servo motor movement in the X and Y plane for computer controlled mapping of a distinct location. All measurements were taken after calibration of the equipment with Silicone, which has a known Raman shift of 520 cm$^{-1}$.

As shown in Figure 5, there are multiple distinct Raman bands for Kevlar®. This research will focus on two bands, specifically, the band at $\sim$1,611 cm$^{-1}$, which stems from the stretching vibrational mode of the C-C phenyl ring. The second band occurs at 1,649 cm$^{-1}$, which stems from the stretching of the C=O bond [36].

![Raman spectrum for Kevlar](image.png)

Figure 5 – Raman spectrum for Kevlar [36]

There is some minor discrepancy in Raman band values for Kevlar® for theoretical and experimental research. A summary of these values is shown in Table 1 [37] [36] [38] [39] The
work by Cen et al [38] is focused on Kevlar®29, while the work by Washer et al [36] is based on Kevlar®49. However, the band shifts are all functions of either the C-C phenyl ring for the 1,611 cm⁻¹ shift, or the stretching of the C==O bond for the 1,649 cm⁻¹ band, which are present in both versions of Kevlar®. The essential difference between Kevlar®29 and Kevlar®49, is that the K49 fiber structure has larger crystallite size, resulting in lower total crystal surface area. This causes a lower total crystal surface area available for moisture absorption. This in turn leads to lower equilibrium moisture in the crystalline structure. The K49 also has a higher orientation angle of the crystalline structure, resulting in a 50% higher modulus than K29. These two factors may attribute for the discrepancy in Raman band seen in the literature between Cen et al [37] and Washer et al [36].

Table 1 – Theoretical and Experimental Raman Peaks for Kevlar

<table>
<thead>
<tr>
<th>Theoretical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kevlar Yarn</td>
<td>Kevlar Strand</td>
</tr>
<tr>
<td>647 nm</td>
<td>488 nm</td>
</tr>
<tr>
<td>1,615</td>
<td>1,612</td>
</tr>
<tr>
<td>1,649</td>
<td>1,654</td>
</tr>
</tbody>
</table>
3.4.2 Scanning Electron Microscope

A scanning electron microscope (SEM) takes images of a sample by scanning with a high-energy beam of electrons in a raster scan pattern. The electrons interact with the atoms that make up the sample, producing signals that can be measured and interpreted for surface topography. Because the samples must be electrically conductive, and the fact that the composite panels to be evaluated are not good conductors, the samples are given a thin coating of gold, and grounded. This coating increases signal and surface resolution. This improvement in resolution comes from enhancement of the backscattering and secondary electron emission near the surface. SEM is capable of magnification that allows for viewing of surface topography in the nanoscale.

Viewing of the tested panels on the nano and micro scale allows for analysis of the failure mechanisms of the particle fillers during crack propagation. It also enables some analysis of the stress transfer from the nano to micro to macro scale.
CHAPTER 4: FINDINGS

4.1 Unnotched Cantilever Beam Impact Testing (ASTM D4812-11)

A total of 504 specimens were produced, and tested. Of these 504 specimens, there were 72 distinct batches of various mixtures of milled carbon fiber and nano-particles, with each batch having a minimum of 7 specimens. The purpose of testing the various mixtures of micron particles of milled carbon fiber and nano particles was two fold. The first goal was to evaluate the effectiveness of different morphologies of nano-particles on their energy absorption characteristics. For this evaluation, we looked at the specimens that only had nano-particles in the mixture; therefore, the results that show under the 0% milled carbon fiber loading. The second goal was to determine if there was any synergistic effect of having micron sized particles (milled carbon fiber), surrounded and reinforced by nano-sized particles in the resin mixture. For nomenclature purposes, the number after the nano-particle designation represents the percentage loading by weight of the specific nano-particle. For example, CNT 0.5 represents a 0.5% loading of Arkema Graphistrength® Multi-Walled Carbon Nanotubes by weight.

The baseline samples were shown to have an average impact resistance of 1.374 (ft-lbf/in), with a standard deviation of 0.417 over 12 samples. This is shown by a horizontal line in Figure 6.
Figure 6 – Impact Resistance

None of the batches with milled fiber in the resin matrix showed to have improvement over the base resin system. Figure 7 and Figure 8 show the fracture line following the milled fiber with the respective nano-particles being effectively bypassed without engaging their energy absorption characteristics.
Figure 7 – Milled fiber fracture with MWCNT – CNT 1-1.5

Figure 8 – Milled fiber fracture with CSR – CSR 1-1
Resin systems with a 1.5% loading by weight of the Arkema Graphistrength® MWCNT’s showed the greatest increase in impact resistance with an average result of 1.961 (ft-lbf/in), for a 43% improvement over the base resin system. Seven specimens were sampled for this average, with a standard deviation of 0.615.

As shown in Figure 6, a total of five batches improved the impact resistance of the resin. These five batches had loadings of 1.5% and 2% of CNT and 1%, 2%, and 4% of CSR. None of the Graphene batches improved the impact resistance of the resin matrix. Results for the individual nano-particles with their standard deviation are shown in Figure 9 to Figure 11:

![Graphene / MCF Impact Resistance](image)

Figure 9 – Graphene Impact Resistance Results
Figure 10 – MWCNT Impact Resistance Results

Figure 11 – CSR Impact Resistance Results
As shown in Figure 6 and Figure 9, graphene performed lower than baseline on all mixture ratios. Orientation of the graphene platelets has a large impact on its performance in energy absorption; however, control of the orientation of the platelet is not possible for sample sizes required for interlaminar shear testing and $V_{50}$ ballistic testing. Due to the degradation of impact resistance for all loadings of graphene, and the inability to control platelet orientation, further testing of this particle is impractical.

Figure 12 – CNT 0-1.5 fracture surface

Figure 13 – CSR 0-1 fracture surface
Figure 12, Figure 13 and Figure 14 show the difference in fracture surface for all three nano-particles. It is evident in Figure 14 that the graphene fracture surface was more brittle in that it “shattered” in a three dimensional mode, whereas both the MWCNT and CSR fracture surface had more of a “tearing” nature, where the nano-particles were able to absorb energy.

4.2 Mixed Mode I-Mode II Interlaminar Fracture Toughness (ASTM D6671-06)

Due to the results from the unnotched cantilever beam impact testing, only loadings of 1% CNT and loadings of 1% and 2% of CSR, were evaluated. First as samples with nano-particles only, and also with 1% and 2% loading of milled carbon fiber. For nomenclature purposes, when a sample is designated, it includes two numbers in parenthesis. The first is the weight percentage of milled carbon fiber, and the second is the weight percentage of nano-particle, with CNT representing Arkema Graphistrength® CS1-25 Multi-Walled Carbon Nanotubes, and CSR representing Kaneka Kane Ace® MX 153 Core Shell Rubber Particles.
Figure 15 shows the Mode I and Mode II strain energy release rate for the baseline of pure epoxy, as well as for the various loadings of milled fiber, MWCNT and CSR. As shown, all batches have an improvement of interlaminar shear strength in both peel (Mode I), and shear (Mode II).

![Mode I and Mode II Strain Energy Release Rate](image)

**Figure 15 – Mixed Mode strain Energy Release Rate**

Figure 16 shows both the critical total strain energy release rate, $G_c$, and the $P_{nl}$ as determined from the iteration for optimization of the linear regression analysis. The baseline pure epoxy resin system had a critical total strain energy release rate, $G_c$, of 0.002 (in.-lbf/in$^2$). The greatest improvement of $G_c$ was seen in the batch of 2% Core Shell Rubber particles with no milled carbon fiber, with a critical total strain energy release rate, $G_c$, of 0.0116 (in.-lbf/in$^2$). This is an order of magnitude of improvement.
The addition of the micron sized milled carbon fiber improved interlaminar shear strength in both peel and shear for the CNT and 1% loading of CSR, at a loading of 2% by weight of milled carbon fiber. However, an addition of 1% by weight of milled carbon fiber caused a reduction in strain energy release rate for all batches.

![Critical Load and Critical Total Strain Energy Release Rate](image)

Figure 16 – Critical Load and Critical Total Strain Energy Release Rate

### 4.3 Split-Hopkinson Bar Results

As shown in Figure 4, the striking of the striker bar into the incident bar creates a stress wave that propagates forward. The stress wave is measured in the two strain gauges, and results in data similar to Figure 17.
The incident signal is taken from the strain gauge on the incident bar as shown in Figure 4. The strain on the bar is in compression directly after the striker bar impacts on the incident bar, and is seen as a negative amplitude. At the interface of the incident bar and the test specimen, the incident stress pulse wave splits into two parts, defined as the transmitted and reflected waves. The amplitude of each specific wave is a function of the impedance mismatch between the tested specimen and the incident bar. The transmitted wave is measured by the strain gauge on the transmitter bar, and is shown in Figure 17 as the blue line with negative amplitude due to the compression of the transmitter bar. The reflected wave is measured by the strain gauge in the incident bar, and has a positive amplitude, due to the bar being in tension during the passing of the reflected wave. The difference between the absolute value of the incident wave, and the summation of the reflected and transmitted wave is a reflection of the energy loss. This energy loss is mainly due to the compression of the specimen sample, but will
also include frictional and vibrational losses. This data can also be used to calculate the stress $\sigma$ and force $P$ through stress propagation theory [40] [41] [42]:

$$\sigma = \left(\frac{\rho}{g}\right) cV$$ (17)

$$P = (A) \left(\frac{\rho}{g}\right) (cV)$$ (18)

Where $\rho$ is the incident bar density, $g$ is the acceleration of gravity, $c$ is the wave velocity in the incident bar, $V$ is the particle velocity in the incident bar, and $A$ is the cross sectional area.

The stress wave propagates forward until it reaches the interface of the incident bar pressed against the test specimen. At this point, the stress wave splits into the reflected stress wave and transmitted stress wave. Their amplitudes determined by the impedance difference between the Inconel incident bar and the test specimen. This splitting of the stress wave reduces the incident stress pulse energy ($E_I$) to create the reflected pulse energy ($E_R$) and transmitted pulse energy ($E_T$). There is also a substantial amount of energy that is absorbed through the plastic deformation of the test specimen. Some energy may also be lost through frictional forces, noise and vibration. This energy loss can be calculated through equation (19) [40].

$$E_L = E_I - E_R - E_T$$ (19)

The energy of a stress wave in a one-dimensional bar is:

$$Energy = \frac{A c}{E} \int_{t=0}^{t} \sigma^2(t) dt$$ (20)

Therefore, the energy loss can be calculated substituting equation (20) into (19) [40]:

$$E_L = \left(\frac{Ac}{E}\right) \int_{t=0}^{t} \left[\sigma_I(t)^2 - \sigma_R(t)^2 + \sigma_T(t)^2\right] dt$$ (21)
Using these equations, you can show the energy loss as the stress wave propagates as shown in Figure 18 and Figure 19.

Figure 18 – Energy Loss for Baseline Sample 8
The total energy loss for each sample as described in equation (21), is the area under the energy loss curve. Therefore, a comparison of this energy loss across samples allows for comparison of the effectiveness of the various nano-particle and milled fiber ratios.
Table 2 – Energy Loss for Split Hopkinson Bar

<table>
<thead>
<tr>
<th>Sample</th>
<th>600 (psi)</th>
<th>800 (psi)</th>
<th>1,000 (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>91.32</td>
<td>105.03</td>
<td>109.00</td>
</tr>
<tr>
<td>CNT 0-1</td>
<td>82.44</td>
<td>98.81</td>
<td>119.59</td>
</tr>
<tr>
<td>CNT 1-1</td>
<td>91.99</td>
<td>104.87</td>
<td>133.20</td>
</tr>
<tr>
<td>CNT 2-1</td>
<td>96.36</td>
<td>114.01</td>
<td>129.08</td>
</tr>
<tr>
<td>CNT 0-1.5</td>
<td>84.40</td>
<td>108.90</td>
<td>132.66</td>
</tr>
<tr>
<td>CNT 1-1.5</td>
<td>85.63</td>
<td>122.95</td>
<td>136.23</td>
</tr>
<tr>
<td>CNT 2-1.5</td>
<td>97.12</td>
<td>117.93</td>
<td>134.91</td>
</tr>
<tr>
<td>CSR 0-1</td>
<td>92.77</td>
<td>107.63</td>
<td>106.70</td>
</tr>
<tr>
<td>CSR 1-1</td>
<td>84.51</td>
<td>104.21</td>
<td>110.96</td>
</tr>
<tr>
<td>CSR 2-1</td>
<td>99.77</td>
<td>128.69</td>
<td>151.08</td>
</tr>
<tr>
<td>CSR 0-2</td>
<td>105.09</td>
<td>122.84</td>
<td>125.19</td>
</tr>
<tr>
<td>CSR 1-2</td>
<td>97.70</td>
<td>104.09</td>
<td>126.19</td>
</tr>
<tr>
<td>CSR 2-2</td>
<td>93.88</td>
<td>107.77</td>
<td>145.94</td>
</tr>
</tbody>
</table>
Figure 20 – Energy Loss for Split Hopkinson Bar

As shown in Table 2 and Figure 20, the largest energy loss was at the 1,000 psi striker pressure for the CSR 2-1, which had a 39% increase in energy absorption over the baseline sample. The amount of energy absorbed is strain rate sensitive, in that each specimen sampled had a different response for the three different levels of striker pressure. In general, the higher the striker pressure and therefore strain rate, the better the nano-particles performed in energy absorption. Using equation (20) to calculate the total energy of the incident bar, the highest kinetic energy of the incident bar for the CSR 2-1 sample was measured during sample 2 and had
a total energy of 365.91 (J). This is in the same energy range as the unnotched cantilever beam testing.

SEM imaging was performed at various magnifications to evaluate the fracture structure of the samples post impact. At 23X magnification of the strike surface, the fractures across the samples look similar; however, Figure 23 of the CSR 2-1 sample shows cracking that is more extensive and appears to be deeper in penetration than the baseline or CNT 1-1.5 samples shown in Figure 21 or Figure 22. The CSR 2-1 sample shown in Figure 23 had the highest energy absorption, and it is evident that it dispersed the energy through extensive crack propagation in the sample while absorbing the compression stress waves during cavitation of the CSR particles. The CNT 1-1.5 sample had a 25% improvement in energy loss over the baseline; however, at this magnification, there is no significant difference in the fracture structure of the two samples.

![Figure 21 – Baseline Sample 10 at 23X](image-url)
Figure 22 – CNT 1-1.5 Sample 7 at 23X

Figure 23 – CSR 2-1 Sample 2 at 23X

Moving higher in magnification to 375X, images of the milled fiber present in the samples are possible as shown in Figure 25 and Figure 27.
Figure 24 – Baseline Sample 10 at 375X

Figure 25 – CNT 1-1.5 Sample 7 at 375X
At the 375X magnification, the surfaces are very similar in appearance between the baseline, CNT 1-1.5 and CSR 2-1. However, for the CNT 1-1.5 there are some locations where the dissipation of the compression stress wave created a fractured structure where cracks propagating through the depth of the sample were redirected around the various CNT particles in
the matrix as shown in Figure 26. This characteristic was unique to the CNT samples; however, was not prevalent over the entire surface of the sample. This redirection of the crack propagation is similar in nature to the “tearing” of the resin structure as shown in analysis of the ballistic panels in section 4.4.5 as shown in Figure 37.

Moving to higher magnification of approximately 22.8 KX, the microstructure of the cracking is similar in nature across baseline, CNT and CSR samples. However the size and density of the crazing is less prominent for the CSR samples as shown in Figure 30. Therefore, the energy absorption mechanism of the cavitation of CSR particles effects the size and density of the micro-crazing present in the resin matrix for the compression testing of the split Hopkinson bar testing.

Figure 28 – Baseline Sample 10 at 22.80 KX
Figure 29 – CNT 1-1.5 Sample 7 at 22.82 KX

Figure 30 – CSR 2-1 Sample 2 at 22.80 KX
4.4 \textit{V}_{50} Ballistic Testing Results

4.4.1 Phenolic Panels with MWCNT Paper Interleaved

For the first round of ballistic testing, phenolic resin and woven S-2 glass per MIL-DTL-64154B [29] was utilized due to the large database available of ballistic data for this system. This would allow for the results to be compared to historical data if improvements were obtained. The baseline panels were constructed to this standard at 1.0 and 1.5 psf aerial density.

For the CNT enhanced panels, paper impregnated with MWCNT at the University of Central Florida was utilized as discrete layers between the first and second layers of woven S-2 glass. Three different panels at 1.0 psf aerial density were pressed per MIL-DTL-64154B [29] with one, two and four layers of CNT impregnated paper between the first two plies of S2 glass as shown in Figure 31.

These panels were then shot with 44 mag soft point rounds to obtain the V50 ballistic limit as per MIL-STD-662 F [6]. No significant improvement in ballistic resistance was found, as shown in Table 3.

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|}
\hline
\textbf{Panel Description} & \textbf{Aerial Density (lbs/sqft)} & \textbf{$V_{50}$ (ft/sec)} & \textbf{Overlap Plies of CNT Paper} \\
\hline
Baseline S-2 Glass & 1.00 & 1,226 & N/A \\
CNT Enhanced & 0.97 & 1,077 & 1 \\
CNT Enhanced & 0.97 & 1,042 & 2 \\
CNT Enhanced & 0.97 & 1,084 & 4 \\
\hline
\end{tabular}
\caption{\textit{V}_{50} Ballistic Results for Interleaved CNT Paper}
\end{table}
After reviewing the panels post shooting, it was evident that the CNT impregnated paper did not allow for bonding between plies of the phenolic impregnated woven S-2 glass, except for along the edge. Therefore, when the projectile struck the panel, the first and second plies delaminated without crack propagation, and the MWCNT particles were effectively pushed aside without any appreciable effect of absorption of the kinetic energy of the projectile.

For this reason, it was decided that embedding of the MWCNT in the resin matrix with appropriate functionalization to enable chemical bonding to the resin, would be desirable.
4.4.2 Zyvex MWCNT in Epoxy Resin Prepreg

The next set of panels were constructed using 3,000 denier Kevlar®29, 17 x 17 pick count standard woven 14 oz/yd² material with epoxy prepreg from Zyvex Performance Materials’ Arovex product line. The resin content was 30% by weight for all panels. The panels were limited to 12” x 12”, and two panels were constructed for each test to allow for accurate values of \( V_{50} \). A total of four baseline panels without CNT’s, and four panels enhanced with CNT’s were produced to allow for testing with both 30 caliber fsp and 44 mag soft point bullets. The loading of CNT’s for the enhanced panels were kept to 0.5% by weight.

16 plies of woven Kevlar® were used for the 44 mag testing for an aerial density of 2.3 lb/ft². 32 plies of woven Kevlar® were used for the 30 caliber fsp testing for an aerial density of 4.6 lb/ft². No significant improvement in ballistic resistance was found, as shown in Table 4.

<table>
<thead>
<tr>
<th>Panel Description</th>
<th>44 mag ( V_{50} ) Result (ft/sec)</th>
<th>30 Cal FSP ( V_{50} ) Result (ft/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>1,230</td>
<td>2,031</td>
</tr>
<tr>
<td>Zyvex MWCNT Enhanced</td>
<td>1,226</td>
<td>2,010</td>
</tr>
</tbody>
</table>

4.4.3 Zyvex MWCNT and Milled Fiber Prepreg

The next set of panels were constructed using 3,000 denier Kevlar®29, 17 x 17 pick count standard woven 14 oz/yd² material with epoxy pre-preg from Zyvex Performance Materials’ Arovex product line. The resin content ranged from 18.6% to 22.7% by weight for all panels. The panels were limited to 12” x 12”, and two panels were constructed for both baseline
and enhanced versions to allow for testing with 44 mag soft point bullets. The enhanced panels were limited to a loading of 1.65% for CNT’s and 1.65% for milled fiber due to the viscosity becoming too high for higher loadings, keeping it from running through the impregnation machine properly. Table 5 shows the results for the ballistic testing. The $V_{50}$ results were 6.57% higher for the enhanced panels.

<table>
<thead>
<tr>
<th>Panel Description</th>
<th>$V_{50}$ Ballistic Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>1,279</td>
</tr>
<tr>
<td>Zyvex MWCNT Enhanced with Milled Fiber</td>
<td>1,363</td>
</tr>
</tbody>
</table>

These results showed improved energy absorption; however, it was unknown if the cause was the nano-particle, the milled fiber, or a synergistic effect from the combination of both. Therefore, a more detailed approach was warranted in order to not only investigate the interaction between micro and nano sized particle reinforcement, but also the effect of the morphology of the nano-particle on the ballistic results.

4.4.4 Nano Particle and Milled Fiber Epoxy Panels

The same nano particle loading used for the mixed mode interlaminar shear testing was utilized for the $V_{50}$ ballistic testing. Only carbon nanotubes and core shell rubber particles were evaluated, due to the degradation of impact toughness for all loadings of graphene as previously discussed. As shown in Figure 32, all loadings of nano particles and milled fiber showed
improvement in $V_{50}$ ballistic performance, with the exception of 2% milled fiber with 1.5% MWCNT (CNT 2-1.5), which showed equivalent results to baseline performance. 1% loading of CSR with 1% milled fiber (CSR 1-1) performed the best with an 8% improvement, and 1% MWCNT with 1% milled fiber (CNT 1-1) had the second highest performance with a 7.3% improvement. The complete test report is listed in Appendix section 4.12.

A noticeable pattern is in the consistent improvement for all loadings of nano particles with 1% loading of milled fiber. This was the optimal loading level for milled fiber, because any higher or lower loadings showed degradation in performance.


Table 6 – $V_{50}$ Ballistic Results for Various Loadings of Nano Particles and Milled Fiber

<table>
<thead>
<tr>
<th>Test Sample</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Weight (lbs)</td>
</tr>
<tr>
<td>Baseline</td>
<td>4.02</td>
</tr>
<tr>
<td>CNT 0-1</td>
<td>4.16</td>
</tr>
<tr>
<td>CNT 1-1</td>
<td>4.08</td>
</tr>
<tr>
<td>CNT 2-1</td>
<td>4.05</td>
</tr>
<tr>
<td>CNT 0-1.5</td>
<td>4.08</td>
</tr>
<tr>
<td>CNT 1-1.5</td>
<td>4.04</td>
</tr>
<tr>
<td>CNT 2-1.5</td>
<td>4.05</td>
</tr>
<tr>
<td>CSR 0-1</td>
<td>3.64</td>
</tr>
<tr>
<td>CSR 1-1</td>
<td>4.09</td>
</tr>
<tr>
<td>CSR 2-1</td>
<td>4.20</td>
</tr>
<tr>
<td>CSR 0-2</td>
<td>3.77</td>
</tr>
<tr>
<td>CSR 1-2</td>
<td>4.04</td>
</tr>
<tr>
<td>CSR 2-2</td>
<td>4.04</td>
</tr>
</tbody>
</table>
In order to evaluate whether the energy absorption is coming from the elongation of the Kevlar® fibers or from the crack propagation through the resin system, an analysis of the back face deformation for the panels is required. Figure 33 shows the baseline panel alongside the two best performing panels, with all three images frozen at their maximum deformation. The black tick marks on the background are exactly 1” apart. Using these tick marks as a reference, measurements of the back face deformation can be obtained for each panel.

Figure 32 - $V_{50}$ Ballistic Results Varying Morphology Nano Particles
Taking into account movement of the panel, all three panels showed a back force deformation of approximately 1.13”. Because the back face deformation, and therefore Kevlar® fiber elongation, is similar for all three panels, the extra energy absorption is coming purely from the amount of energy absorbed during crack propagation through the resin matrix.

4.4.5 SEM Imaging of Ballistic Panels

In order to understand the failure mechanisms of the panels during the ballistic event, SEM images were taken of the panel that was tested with the 44 mag projectiles. The first set of images were taken from the panels that were constructed with only MWCNT’s dispersed in the epoxy resin of prepreg.

Scans were taken from a fiber cut out from the location where the bullet passed through the panel. Figure 34 shows the elongation of the Kevlar® fiber.
To gain an understanding of the nature of the crack propagation, it is useful to look at images showing whether the fracture of the resin was brittle in nature, or whether the presence of the nano-particle filler allowed for enhanced energy absorption by consistent diversion of the crack line. Figure 35 shows the baseline panel with no nano particle fillers in the resin matrix. It is evident from the brittle nature of the fracture lines that the crack propagation through the resin matrix encountered minimal deflection.

Figure 34 – Elongation of Kevlar® fiber at location of pass through of projectile
Figure 35 – SEM image showing brittle fracture of baseline epoxy

Comparing this brittle fracture to the failure mechanism shown in Figure 36 of the CNT enhanced epoxy resin, highlights the amount of energy absorption due to the presence of the CNT’s. The stepped “tearing” of the resin matrix between the fibers explains the improved energy absorption shown in the previous test results.
Figure 36 – SEM image at 1.08 KX magnification of CNT enhanced epoxy
Figure 37 takes the image in Figure 36 and magnifies it to 86.02 KX, allowing for viewing of the CNT that is bonded into the resin system. It’s this bonding that creates the mechanism for “tearing” of the resin during failure. This “tearing” of the resin matrix is due to the redirection of the crack during propagation. This is similar to what was evident during the compression testing of the Hopkinson bar testing as shown in Figure 26.

Panels that showed the improvement in ballistic performance also had milled fiber reinforcement along with the nano particles. Figure 38 shows the panel at 1.65% loading of milled fiber with 1.65% loading of MWCNT. In it, the micro sized milled fiber particle is surrounded by the MWCNT’s. The loading of milled fiber between 1% and 1.65% had the optimal ratio for energy absorption, allowing for the right volumetric relationship to enable transfer of the stress wave between the plies of fabric. Figure 39 shows a similar image with the milled fiber surrounded by the core shell rubber particles. This same optimum ratio of milled fiber to nano-particle held true for the CSR particles as well.
Figure 38 – Milled Fiber Surrounded by MWCNT’s

Figure 39 - Milled Fiber Surrounded by CSR’s
4.4.6 Raman Spectroscopy for Evaluation of Residual Strain in Kevlar®29

Raman spectroscopy was utilized to evaluate the residual strain in the fibers of the various panels. Strain in the sample has been shown to cause a Raman shift, and can be measured directly [37]. To calculate the relation between Raman shift and strain, the “secular equation” must be solved [43]. This change in Raman frequency $\Delta \omega$ is calculated from the frequency of the Raman signal under study $\omega$, and the stress-free value $\omega_0$ as shown in equation (22):

$$\Delta \omega = \omega - \omega_0 \approx \frac{\lambda}{2\omega_0} - f(\varepsilon_{ij})$$

(22)

In order to solve the secular equation mentioned before, assumptions must be made about the stress or strain distribution in the sample, for the strain tensor components to be simplified [43]. For uniaxial stress, the linear relation between fiber axial stress and Raman band shift at 1611 cm$^{-1}$ for Kevlar®29 aramid fiber is shown in equation (23), where a positive shift indicates a compressive stress, and a negative shift is indicative of a tensile stress [37]:

$$\sigma^{-1} = \frac{-K}{\Delta \omega}$$

(23)

where $\sigma$ is the fiber axial stress; $K$ is stress sensitivity which is determined by the material properties. For Kevlar®29 aramid fiber at 1611 cm$^{-1}$, the value of $K$ is 4.0±0.5 cm$^{-1}$/GPa [44]; $\Delta \omega$ is the band Raman shift at 1611 cm$^{-1}$.
Figure 40 shows the Raman spectroscopy results for three different panels that were tested per MIL-STD-662 F [6], with 44 caliber soft-point. The light blue line represents the baseline panel constructed using 3,000 denier Kevlar®29, 17 x 17 pick count standard woven 14 oz/yd² material with epoxy pre-preg from Zyvex Performance Materials’ Arovex product line. The magnified view in the upper left corner of the figure zooms into the Raman shift band at 1611 cm⁻¹. The green line shows the panels constructed with the same materials, but with an addition of 0.5% by weight MWCNT’s. The red line represents the panels that were enhanced with 1.65% by weight MWCNT’s, and 1.65% by weight milled fiber. The band shift for the milled fiber and CNT panel is approximately 25 cm⁻¹. When this band shift is inserted into equation (23), you get a fiber axial stress of 906.5 ksi, as shown in equation (24).

\[
\sigma^{-1} = \frac{-K}{\Delta \omega} = \frac{-4\left(cm^{-1}\right)}{25(GPa)} = -0.16(GPa) \Rightarrow \sigma = 6.25(GPa) = 906.5 ksi
\]  

Figure 40 – Raman Spectroscopy Data
However, this data only represents a single scan on each panel. In order to improve the level of confidence of this data, averages of 3 scans for each line with an exposure between 3 and 10 seconds were done for multiple points on both the CNT only panel and the milled fiber and CNT panel. Figure 41 illustrates that this same Raman shift was seen for the CNT and milled fiber panel that had the improved ballistic performance. The absorbed stress seen by residual strain from the stress wave during the ballistic event is measured by this Raman shift. The panel with the improved ballistic performance measures a higher absorption of this stress wave.

Figure 41 – Raman Spectroscopy data for CNT only and CNT and Milled Fiber Panels

In order to validate that these results are not tainted by either polarization of the monochromatic laser light, or contamination of the bullet, further testing was done. The Raman shift was measured again on the CNT enhanced panel that showed no $V_{50}$ ballistic improvement. Figure 42 shows how the three measurements were taken parallel, at a 45 degree angle, and perpendicular to the fiber orientation, with the results graphed in Figure 43. The orientation of the Kevlar®29 fiber did not have an effect on the Raman shift; however, at measurements taken
off of the parallel orientation had a higher intensity measurement. This is due to the wavelength of the monochromatic laser light hitting a higher portion of the Kevlar® fiber, resulting in a higher intensity measurement. The polarization has no effect on the band shift; therefore, it does not taint the residual strain data.

Figure 42 – View of Fiber Orientation for Polarization Effect

![Fiber Orientation Images](image)

Figure 43 – Effect of Polarization on Raman Spectroscopy data

In order to rule out contamination from the bullet on the Raman shift data, measurements were taken from a bullet post-shoot, of both the copper jacketing (Figure 44), and the lead core
(Figure 45). The general noise of the data without any significant peaks, demonstrates that any contamination of the bullet on the fibers would have a negligible effect on the Raman band shift measurements.

**Figure 44 – Raman Spectroscopy Data on Copper from Bullet**

**Figure 45 – Raman Spectroscopy Data on Lead from Bullet**

Due to the elimination of concern for contamination of the Raman shift data from either polarization effects, or contamination from the projectile, we can estimate that the Raman shift of
-25 cm³ measured in the panels with a 6.57% improvement of \( V_{50} \), is a representation of the amount of the stress wave absorbed by the composite panel.

Further Raman Spectroscopy data was obtained for the ballistic testing conducted on the panels enhanced with both MWCNT and CSR. However, the measurement device was mounted on a moveable framework, allowing for multiple controlled measurements in a mapping configuration.

For the baseline sample a 6x6 map of Raman shift readings was conducted around the location of penetration by the projectile for shot number 5, where the velocity of the projectile was 1,159 (ft/sec). The area of the map was approximately 25 mm x 25 mm. Therefore, 36 separate locations for measurement were completed. Figure 46 shows the Raman spectroscopy wavelength shifts for Kevlar at the 36 different locations for the mapping of the baseline sample.
As shown, the fit peak positions fell between 1610.5 and 1611.8, with an average of 1,611 cm\(^{-1}\). This falls in line with the published data by Cen et al [37], but falls short of the published value of 1,613 cm\(^{-1}\) by Washer et al [36]. All 36 fitted peak data points are displayed in section 6.5 of the appendix.

Analysis was also conducted around the 1,649 cm\(^{-1}\) band to evaluate its sensitivity to the axial stresses. As shown in Figure 47, the average for 34 peaks was 1,647.0 cm\(^{-1}\). This is a distinct 2 cm\(^{-1}\) shift from the published location of the band at 1,649 cm\(^{-1}\) [36]. All 36 fitted peak data points are displayed in section 6.8 of the appendix.
An 8 point map was measured on the bottom left quadrant of the penetration location for shot number 6 of the CNT 1-1 sample, where the projectile was traveling at 1,299 (ft/sec). The area of mapping was approximately 17.5 mm x 17.5 mm. The range of Raman peak shifts for the Kevlar®29 was in the range of 1,607 to 1,610.4 cm\(^{-1}\) with an average of 1,609.2 cm\(^{-1}\) as shown in Figure 48. Therefore, the band shift for the CNT 1-1 panel is approximately 1.8 cm\(^{-1}\). When this band shift is inserted into equation (18), you get a fiber axial stress of 322.3 ksi. All 8 fitted peak data is displayed in section 6.6 of the appendix.
Figure 48- Raman Shift Peaks for Kevlar®29 of CNT 1-1 at 1,611 cm\(^{-1}\) band

Analysis of the 1,649 cm\(^{-1}\) band for the CNT 1-1 panel shows a negative shift for tensile stress. As shown in Figure 49, the average for 8 peaks was 1,647.8 cm\(^{-1}\). This is a distinct 1.2 cm\(^{-1}\) shift from the published location of the band at 1,649 cm\(^{-1}\) [36]. All 8 fitted peak data points are displayed in section 6.9 of the appendix.
A 13 point map was measured in line with the penetration location for shot number 5 of the CSR 1-1 sample, where the projectile was traveling at 1,278 (ft/sec). The area of mapping was approximately 25mm x 25 mm. The range of Raman peak shifts for the Kevlar®29 was in the range of 1,610.5 to 1,611.8 cm$^{-1}$ with an average of 1,611.1 cm$^{-1}$ as shown in Figure 50. Therefore, the band shift for the CSR 1-1 panel is comparative to the baseline, despite the better ballistic performance. All 13 fitted peak data is displayed in section 6.7 of the appendix.
Analysis of the 1,649 cm\(^{-1}\) band for the CSR 1-1 panel shows a negative shift for tensile stress. As shown in Figure 51, the average for 13 peaks was 1,648.9 cm\(^{-1}\). This is in line with the published location of the band at 1,649 cm\(^{-1}\) [36]. All 13 fitted peak data points are displayed in section 6.10 of the appendix.
Figure 51 - Raman Shift Peaks for Kevlar®29 of CSR 1-1 at 1,651 cm$^{-1}$ band
CONCLUSION

Energy absorption in ballistic events for composite hard armor applications occurs through two mechanisms. Specifically, elongation of the reinforcement fiber and propagation of the crack through the resin matrix during delamination of the discreet plies. This research maintained the same Kevlar® through the testing, thereby eliminating the fiber elongation as a variable. Therefore, this research is able to conclusively show improvements in energy absorption purely in crack propagation phase through additions of nano sized particles of various morphologies. Some understanding of the energy absorption characteristics of the resin system in the thermoset armor applications have been obtained through evaluation of the composite systems in dynamic testing where crack propagation occurs. Using both unnotched cantilever beam impact testing and mixed mode interlaminar shear testing allowed for investigation of the energy absorption characteristics of nano and micro particle enhanced resin systems in a dynamic environment.

Morphologies of the nano-particles used as reinforcement in the resin system have an effect on the energy absorption characteristics of the finished composite panels. Interactions between nano-sized particles and micro-sized particles in the reinforcement of the resin system also modify energy absorption characteristics in both tests. However, this modification can serve to hinder or benefit the results depending on the nano-particle morphology, and the type of test.

4.5 Unnotched Cantilever Beam Impact Testing (ASTM D4812-11)

The graphene platelets showed a detrimental effect to the impact resistance, when compared to the baseline of unmodified epoxy. Graphene has a thin but wide aspect ratio,
causing a relative surface area between 120 to 150 m$^2$/g. The graphene utilized was not sized nor functionalized. While this could have a detrimental effect, it’s worth noting that neither were the MWCNT’s, and yet they showed the greatest improvement in impact resistance at the 1.5% loading. The MWCNT have a typical surface area between 100 to 250 m$^2$/g, which is in the same range as the graphene. Due to the relative surface areas being similar, and neither nano-particle system being functionalized, the negative effect of the graphene is most likely attributable to the sliding of the graphene platelet sheets. Use of individual graphene platelets that were not in stacked form could provide better performance. As seen in Figure 14 the fracture nature of the graphene particles were more brittle in nature, quickly shattering through the resin with minimal energy absorption.

The CSR nano-particle reinforcement showed the most consistent improvement to the impact resistance. As shown in Figure 6, all loadings of the CSR without milled fiber, improved the impact resistance, with the exception of 3% loading. The energy absorption characteristics of CSR enhanced resin is different than the other two nano-particles. The core of the particle is a rubber that cavitates upon impingement of the crack, thereby reducing the stress intensity factor [45]. Due to its spherical morphology, it is not limited to orientation of the particle with respect to the crack propagation.

As shown in Figure 6 and Figure 10, the 1.5% loading of the MWCNT had the greatest improvement to impact resistance, with a 43% enhancement over the baseline epoxy samples. However, loadings at 1% and 2 to 5%, decreased the impact resistance of the resin. Due to the high aspect ratio of the tubular morphology of the MWCNT, orientation of the particles in
respect to the crack propagation impacts the effectiveness of the MWCNT to enhance impact resistance.

As shown in Figure 10 and Figure 11, the addition of micro-sized milled carbon fiber lowered the impact resistance of the CSR and MWCNT resin systems. However, Figure 9 shows that addition of the milled carbon fiber tended to improve the impact resistance of the graphene resin system, but not enough to match or exceed the baseline epoxy samples. As seen in Figure 7 and Figure 8 the micro-sized milled particle enabled the crack to bypass the nano-particles by propagating along the milled fiber, where energy absorption was less than if more nano-particles were engaged.

4.6 Mixed Mode I-Mode II Interlaminar Fracture Toughness (ASTM D6671-06)

The use of the iterative technique of linear regression while optimizing the coefficient of determination, as described in section 3.3.2, removes subjective decisions as to the point of non-linearity, or the point at which crack initiation occurs.

As shown in Figure 15, all mixtures of CSR and MWCNT including addition of milled carbon fiber enhanced both peel (Mode I) and shear (Mode II) modes of the strain energy release rate of the composite panels.

The most significant improvement was seen in the 2% loading of CSR without milled carbon fiber, resulting in a $G_c$ of 0.0116 (in.-lbf/in$^2$). This is a magnitude greater than the $G_c$ of the baseline epoxy system of 0.0002 (in.-lbf/in$^2$).
The addition of the micro-sized milled carbon fiber was a detriment to the critical strain energy release rate, $G_c$, of both the CNT at 1% loading, and CSR at 2% loading. However, it significantly improved the response of the CSR at 1% loading.

### 4.7 Split-Hopkinson Bar Testing

Energy absorption by the nano-particles is strain rate sensitive. In general the higher the incident bar energy, the better the nano-particles performed in improvement over baseline results. All but one nano-particle / milled fiber ratio performed better than baseline data for energy absorption with a striker bar pressure of 1,000 (psi), while four had degraded performance to baseline at a striker bar pressure of 600 (psi). The CSR 2-1 sample had a 39% improvement in energy absorption over the baseline samples at a striker bar pressure of 1,000 (psi).

The largest incident bar kinetic energy for the CSR 2-1 samples was recorded for sample 2 with a measured energy of 365.91 (J). This is in the range of energy levels for the unnotched cantilever beam testing. However, the split-Hopkinson bar testing showed improvements for many levels of milled fiber ratios. Therefore, the compressive nature of this testing allows for better distribution of the stress wave through the micro-sized milled fiber particles, down into the nano-sized particles. The best impact resistance during the unnotched cantilever beam testing came from a 43% improvement by the CNT 0-1.5 sample; whereas, this same sample had a 22% improvement over baseline for the split-Hopkinson bar testing.
4.8 $V_{50}$ Ballistic Testing

The process of shooting the panels with multiple projectiles while refining the measured $V_{50}$ allows for a certain level of statistical significance as per Military Specification MIL-DTL-662 F [30].

The addition of CSR particles into the resin matrix increases the energy absorption characteristics through the means of cavitation upon crack impingement. The mechanics of this improvement is described by Yee et al [24] where a high hydrostatic tension appears ahead of the crack tip. This tension causes rapid cavitation of the rubber particle, which results in growth of the resultant voids. This area of voids and shear bands in front of the crack tip, blunts the crack when stress is applied to open the crack faces. Upon application of added tension, larger plastic zones are formed, and force a large volume of material above and below the crack to undergo plastic deformation. According to Yee et al, it is this plastic zone that is the principal toughening mechanism. Bugarin [26] developed an axisymmetric finite element technique to determine the stress concentration distribution around a spheroidal particle with an interphase layer under asymmetric dynamic loading. His work concludes that the dynamic stress field at the particle matrix interface is significantly affected by surface/interface elasticity as the particle size is reduced to nanometers. As the stiffness ratio between nano-particle and matrix is reduced, the stress concentration values at the nano-particle interface are significantly reduced. The shear modulus of the CSR particles is drastically lower than the shear modulus of the epoxy matrix, thus the stress concentration values at the CSR/epoxy interface are reduced. Therefore, Bugarin’s model in addition to the explanation by Yee fundamentally explain the increase in
energy absorption for the ballistic panels reinforced with CSR particles. This toughening mechanism is unique to the core shell rubber particles tested.

The energy absorption mechanism by the MWCNT’s is distinctly different. As crack propagation occurs, the energy absorption through the MWCNT’s is dominated by a sword-in-sheath until fracture occurs, at which point, pullout of the MWCNT from the resin dominates energy dissipation. This mechanism is reliant upon the bonding characteristics of the MWCNT to the resin matrix. Therefore, functionalization of the MWCNT can have an impact on the energy absorption characteristics. Based on similar ballistic results by percentage improvement between the Zyvex functionalized MWCNT test and the Arkema Graphistrength® MWCNT ballistic test, it is evident that both are comparable in effectiveness for bonding to the epoxy matrix.

The energy release rate improvement through the combination of milled fiber and nano-sized particles can be explained through the analytical model detailed by Zhao et al [17]. As particle partition increases through the reduction in particle size, the analytical model shows an increase in energy release. However, for the highly dynamic transfer of the stress wave through the matrix, larger micro sized particles act as local transfer of the load from the macro sized fiber reinforcement down into the nano-sized particles where the analytical model applies.

For all nano-particle loadings, the best performance came with the addition of 1% by weight of milled carbon fiber. Therefore, for ballistic performance, there is a synergy between utilizing micro-sized milled carbon fiber in addition to the nano-particle loading. This interaction is optimum at the 1% loading with the performance dropping off at a milled fiber
loading of 2%. This loading allows for the optimal reinforcement in the resin matrix for transfer
of the stress wave from the macro scale of the fiber reinforcement, down to the micro scale of the
milled fiber, and subsequent dispersion to the nano scale of the nano particles. Correlation of
results across the ballistic testing at 1% to 1.65% loading of milled fiber for both Arkema
MWCNT and Zyvex functionalized MWCNT supports the conclusion that transferring of the
stress wave down to the nano scale through addition of micro sized particles is beneficial for
energy absorption.

Both the CNT 1-1 and CSR 1-1 panel had similar improvements between 7-8% over the
baseline. This is particularly interesting, due to similar estimated results through computer
simulation by Grujicic et.al [28], utilizing multi-walled carbon nanotubes for 30 cal fsp ballistic
testing. While the computer simulations completed by Grujicic showed only a 6.5%
improvement in $V_{50}$ ballistic performance, it did not consider the stress transfer characteristics
through the particle reinforcement sizing. The model was based off of modulus improvements of
the resin matrix through rule of mixture calculations. However, if you look at the $V_{50}$ ballistic
results for the two best performing nano particle loading without milled fiber, specifically, CNT
0-1 and CSR 0-1, you have an improvement of 5.6% and 5.2% respectively. This falls just short
of the idealized case simulated by Grujicic [28].

4.9 **Raman Spectroscopy**

Redundancy of Raman shift measurements for the Kevlar®29 across multiple panels
shows that shifts of Raman peaks are indicative of increased ballistic performance due to residual
strains. Reinforcement of this conclusion was achieved through elimination of concern for
contamination of the Raman shift data from either polarization effects, or contamination from the projectile.

Mounting of the probe on a fixture capable of controlled movement in the X and Y direction, allowed for consistent step measurements in the form of a Raman shift map. Measurements taken closer to the penetration location of the projectile had the largest shifts indicating the highest residual strains. Correlation between fiber axial stress and Raman shift are calculated using equation (23).

Baseline panels with no nano or micro particle reinforcement had distinct Raman shifts for Kevlar®29 at the published value of 1,611 cm$^{-1}$ [37]. MWCNT enhanced panels consistently showed Raman peak shifts to the left, showing residual strain from the tensile stress of the fibers. CSR enhanced panels did not show this Raman shift for axial strain at either Raman band location, despite the superior ballistic performance. This is due to the energy absorption characteristics of the CSR particles. The cavitation of the particles causes a reduction in the triaxiality of the stress of the surrounding matrix. This reduction in stress and absorption through the cavitation of the CSR particle minimizes the transfer of loading to the C-C phenyl ring and stretching of the C==O bond of the Kevlar® fiber. The Raman band for Kevlar® centered at 1,649 cm$^{-1}$ due to the stretching of the C==O bond shows more sensitivity to the axial strain loading, based on the baseline panels only registering a tensile shift for this Raman band.

4.10 Summary

Energy absorption in composite armor panels during highly dynamic ballistic events has been shown to improve through the addition of both nano and micro sized particles. This holds
true for two different types of morphologies of nano particles. Despite the different mechanisms employed by the two different morphologies, both core shell rubber particles and multi-walled carbon nanotubes can enhance $V_{50}$ ballistic performance by 7% to 8% over baseline panels with the addition of 1% by weight of nano and micro sized particles.

The synergistic effect of transferring of the stress waves from the macro sized fiber reinforcement down to the micro scale of the milled fiber and finally into the differing energy absorption methods of the various nano particles is appropriate for ballistic events. As shown in equation (20), the kinetic energy absorbed by the panel for the CSR1-1 specimen for shot 5, where the velocity was 1,278 (ft/s) is 37,961 (J). (Note: Weight of the bullet is 240 grains = 0.0342857 lbs) But this does not hold true for the less dynamic event of interlaminar shear strength or unnotched cantilever beam testing. The maximum potential energy for the unnotched cantilever beam testing can be calculated from the highest point of the pendulum, where the weight set is 4 (lbs). As shown in equation (27), the maximum energy for this test is 352.47 (J).

Highest absorbed kinetic energy of $V_{50}$ testing:      \[ E_k = \frac{1}{2}mv^2 = \frac{1}{2} \times 0.0342857(\text{lbs}) \times 1,278\left(\frac{\text{ft}}{\text{s}}\right)^2 = 27,999(\text{ft} \cdot \text{lbf}) = 37,961(\text{J}) \]  \[ \text{Highest kinetic energy of incident bar for split-Hopkinson Bar testing} \]

\[ E_k = \frac{Ac}{E} \int_{t=0}^{t} \sigma^2(t) \, dt = 4.91E^{-7} \int_{t=0}^{t} \sigma_t^2 \, (t) \, dt = 365.91 \, (\text{J}) \]  \[ \text{Maximum potential energy for unnotched cantilever beam test:} \]

\[ E_p = h_m W_p g = 2.02(f \cdot t) \times 4(\text{lb}) \times 32.174 \left(\frac{\text{ft}}{\text{s}^2}\right) = 259.97(f \cdot \text{lb}) = 352.47(\text{J}) \]
Therefore, as the energy levels increase exponentially for the ballistic event, and the duration of stress transfer decreases into the micro seconds, the addition of the micro-sized milled fiber enhances the efficiency of the load transfer down to the nano-scale particles for additional energy absorption.

The lack of macro-sized fiber particle reinforcement during the unnotched cantilever beam testing allowed for the impact energy of the pendulum to transfer directly into the resin matrix. The degradation of performance by the addition of the micro-sized milled fiber indicates that these fibers allowed for the crack propagation to bypass some of the nano-sized particles where the largest amount of energy absorption was created.

The mixed mode energy release rate test shows the greatest improvement for composite panels enhanced with 2% loading of core shell rubber particles without micro sized particle additions. With the longer duration of load transfer, intermediate sized micro particles are not useful for enhancement.

This research confirms micro sized particles add efficiencies to the load transfer into nano particle energy dissipation methods during high energy events on the scale of 37,000 (J) with durations of micro-seconds. The micro-sized particles of milled fiber act as a means of distribution of the stress wave down into the nano-sized particles at these high energy levels. Their detrimental effect at the lower energy levels of the unnotched cantilever beam testing show that what energy dissipation originates from the milled fiber is offset by the fact that they allow the crack to bypass nano-sized particles where energy dissipation would be greater.
4.11 Future Work

There is a distinct dissipation of the stress wave from the projectile as it penetrates further into the composite panel. Ascertaining the rate of dissipation through the thickness of the panel would provide deeper understanding of the energy dissipation mechanisms. Measurement of the strain of each individual ply would help to map this and correlate the dissipation to the beginning of the delamination of individual plies. This could be done through imbedding of piezoelectric strain gauges, or coating of the edge of the panel with nano-particles with known raman shifts, allowing for strain measurements across the thickness through Raman spectroscopy during the impact. Based on published work with single filament Kevlar®29 during axial loading [37], it is theoretically possible to measure real time axial stresses through Raman spectroscopy during the ballistic event. However, practical concerns of protection for the monochromatic light source probe from flying fragmentation would have to be considered. Speed of acquisition of the Raman spectroscopy readings would have to be taken into account to allow for measurements at the precise timing of the penetration of the projectile.

All of the findings in this research are based around using a thermoset resin matrix, specifically epoxy. Do these findings translate to a thermoplastic matrix, which is commonly used in composite armor panels, where flame smoke and toxicity is not critical. Based on the differing absorption of energy with the thermoplastic core shell rubber particles, these findings may differ when a thermoplastic polymer is used for the binding matrix. It could also drastically impact the evaluation of the panels through utilization of Raman spectroscopy.
The iterative technique of optimizing the coefficient of determination in linear regression analysis for determining the point of non-linearity in the mixed mode interlaminar shear testing is an objective method that should be transferrable and consistent among various researchers. A round robin evaluation of multiple researchers with a single data set would allow for confirmation of this theory.
April 17, 2013

Composites One
3912 Oak Crest Circle
Port Orange, FL 32129

Dear Mr. Gibson:

In accordance with your instructions, Oregon Ballistic Laboratories conducted Ballistic Limit (V₀) testing on 13 samples. The samples were tested in accordance with MIL-STD-662F in an indoor range with the muzzle of the test barrel mounted 16.5 feet away from the target and positioned to produce 0 degree obliquity impacts. Four infrared light screens, in conjunction with time-based frequency counters, were positioned such that bullet velocity was measured 8.25 feet from the target. Penetrations were determined by examination of a piece of 0.020 inch 2024-T3 aluminum mounted 6 inches behind and parallel to the test sample. Results for all testing performed for this purpose are summarized in the following table.

<table>
<thead>
<tr>
<th>Test Sample</th>
<th>Threat</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S/N</td>
<td>Weight (lbs)</td>
</tr>
<tr>
<td>Baseline</td>
<td>4.02</td>
<td>0.307</td>
</tr>
<tr>
<td>CNT 0-1</td>
<td>4.15</td>
<td>0.301</td>
</tr>
<tr>
<td>CNT 1-1</td>
<td>4.08</td>
<td>0.306</td>
</tr>
<tr>
<td>CNT 2-1</td>
<td>4.05</td>
<td>0.300</td>
</tr>
<tr>
<td>CNT 0-1.5</td>
<td>4.08</td>
<td>0.310</td>
</tr>
<tr>
<td>CNT 1-1.5</td>
<td>4.04</td>
<td>0.309</td>
</tr>
<tr>
<td>CNT 2-1.5</td>
<td>4.05</td>
<td>0.309</td>
</tr>
<tr>
<td>CSR 0-1</td>
<td>3.64</td>
<td>0.306</td>
</tr>
<tr>
<td>CSR 1-1</td>
<td>4.09</td>
<td>0.309</td>
</tr>
<tr>
<td>CSR 2-1</td>
<td>4.20</td>
<td>0.309</td>
</tr>
<tr>
<td>CSR 0-2</td>
<td>3.77</td>
<td>0.308</td>
</tr>
<tr>
<td>CSR 1-2</td>
<td>4.04</td>
<td>0.306</td>
</tr>
<tr>
<td>CSR 2-2</td>
<td>4.04</td>
<td>0.307</td>
</tr>
</tbody>
</table>

Sincerely,

Brandon Bertsch
Oregon Ballistic Laboratories
BALLISTIC LIMIT TEST V50 BL(P)

OREGON BALLISTIC LABORATORIES

TEST SAMPLE
Sample No.: Baseline
Size (in.): 18 x 18
Weight (lbs.): 4.03
Description: Spray with 6745/RC 16.06%

Thickness:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Thk. (in.)</td>
<td>0.307</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardness</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RANGE SETUP
Range to Target: 16.5 ft.
Primary Vel. Location: 6.35 ft. from target
Witness Panel: 0.062 3004-T3 Aluminum
Target to Witness: 6 in.
Climatic: 0 Degrees

Range #2
Temp.: 69.0 °F
Ph.: 21.72 in. Hg
R.H.: 43.0 %

Recorder: Brandon Bettsch
Gunner: Jethrain Johnson

ASSUMPTIONS
Projectile: .44 Mag 240gr, SWC/GC
Powder: Accurate No. 5

STANDARDS AND PROCEDURES

SHOT NO. | PROJECTILE WT. (gr.) | POWDER WT. (gr.) | Time 1 | VELOCITY 1 | Time 2 | VELOCITY 2 | AVERAGE | VELOCITY | PENETRATION | INCLUSION | FOOTNOTES |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>474</td>
<td>11.5</td>
<td>2109</td>
<td>1110</td>
<td>380</td>
<td>1175</td>
<td>1175</td>
<td>E</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>477</td>
<td>11.0</td>
<td>4444</td>
<td>1296</td>
<td>484</td>
<td>1128</td>
<td>1128</td>
<td>P</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>481</td>
<td>11.5</td>
<td>3155</td>
<td>1202</td>
<td>475</td>
<td>1196</td>
<td>1196</td>
<td>P</td>
<td>C</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>477</td>
<td>11.5</td>
<td>2105</td>
<td>1110</td>
<td>380</td>
<td>1175</td>
<td>1175</td>
<td>E</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>477</td>
<td>11.5</td>
<td>4444</td>
<td>1296</td>
<td>484</td>
<td>1128</td>
<td>1128</td>
<td>P</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

REMARKS
No. of Points: 8
High Penetration: 1175
Low Complete: 1175
Range of Results: 22
Range of Mixed Results: 22
Margin: 22

Quality Manager: [Signature]
Test Director: [Signature]

Customer: Composites One
PN: 88431
Test Date: 8/16/13
Start: 1000
Stop: 1040
Purchase Order: [Number]
### BALLISTIC LIMIT TEST V50 BL(P)

**OREGON BALLISTIC LABORATORIES**

**TEST SAMPLE**
- Sample No.: CNT 0-1
- Size (In.): 18 x 19
- Weight (lb.): 4.16
- Description: Spray with 6745 / RC 25.6%

**RANGE SETUP**
- Range to Target: 16.5 ft.
- Screen Dist. Vol. 2: 5 ft.
- Primary Vel. Location: 6.25 ft. from target
- Witness Panel: 0.030" 5052-T3 Alum.
- Target to Witness: 6 in.
- Obliquity: 0 Degrees
- Barrel: .44 Mag/1250*

**ASSUMPTIONS**
- Projectile: .44 Mag 240gr; SWC/BC
- Powder: Accurate No. 5

**STANDARDS AND PROCEDURES**

**SHOT NO.** | PROJECTILE WT. (g.) | POWER | VELOCITY | VELOCITY | AVERAGE VELOCITY | PENETRATION P | PENETRATION C | NAIL FREE | FOOTNOTES |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>247.1</td>
<td>11.5</td>
<td>4160</td>
<td>4178</td>
<td>4178</td>
<td>116</td>
<td>C</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>247.2</td>
<td>11.5</td>
<td>4160</td>
<td>4178</td>
<td>4178</td>
<td>116</td>
<td>C</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>247.3</td>
<td>11.5</td>
<td>4160</td>
<td>4178</td>
<td>4178</td>
<td>116</td>
<td>C</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>247.4</td>
<td>11.5</td>
<td>4160</td>
<td>4178</td>
<td>4178</td>
<td>116</td>
<td>C</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>247.5</td>
<td>12.2</td>
<td>3950</td>
<td>3964</td>
<td>3964</td>
<td>1261</td>
<td>P</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**REMARKS:**
- No. of Points: 4
- High Partial: 1303
- Low Partial: 3113
- Range of Results: 44
- Range of Mixed Results: 44
- Margin: 82

**QUALITY MANAGER:**

**TEST DIRECTOR:**

Alice Delittle
Brandon Berbach
# BALLISTIC LIMIT TEST V50 BL(P)

## TEST SAMPLE
- **Sample No.**: CNT 1-1
- **Size (in.)**: 18 x 18
- **Weight (lb.)**: 4.08
- **Description**: Epoxy with 67/35 BC 16.6%
- **Thickness**: 1

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Thk. (in.)</td>
<td>0.306</td>
<td>0.306</td>
<td>0.306</td>
<td>0.306</td>
</tr>
<tr>
<td>Hardness</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

## RANGE SETUP
- **Range to Target**: 16.5 ft
- **Screen Dist. Vol.**: 6 ft
- **Primary Vel. Location**: 6.25 ft from target
- **Witness Panel**: 0.020" 2024-T3 Alum.
- **Target to Witness**: 6 in.
- **Obliquity**: 0 Degrees
- **Barrel**: .44 Mag/12/30"

## ABSTRACT
- **Projectile**: .44 Mag 340gr. SWCGC
- **Powder**: Accurate No. 5

## STANDARD AND PROCEDURES

<table>
<thead>
<tr>
<th>SHOT NO.</th>
<th>PROJECTILE WT. (gr.)</th>
<th>POWDER WT. (gr.)</th>
<th>Time 1 (μsec)</th>
<th>VELOCITY 1 (fps)</th>
<th>Time 2 (μsec)</th>
<th>VELOCITY 2 (fps)</th>
<th>AVERAGE VEL. (fps)</th>
<th>PENETRATION P</th>
<th>C</th>
<th>NAIL IN FOOTNOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>247.6</td>
<td>12.0</td>
<td>3970</td>
<td>2160</td>
<td>3950</td>
<td>1160</td>
<td>1050</td>
<td>P</td>
<td>C</td>
<td>Y</td>
</tr>
<tr>
<td>2</td>
<td>248.8</td>
<td>12.5</td>
<td>3970</td>
<td>2160</td>
<td>3950</td>
<td>1160</td>
<td>1050</td>
<td>P</td>
<td>C</td>
<td>Y</td>
</tr>
<tr>
<td>3</td>
<td>247.7</td>
<td>12.5</td>
<td>3970</td>
<td>2160</td>
<td>3950</td>
<td>1160</td>
<td>1050</td>
<td>P</td>
<td>C</td>
<td>Y</td>
</tr>
<tr>
<td>4</td>
<td>247.7</td>
<td>12.5</td>
<td>3970</td>
<td>2160</td>
<td>3950</td>
<td>1160</td>
<td>1050</td>
<td>P</td>
<td>C</td>
<td>Y</td>
</tr>
<tr>
<td>5</td>
<td>247.7</td>
<td>12.5</td>
<td>3970</td>
<td>2160</td>
<td>3950</td>
<td>1160</td>
<td>1050</td>
<td>P</td>
<td>C</td>
<td>Y</td>
</tr>
<tr>
<td>6</td>
<td>247.7</td>
<td>12.5</td>
<td>3970</td>
<td>2160</td>
<td>3950</td>
<td>1160</td>
<td>1050</td>
<td>P</td>
<td>C</td>
<td>Y</td>
</tr>
</tbody>
</table>

## REMARKS:
- **Total Shots**: 1200
- **Test Director**: Brandon Bertsch

---

Quality Manager: [Signature]  
Test Director: [Signature]

---

[NVLA] This report must not be used to claim product performance against a standard without conformance to NCSL.

**BALLISTIC LIMIT TEST V₅₀ BL(P)**

**OREGON BALLISTIC LABORATORIES**

**TEST SAMPLE**
- Sample No: CNT 2-1
- Size (in.): 18 x 18
- Weight (lb): 4.08
- Description: Spexy with 6745/RC 16.7%

<table>
<thead>
<tr>
<th>Thickness</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Thk. (in)</td>
<td>0.399</td>
<td>0.397</td>
<td>0.399</td>
<td>0.399</td>
</tr>
<tr>
<td>Hardness</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**RANGE SETUP**
- Range to Target: 16.5 ft
- Screen Dist. Vol: 6 ft
- Screen Dist. Vol: 2 ft
- Primary Vel. Location: 6.25 ft from target
- Witness Panel: 0.020” 3004-T3 Alum.
- Target to Witness: 4 in
- Direction: 0 Degrees
- Barrel: .44 Mag/1200"

**ABSTRACT**
- Project: .44 Mag 340gr. SWC/SC
- Powder: Accurate No. 5

**STANDARD AND PROCEDURES**

<table>
<thead>
<tr>
<th>SHOT NO.</th>
<th>PROJECTILE WT (gr)</th>
<th>POWDER WT (gr)</th>
<th>TRAVEL TIME 1 (ms)</th>
<th>VELOCITY 1 (fps)</th>
<th>TRAVEL TIME 2 (ms)</th>
<th>VELOCITY 2 (fps)</th>
<th>AVERAGE VELOCITY (fps)</th>
<th>PENETRATION</th>
<th>FALL-LEVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>P</td>
<td>C</td>
</tr>
<tr>
<td>2</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>P</td>
<td>C</td>
</tr>
<tr>
<td>3</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>P</td>
<td>C</td>
</tr>
<tr>
<td>4</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>217.5</td>
<td>P</td>
<td>C</td>
</tr>
</tbody>
</table>

**FOOTNOTES**

**RESULTS**
- No. of Panels: 1
- High Panel: 1
- Low Panel: 1
- Range of Results: 48
- Range of Mixed Results: 48

**Remarks:**
- 48

**Quality Manager:**
- Nils Dellwilde

**Test Director:**
- Brandon Bertsch

---

**NIJ**

This report must not be used to claim product certification against or endorsement by NIJ.

BALLISTIC LIMIT TEST V_{50} BL(P)

OREGON BALLISTIC LABORATORIES

TEST SAMPLE
Sample No.: CNT 1-15
Size (in.): 18 x 18
Weight (lb.): 4.00
Description: epoxy with 67/45/RC 15:64%

THICKNESS

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Thk. (in.)</td>
<td>0.250</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardness</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RANGE SET-UP
Range to Target: 16.5 ft.
Screen Dist: 10 ft.
Screen Dist: 2 ft.
Primary Vel. Location: 6.25 ft. from target
Witness Panel: 0.030" 3052-T3 Alum.
Target to Witness: 6 in.
Obliquity: 0 Degrees
Barrel: .44 Mag/1250"

ASSUMPTIONS
Projectile: .44 Mag 240gr. SWC-GC
Powder: Accurate No. 5

STANDARD AND PROCEDURES
V_{RMS} = 1193

<table>
<thead>
<tr>
<th>SHOT NO.</th>
<th>PROJECTILE WT. (gr.)</th>
<th>POWDER WT. (gr.)</th>
<th>Time 1 (us)</th>
<th>VELOCITY 1</th>
<th>Time 2 (us)</th>
<th>VELOCITY 2</th>
<th>AVERAGE VELOCITY</th>
<th>PENETRATION</th>
<th>BULLET EXTRUDED Y/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>247.5</td>
<td>0.5</td>
<td>1211</td>
<td>1290</td>
<td>1330</td>
<td>1395</td>
<td>1395</td>
<td>C</td>
<td>Y</td>
</tr>
<tr>
<td>2</td>
<td>247.5</td>
<td>0.5</td>
<td>1211</td>
<td>1395</td>
<td>1330</td>
<td>1395</td>
<td>1395</td>
<td>C</td>
<td>Y</td>
</tr>
<tr>
<td>3</td>
<td>247.5</td>
<td>0.5</td>
<td>1211</td>
<td>1395</td>
<td>1330</td>
<td>1395</td>
<td>1395</td>
<td>C</td>
<td>Y</td>
</tr>
<tr>
<td>4</td>
<td>247.5</td>
<td>0.5</td>
<td>1211</td>
<td>1395</td>
<td>1330</td>
<td>1395</td>
<td>1395</td>
<td>P</td>
<td>Y</td>
</tr>
<tr>
<td>5</td>
<td>247.5</td>
<td>0.5</td>
<td>1211</td>
<td>1395</td>
<td>1330</td>
<td>1395</td>
<td>1395</td>
<td>P</td>
<td>Y</td>
</tr>
<tr>
<td>6</td>
<td>247.5</td>
<td>0.5</td>
<td>1211</td>
<td>1395</td>
<td>1330</td>
<td>1395</td>
<td>1395</td>
<td>P</td>
<td>Y</td>
</tr>
</tbody>
</table>

REMARKS:

- 1193
- No. of Points: 4
- High Failure: 1192
- Low Complete: 1192
- Range of Result: 61
- Range of Mixed Results: 10
- Margin: 10

Quality Manager: [Signature]  Test Director: [Signature]

Quality Manager: [Signature]  Test Director: [Signature]
BALLISTIC LIMIT TEST V_{50} BL(P)

OREGON BALLISTIC LABORATORIES

Sample No.: CNT D-1.5
Size (in.): 10 x 10
Weight (oz.): 4.09

Thickness: 0.210 0.210 0.211 0.210

Avg. Thk. (in.): 0.210
Hardness: NA

Velocity vs. Shot Number

- V_{50}
- Partial
- Complete
- BL(p)

Sample IDs:
- 1: 1932
- 2: 1932

Results:
- No. of Shots: 1932
- Shot Range: 1932
- Range of Results: 1932
- Min.: 1932
- Max.: 1932

NIJ Approved

This report must not be used to claim product certification against or endorsement by NIJ.
## BALLISTIC LIMIT TEST V₂₅ BL(P)

**TEST SAMPLE**
- Sample No.: CNT 1.x
- Size (in.): 18 x 19
- Weight (lb.): 4.04
- Description: epoxy with 6745/RC 16.11%

### RANGE SETUP
- Range to Target: 16.5 ft.
- Screen Dist. Vol.: 6 ft.
- Primary Vol. Location: 6.25 ft.
- Witness Panel: 0.020" 5052-H3 Alum.
- Target to Witness: 6 in.

### LOGISTICS
- Range E: 2
- Temp.: 68.0 °F
- Ph.: 29.72 in. Hg
- RH: 32.0 %
- Recorder: Brandon Bertch
- Gunner: Jeremiah Johnson
- Barrels: .44 Mag/1079®

### ABSTRACTION
- Projector: .44 Mag 340gr, SWC/GC
- Powder: Accurate No. 5

### STANDARDS AND PROCEDURES
- Required V₂₅ (Rf): 1100
- V₂₅ Rim: 2P + 2C

### DATA

<table>
<thead>
<tr>
<th>SHOT NO.</th>
<th>PROJECTILE WT.</th>
<th>PROJECTILE WT.</th>
<th>POKER WT.</th>
<th>POKER WT.</th>
<th>Time 1</th>
<th>Time 2</th>
<th>VELOCITY 1</th>
<th>VELOCITY 2</th>
<th>AVERAGE VELOCITY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g</td>
<td>lb</td>
<td>g</td>
<td>lb</td>
<td>μs</td>
<td>μs</td>
<td>μs</td>
<td>μs</td>
<td>μs</td>
</tr>
<tr>
<td>1</td>
<td>11.8</td>
<td>11.8</td>
<td>11.8</td>
<td>11.8</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
</tr>
<tr>
<td>2</td>
<td>11.8</td>
<td>11.8</td>
<td>11.8</td>
<td>11.8</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
</tr>
<tr>
<td>3</td>
<td>11.8</td>
<td>11.8</td>
<td>11.8</td>
<td>11.8</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
</tr>
<tr>
<td>4</td>
<td>11.8</td>
<td>11.8</td>
<td>11.8</td>
<td>11.8</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
</tr>
<tr>
<td>5</td>
<td>11.8</td>
<td>11.8</td>
<td>11.8</td>
<td>11.8</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
</tr>
<tr>
<td>6</td>
<td>11.8</td>
<td>11.8</td>
<td>11.8</td>
<td>11.8</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
</tr>
</tbody>
</table>

### REMARKS
- FD: 1345
- No. of Points: 5
- High Pressure: 13.8
- Low Pressure: 13.8
- Range of Results: 27
- Range of Mixed Results: 27
- Margin: 0.28

Quality Manager: [Signature]
Test Director: [Signature]

[Signature: NIJ]
[Signature: NVLAP]
## BALLISTIC LIMIT TEST V<sub>50</sub> BL(P)

### Test Sample
- Sample No.: CNT 3.1-5
- Size (in.): 18 x 18
- Weight (oz): 4.08
- Description: Sample with 6745/RC 18.0%

### Range Setup
- Range to Target: 16.5 ft
- Screen Dist: 6 ft
- Primary Vel. Location: 6.25 ft from target
- Witness Panel: 0.020" 3004-T6 Aluminum
- Target to Witness: 6 in
- Range: 2
- Temp: 69.7 °F
- Ph: 7.63 in. Hg
- R.H.: 43.0%
- Recorder: Brandon Bertsch
- Gunner: Jermaine Johnson
- Barrel: .44 Mag 1:200"

### Absorption
- Powder: .44 Mag 340gr. SWC/GB
- Powder: Accurate No. 5

### Standards and Procedures
- Required V<sub>50</sub> (MPH): 1160
- V<sub>50</sub> Min: 2P ± 2C

<table>
<thead>
<tr>
<th>SHOT NO.</th>
<th>PROJECTILE WT (g)</th>
<th>PROJECTILE WT (gr)</th>
<th>Time 1 (us 10&lt;sup&gt;14&lt;/sup&gt;</th>
<th>VELOCITY 1 (ft/s)</th>
<th>Time 2 (us 10&lt;sup&gt;14&lt;/sup&gt;</th>
<th>VELOCITY 2 (ft/s)</th>
<th>AVERAGE VELOCITY (ft/s)</th>
<th>PENETRATION (mm)</th>
<th>BULLET Y/N</th>
<th>FOOTNOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3271</td>
<td>11.8</td>
<td>112</td>
<td>117</td>
<td>114</td>
<td>115</td>
<td>114</td>
<td>C</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3271</td>
<td>11.8</td>
<td>112</td>
<td>117</td>
<td>114</td>
<td>115</td>
<td>114</td>
<td>C</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3274</td>
<td>11.5</td>
<td>114</td>
<td>110</td>
<td>113</td>
<td>115</td>
<td>114</td>
<td>P</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3274</td>
<td>11.5</td>
<td>114</td>
<td>110</td>
<td>113</td>
<td>115</td>
<td>114</td>
<td>C</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3273</td>
<td>11.2</td>
<td>120</td>
<td>114</td>
<td>113</td>
<td>115</td>
<td>114</td>
<td>C</td>
<td>Y</td>
<td></td>
</tr>
</tbody>
</table>

| REMARKS | No. of Points: 8 | High Score: 1181 | Low Complete: 1160 | Range of Result: 31 | Range of Mixed Results: Margin: 1 |

### Quality Manager
- Name: DeWilde

### Test Director
- Name: Brandon Bertsch
# BALLISTIC LIMIT TEST V_{50} BL(P)

## TEST SAMPLE
- **Sample No.**: CSM-0-1
- **Size (in.)**: 18 x 18
- **Weight (lbs)**: 3.64
- **Description**: Spray with 6745/RC 16.30%
- **Thickness**: 1
- **Avg. Thk. (in)**: 0.300
- **Hardness**: NA

## RANGE SETUP
- **Range to Target**: 16.5 ft.
- **Screen Dist. Vel.**: 6 ft.
- **Primary Vel. Location**: 6.25 ft. from target
- **Witness Panel**: 0.020" 3004-T3 Alum.
- **Target to Witness**: 6 in.
- **Obliquity**: 0 Degrees

## ASSUMPTIONS
- **Projectile**: 64 Mag 140gr, SWC/HC
- **Powder**: Accurate No. 5

## BALLISTIC AND PHYSICAL PROPERTIES

### SHOT NO.

<table>
<thead>
<tr>
<th>SHOT NO.</th>
<th>PROJECTILE WT. (g)</th>
<th>PROJECTILE WT. (l)</th>
<th>Time 1 (us)</th>
<th>VELOCITY 1 (fps)</th>
<th>VELOCITY 2 (fps)</th>
<th>VELOCITY 2 (fps)</th>
<th>AVERAGE VEL. (fps)</th>
<th>PENETRATION (in)</th>
<th>BALLISTIC Y/N</th>
<th>FOOTNOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>347.2</td>
<td>11.5</td>
<td>20.20</td>
<td>2100</td>
<td>1100</td>
<td>1100</td>
<td>1100</td>
<td>P</td>
<td>C</td>
<td>Y</td>
</tr>
<tr>
<td>2</td>
<td>347.7</td>
<td>11.0</td>
<td>2120</td>
<td>1200</td>
<td>1100</td>
<td>1100</td>
<td>1200</td>
<td>P</td>
<td>C</td>
<td>Y</td>
</tr>
<tr>
<td>3</td>
<td>347.8</td>
<td>11.0</td>
<td>2120</td>
<td>1200</td>
<td>1100</td>
<td>1100</td>
<td>1200</td>
<td>P</td>
<td>C</td>
<td>Y</td>
</tr>
<tr>
<td>4</td>
<td>347.9</td>
<td>11.0</td>
<td>2120</td>
<td>1200</td>
<td>1100</td>
<td>1100</td>
<td>1200</td>
<td>P</td>
<td>C</td>
<td>Y</td>
</tr>
</tbody>
</table>

## REMARKS
- **Remarks**: 44
- **Remarks of Points**: 44
- **Remarks of High Points**: 96
- **Remarks of Low Points**: 96
- **Remarks of Mixed Results**: 44
- **Remarks of Margin**: 96

## QUALITY MANAGER
- **Quality Manager**: [Signature]

## TEST DIRECTOR
- **Test Director**: Brandon Bertach
# BALLISTIC LIMIT TEST \( V_{50} \) BL(P)

**TEST SAMPLE**

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>CSM 5-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (in.)</td>
<td>18 x 18</td>
</tr>
<tr>
<td>Weight (lb.)</td>
<td>4.09</td>
</tr>
</tbody>
</table>

Description: epoxy with 6745/RC 16.8%

<table>
<thead>
<tr>
<th>Thickness</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Thk. (in.)</td>
<td>0.311</td>
<td>0.306</td>
<td>0.310</td>
<td>0.300</td>
</tr>
</tbody>
</table>

| Hardness | N/A |

**RANGE SETUP**

<table>
<thead>
<tr>
<th>Range to Target</th>
<th>16.5 ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen Dist. Vel</td>
<td>6 ft.</td>
</tr>
<tr>
<td>Screen Dist. Vel 2</td>
<td>5 ft.</td>
</tr>
<tr>
<td>Primary Vel. Location</td>
<td>6.25 ft. from target</td>
</tr>
<tr>
<td>Witness Panel</td>
<td>0.020&quot; 3024-T3 Alum.</td>
</tr>
<tr>
<td>Target to Witness</td>
<td>6 in.</td>
</tr>
<tr>
<td>Obliquity</td>
<td>0 Degrees</td>
</tr>
<tr>
<td>Barrel</td>
<td>.44 Mag 1:2073&quot;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Range #</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp.</td>
<td>69.7 °F</td>
</tr>
<tr>
<td>Ph</td>
<td>28.72 in. Hg</td>
</tr>
<tr>
<td>Rh</td>
<td>43.0 %</td>
</tr>
</tbody>
</table>

Recorded: Brandon Bertech

Gyro: Jethin Johnson

**ASSUMPTION**

Project: .44 Mag 150gr, SWC/GC

Powder: Accurate No. 5

**REQUIRED AND PROCEDURES**

<table>
<thead>
<tr>
<th>Shot</th>
<th>Projectile WT (gr)</th>
<th>Powder WT (gr)</th>
<th>Time 1</th>
<th>1g Vel (fps)</th>
<th>Velocity 1</th>
<th>Time 2</th>
<th>1g Vel (fps)</th>
<th>Velocity 2</th>
<th>Average Vel (fps)</th>
<th>Penetration</th>
<th>Collar</th>
<th>Footnotes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>447 E</td>
<td>12.5</td>
<td>4016</td>
<td>1205</td>
<td>1230</td>
<td>1234</td>
<td>Y</td>
<td></td>
<td></td>
<td>P</td>
<td>C</td>
<td>Y</td>
</tr>
<tr>
<td>2</td>
<td>447F</td>
<td>12.5</td>
<td>4019</td>
<td>1209</td>
<td>1231</td>
<td>1231</td>
<td>Y</td>
<td></td>
<td></td>
<td>C</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>447G</td>
<td>12.5</td>
<td>4019</td>
<td>1206</td>
<td>1230</td>
<td>1231</td>
<td>Y</td>
<td></td>
<td></td>
<td>C</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>447H</td>
<td>12.5</td>
<td>3910</td>
<td>1179</td>
<td>1215</td>
<td>1217</td>
<td>Y</td>
<td></td>
<td></td>
<td>P</td>
<td>C</td>
<td></td>
</tr>
</tbody>
</table>

**RESULTS**

<table>
<thead>
<tr>
<th>Shot</th>
<th>Velocity (fps)</th>
<th>Penetration</th>
<th>Collar</th>
<th>Footnotes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4305</td>
<td>P</td>
<td>C</td>
<td>Y</td>
</tr>
<tr>
<td>2</td>
<td>1207</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1207</td>
<td>C</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1207</td>
<td>P</td>
<td>C</td>
<td></td>
</tr>
</tbody>
</table>

**GARMIN**

<table>
<thead>
<tr>
<th>Shot</th>
<th>No. of Points</th>
<th>High Partial</th>
<th>Low Composite</th>
<th>Range of Results</th>
<th>Range of Mixed Results</th>
<th>Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

**QUALITY MANAGER**

Mike DelRitte

**TEST DIRECTOR**

Brandon Bertech

---

*This report must not be used to claim product certification against any standard recognized by NVALP.*

www.oregonlab.com | 3873 22nd Street SE Salem, OR 97302 | p: 503.965.8114 | f: 503.365.9500

107
BALLISTIC LIMIT TEST V\textsubscript{50} BL(P)

TEST SAMPLE
Sample No.: C3M-2-1
Size (in.): 18 x 18
Weight (lb.): 4.30
Description: Epoxy with 6745/RC 20.30%

Thickness:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Thk. (in.):</td>
<td>0.337</td>
<td>0.307</td>
<td>0.311</td>
<td>0.308</td>
</tr>
<tr>
<td>Hardness:</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RANGE SETUP
Range to Target: 16.5 ft.
Primary Vel. Location: 6.25 ft. from target
Witness Panel: 0.020" 7024-T3 Aluminum
Target to Witness: 6 in.
Obliquity: 0 Degrees
Barrel: A4 Magpul 1:20 TPI

Range # 2
Temp.: 69.7 °F
Ph.: 29.72 in. Hg
R.H.: 43.0%

Basket: Accuracy No. 5

LOADING AND PROCEDURES

Required V\textsubscript{50} (RMP): 1100
V\textsubscript{50} Max: 2P + 2C

<table>
<thead>
<tr>
<th>SHOT NO.</th>
<th>PROJECTILE WT. (g.)</th>
<th>POWER WT. (g.)</th>
<th>Time 1 (μs)</th>
<th>VELOCITY 1 (fps)</th>
<th>Time 2 (μs)</th>
<th>VELOCITY 2 (fps)</th>
<th>AVERAGE VELOCITY (fps)</th>
<th>PENETRATION (in.)</th>
<th>P C Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>247.2</td>
<td>11.5</td>
<td>4110</td>
<td>1270</td>
<td>3393</td>
<td>1003</td>
<td>1004</td>
<td>6</td>
<td>V</td>
</tr>
<tr>
<td>2</td>
<td>247.3</td>
<td>11.0</td>
<td>4175</td>
<td>1170</td>
<td>3506</td>
<td>1002</td>
<td>1000</td>
<td>6</td>
<td>C</td>
</tr>
<tr>
<td>3</td>
<td>247.4</td>
<td>11.6</td>
<td>4150</td>
<td>1100</td>
<td>3651</td>
<td>1299</td>
<td>1291</td>
<td>6</td>
<td>V</td>
</tr>
<tr>
<td>4</td>
<td>247.5</td>
<td>11.7</td>
<td>4050</td>
<td>1220</td>
<td>4890</td>
<td>1221</td>
<td>1223</td>
<td>6</td>
<td>Y</td>
</tr>
</tbody>
</table>

RESULTS

<table>
<thead>
<tr>
<th>SHOT NO.</th>
<th>PENETRATION</th>
<th>C</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1003</td>
<td>6</td>
<td>V</td>
</tr>
<tr>
<td>2</td>
<td>1002</td>
<td>6</td>
<td>C</td>
</tr>
<tr>
<td>3</td>
<td>1000</td>
<td>6</td>
<td>V</td>
</tr>
<tr>
<td>4</td>
<td>1299</td>
<td>6</td>
<td>V</td>
</tr>
</tbody>
</table>

COMMENTS

- No. of Points: 4
- High Partial: 1000
- One Complete: 1000
- Total Points: 39
- Range of Results: 1000
- Range of Mixed Results: 44

Quality Manager: Mike DelGhide
Test Director: Brandon Bertech

NVLAP This report must not be used to claim product performance against or endorsement by National Institute of Justice

www.oregonlab.com / 3673 22nd Street SE Salem, OR 97302 / p 503.650.8111 / f 503.362.5997

109
BALLISTIC LIMIT TEST V_{50} BL(P)

OREGON BALLISTIC LABORATORIES

Sample No.: CSR 2-1
Size (in.): 10 x 10
Weight (lb.): 4.20
Description: Stab with 0745/4C, 26.36%

Thickness: 0.250
Avg. Thk. (in.): 0.300
Hardness: N/A

Velocity vs. Shot Number

- V50
- Partial
- Complete
- BL(p)

Velocity vs. Shot Number

- V50
- Partial
- Complete
- BL(p)

SHOTS:
- Firing: 1228
- No. of Shots: 6
- High and Low: 1222
- Low Complete: 1224
- Range of Results: 50
- Range of Wood Results: 44

This report must not be used to claim product certification against or compliance to any NIJ Standards.
### BALLISTIC LIMIT TEST V_{50} BL(P)

**OREGON BALLISTIC LABORATORIES**

**TEST SAMPLE**
- Sample No.: C118-0.2
- Size (in.): 19 x 16.5
- Weight (lb.): 3.77
- Description: Spray with 6745/RC 1670%

**Thickmess:**
<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Thk. (in.)</td>
<td>0.300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardness</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**RANGE SETUP**
- Range to Target: 16.5 ft.
- Screen Dist. Val.: 6 ft.
- Screen Dist. Val. 2: 5 ft.
- Primary Vel. Location: 0.25 ft. from target
- Witness Panel: 0.020" 3004-T3 Alum.
- Target to Witness: 6 in.
- Calibrator: 0 Degrees
- Barrel: .44 Mag/1:20"*

**AMMUNITION**
- Projectile: 44 Mag 240gr. SWC/GC
- Powder: Accurate No. 5

**STANDARDS AND PROCEDURES**
- Required V_{50} (ft/s): 1100
- V_{50} Rm: 2P + 2C

| SHOT | PROJECTILE WT. (gr) | POWDER WT. (gr) | Time 1 (us) | VELOCITY 1 (ft/s) | VELOCITY 2 (ft/s) | VELOCITY AR (ft/s) | AVERAGE VELOCITY | PENETRATION | BULLET | SACCHAR | FOOTNOTES |
|------|---------------------|-----------------|-------------|-------------------|-------------------|--------------------|-----------------|-------------|--------|---------|----------|----------|
| 1    | 377.8               | 16.0            | 1410        | 1105              | 1105              | 1054               | 1104            | C           | Y      | Y       |          |          |
| 2    | 377.8               | 16.0            | 1410        | 1105              | 1105              | 1054               | 1104            | P           | Y      | Y       |          |          |
| 3    | 377.8               | 16.0            | 1410        | 1105              | 1105              | 1054               | 1104            | Y           | Y      | Y       |          |          |
| 4    | 377.8               | 16.0            | 1410        | 1105              | 1105              | 1054               | 1104            | Y           | Y      | Y       |          |          |

**REMARKS**
- V_{50} (ft/s): 1129
- % of Points: 8
- High/Path: 1.04
- Low/Impossible: 1.04
- Range of Points: 56
- Range of Mixed Results: 27

**Quality Manager:**
- Mike Dellbride

**Test Director:**
- Brandon Bertech
### BALLISTIC LIMIT TEST V50 BL(P)

**TEST SAMPLE**
- Sample No.: C36-2-2
- Size (in.): 18 x 18
- Weight (lb.): 4.04
- Description: Spexy with 6745/RC 17.5%
- Thickness: 1 0.307 2 0.307 3 0.307 4 0.307
- Hardness: N/A

**RANGE SETUP**
- Range to Target: 16.5 ft.
- Screen Dist. Vol.: 6 ft.
- Screen Dist. Val.: 5 ft.
- Primary Vel. Location: 6.25 ft. from target
- Witness Panel: 0.020” 3024-T5 Aluminum
- Target to Witness: 6 in.
- Obliquity: 0 Degrees
- Barrel: .44 Mag/S1 (2019)

**FABRICATION**
- Projector: .44 Mag 130 gr. SWC/GC
- Powder: Accurate No. 5

**STANDARDS AND PROCEDURES**
- Required V50 (Rft): 1192
- V50 Rim: 2P + 0C

<table>
<thead>
<tr>
<th>SHOT NO.</th>
<th>PROJECTILE WT. (gr.)</th>
<th>POWDER WT. (gr.)</th>
<th>Time 1 (ms)</th>
<th>VELOCITY 1 (fps)</th>
<th>Time 2 (ms)</th>
<th>VELOCITY 2 (fps)</th>
<th>AVERAGE VELOCITY (fps)</th>
<th>PENETRATION (Rft)</th>
<th>P</th>
<th>C</th>
<th>Y</th>
<th>FAIL?</th>
<th>Y/N</th>
<th>FOOTNOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>247.2</td>
<td>46.0</td>
<td>0.05</td>
<td>2100</td>
<td>0.05</td>
<td>2100</td>
<td>2100</td>
<td>12.0</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>247.4</td>
<td>46.0</td>
<td>0.05</td>
<td>2110</td>
<td>0.05</td>
<td>2110</td>
<td>2110</td>
<td>14.0</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>247.5</td>
<td>46.0</td>
<td>0.05</td>
<td>2105</td>
<td>0.05</td>
<td>2105</td>
<td>2105</td>
<td>14.0</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>247.7</td>
<td>46.0</td>
<td>0.05</td>
<td>2110</td>
<td>0.05</td>
<td>2110</td>
<td>2110</td>
<td>14.0</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>247.8</td>
<td>46.0</td>
<td>0.05</td>
<td>2110</td>
<td>0.05</td>
<td>2110</td>
<td>2110</td>
<td>14.0</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>247.5</td>
<td>46.0</td>
<td>0.05</td>
<td>2110</td>
<td>0.05</td>
<td>2110</td>
<td>2110</td>
<td>14.0</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>247.2</td>
<td>46.0</td>
<td>0.05</td>
<td>2110</td>
<td>0.05</td>
<td>2110</td>
<td>2110</td>
<td>14.0</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**REMARKS**
- Cal: 1325
- No. of Points: 4
- High Point: 1342
- Low Point: 1310
- Range of Results: 76
- Range of Mixed Results: 64
- Margin: 39

**Quality Manager:**
- Mike Derriff

**Test Director:**
- Brandon Bertisch
### BALLISTIC LIMIT TEST V_{50} BL(P)

**OREGON BALLISTIC LABORATORIES**

<table>
<thead>
<tr>
<th>Sample No.:</th>
<th>CER-2-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (in.):</td>
<td>10 x 10</td>
</tr>
<tr>
<td>Weight (gr.):</td>
<td>4.54</td>
</tr>
<tr>
<td>Description:</td>
<td>Silvery with 67% / NC 17.8%</td>
</tr>
</tbody>
</table>

### Velocity vs. Shot Number

<table>
<thead>
<tr>
<th>Shot Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m/s)</td>
<td>1275</td>
<td>1250</td>
<td>1225</td>
<td>1200</td>
</tr>
<tr>
<td>Average Thickness (in.)</td>
<td>0.009</td>
<td>0.009</td>
<td>0.009</td>
<td>0.009</td>
</tr>
<tr>
<td>Hardness</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**PRELIMINARY**

**NVLAP**

This report may not be used to claim product certification, approval or endorsement by the National Institute of Justice.

www.oregonlab.com / 3873 S. 22nd street, Salem, OR 97302 / P: 503.365.8116 / F: 503.365.0057

114
115
BALLISTIC LIMIT TEST $V_{50}$ BL(P)

OBL
OREGON BALLISTIC LABORATORIES

Sample No.: CLR 1-2
Size (in.): 10 x 10
Weight (lb.): 4.04

Thickness:
1 | 0.004
2 | 0.004
3 | 0.004
4 | 0.004

Avg. Thk. (in.): 0.004
Hardness: N/A

Description: Stipple with 6745/RC 10.00%

Velocity vs. Shot Number

Shot Number

1200
1250
1300
1350
1400

1 2 3 4 5

$V_{50}$
partial complete BL(p)

Summary:

DETAILED

Caliber: 12.84
No. of Points: 4
Flap Pattern: 1.913
Condition Complete: 1.242
Range of Results: 15
Range of Wood Results: 9

NVLAP
NIJ
This report must not be used to claim product certification, approval or endorsement by the National Institute of Justice.

www.oregonlab.com / 3673 22nd St SE Salem, OR 97302 / p 503.680.8115 / F 503.362.9957

116
4.13 High Com Test Report – 11/02/2010 Shoot

Date Received: 11/2/2010  
Job No: 161102.01.CAW

Courier:  
Test Date: 11/2/2010

Comp File: LN16-122-1, 16 PLY  
Client:

Description 1:  
Report No:

Description 2: CONTROL SAMPLE

Sample No: SEE REMARKS

Manufacturer: COMPOSITES ONE  
Muzzle To Range: 16.4'

Part No: ZYVEK  
No Of Screens: 2

Size: 12" x 12"  
Screen Spacing: 5'

Barrel Serial No: 44 MAG  
MidPoint To Target: 9.06'

Barrel Length: 12"  

Twist Range: 1-10  

Weight: SEE REMARKS  

Avg Thickness:  

Specification: MIL-STD-662F  

Powder: IMR 4227

Temperature: 67.1  

Witness Material: 2024 T3  

Relative Humidity: 30%  

Distance To Target: 16.4'

Conditioning: AMBIENT  

Inspector: WRIGHT

 Visual Examination:  

<table>
<thead>
<tr>
<th>Round</th>
<th>Powder</th>
<th>Striking Velocity 1</th>
<th>Striking Velocity 2</th>
<th>Avg Striking Velocity</th>
<th>Observation PC</th>
<th>Included</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.7</td>
<td>1224</td>
<td>1223</td>
<td>1224</td>
<td>P</td>
<td></td>
<td>(a)</td>
</tr>
<tr>
<td>2</td>
<td>21.3</td>
<td>1286</td>
<td>1255</td>
<td>1266</td>
<td>C</td>
<td>✓</td>
<td>(b)</td>
</tr>
<tr>
<td>3</td>
<td>20.5</td>
<td>1142</td>
<td>1143</td>
<td>1142</td>
<td>P</td>
<td></td>
<td>(a)</td>
</tr>
<tr>
<td>4</td>
<td>21.0</td>
<td>1246</td>
<td>1245</td>
<td>1246</td>
<td>P</td>
<td>✓</td>
<td>(a)</td>
</tr>
<tr>
<td>5</td>
<td>21.5</td>
<td>1234</td>
<td>1225</td>
<td>1230</td>
<td>P</td>
<td></td>
<td>(a)</td>
</tr>
<tr>
<td>6</td>
<td>21.7</td>
<td>1254</td>
<td>1253</td>
<td>1254</td>
<td>C</td>
<td>✓</td>
<td>(b)</td>
</tr>
<tr>
<td>7</td>
<td>21.6</td>
<td>1271</td>
<td>1265</td>
<td>1268</td>
<td>P</td>
<td>✓</td>
<td>(b)</td>
</tr>
<tr>
<td>8</td>
<td>22.0</td>
<td>1234</td>
<td>1239</td>
<td>1236</td>
<td>P</td>
<td>✓</td>
<td>(b)</td>
</tr>
<tr>
<td>8</td>
<td>22.3</td>
<td>1322</td>
<td>1327</td>
<td>1334</td>
<td>C</td>
<td>✓</td>
<td>(b)</td>
</tr>
</tbody>
</table>

Remarks:
(a)161102.01.CAW.A - 862g, AVG THICKNESS: .306"  
(b)161102.01.CAW.B - 1032g, AVG THICKNESS: .306"

Shots Included Partial: 3  
Shots Included Complete: 3

V50: 1279  
High Partial: 1327  
Low Complete: 1254  
Reg Range: 125  
Range Of Results: 81  
Range Of Mixed Results: 73

All values out of tolerance must be clearly marked, product tagged for disposition and contained.
<table>
<thead>
<tr>
<th>Round</th>
<th>Powder</th>
<th>Striking Velocity 1</th>
<th>Striking Velocity 2</th>
<th>Avg Striking Velocity</th>
<th>Observation PC</th>
<th>Included</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.0</td>
<td>1251</td>
<td>1280</td>
<td>1260</td>
<td>P</td>
<td>(a)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>22.0</td>
<td>1342</td>
<td>1341</td>
<td>1342</td>
<td>C</td>
<td>(a)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>21.5</td>
<td>1303</td>
<td>1308</td>
<td>1306</td>
<td>P</td>
<td>(a)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>22.2</td>
<td>1327</td>
<td>1322</td>
<td>1330</td>
<td>P</td>
<td>(a)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>22.7</td>
<td>1368</td>
<td>1392</td>
<td>1390</td>
<td>C</td>
<td>(b)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>22.0</td>
<td>1331</td>
<td>1336</td>
<td>1334</td>
<td>P</td>
<td>(b)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>22.8</td>
<td>1368</td>
<td>1367</td>
<td>1358</td>
<td>P</td>
<td>(b)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>22.8</td>
<td>1426</td>
<td>1424</td>
<td>1426</td>
<td>C</td>
<td>(b)</td>
<td></td>
</tr>
</tbody>
</table>

Remarks: (a)101102.02.CAW.A-- 807g, AVG THICKNESS:.309"
(b)101102.02.CAW.B-- 1033g, AVG THICKNESS:.311"
### High Com Test Report – 7/28/2010 Shoot

**Date Received:** 119

**Job No:** 100727.03.CAW

**Courier:**

**Test Date:** 7/27/2010

**Comp File:** CONTROL SAMPLE

**Client:**

**Report No:**

**Description 1:** AMBA 03-32 PLY

**Description 2:**

---

### Sample No: SEE REMARKS

<table>
<thead>
<tr>
<th>Manufacturer:</th>
<th>COMPOSITE ONE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part No:</td>
<td>ZYVEX</td>
</tr>
<tr>
<td>Size:</td>
<td>12&quot; X 12&quot;</td>
</tr>
<tr>
<td>Batch No:</td>
<td></td>
</tr>
<tr>
<td>Manufacture Date:</td>
<td></td>
</tr>
<tr>
<td>Weight:</td>
<td>SEE REMARKS</td>
</tr>
<tr>
<td>Avg Thickness:</td>
<td>SEE REMARKS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Caliber:</th>
<th>.30 cal FSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projectile Weight:</td>
<td>44g</td>
</tr>
<tr>
<td>Barrel Serial No:</td>
<td>7.02 x 39</td>
</tr>
<tr>
<td>Barrel Length:</td>
<td>16.5&quot;</td>
</tr>
<tr>
<td>Twist Range:</td>
<td>1-8.45</td>
</tr>
<tr>
<td>Specification:</td>
<td>MIL-STD-462F</td>
</tr>
<tr>
<td>Powder:</td>
<td>Accurate No.2</td>
</tr>
</tbody>
</table>

**Temperature:** 70.7

**Witness Material:** 2024 T3

**Relative Humidity:** 63%

**Distance To Target:** 16.4’

**Conditioning:** AMBIENT

**Visual Examination:**

<table>
<thead>
<tr>
<th>Round</th>
<th>Powder</th>
<th>Striking Velocity 1</th>
<th>Striking Velocity 2</th>
<th>Avg Striking Velocity</th>
<th>Striking Velocity</th>
<th>Observation PC Included</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.0</td>
<td>2665</td>
<td>2599</td>
<td>2602</td>
<td>2534</td>
<td>C</td>
<td>(a)</td>
</tr>
<tr>
<td>2</td>
<td>9.0</td>
<td>2419</td>
<td>2415</td>
<td>2417</td>
<td>2364</td>
<td>C</td>
<td>(a)</td>
</tr>
<tr>
<td>3</td>
<td>7.0</td>
<td>2079</td>
<td>2075</td>
<td>2077</td>
<td>2023</td>
<td>C</td>
<td>(a)</td>
</tr>
<tr>
<td>4</td>
<td>5.0</td>
<td>1519</td>
<td>1516</td>
<td>1518</td>
<td>1478</td>
<td>P</td>
<td>(a)</td>
</tr>
<tr>
<td>5</td>
<td>6.0</td>
<td>1814</td>
<td>1810</td>
<td>1812</td>
<td>1765</td>
<td>P</td>
<td>(a)</td>
</tr>
<tr>
<td>6</td>
<td>6.5</td>
<td>1977</td>
<td>1973</td>
<td>1975</td>
<td>1926</td>
<td>P</td>
<td>(a)</td>
</tr>
<tr>
<td>7</td>
<td>6.9</td>
<td>1989</td>
<td>1986</td>
<td>1986</td>
<td>1934</td>
<td>P</td>
<td>(a)</td>
</tr>
<tr>
<td>8</td>
<td>7.2</td>
<td>2101</td>
<td>2126</td>
<td>2128</td>
<td>2073</td>
<td>C</td>
<td>(b)</td>
</tr>
<tr>
<td>9</td>
<td>7.0</td>
<td>2068</td>
<td>2052</td>
<td>2056</td>
<td>2011</td>
<td>P</td>
<td>(b)</td>
</tr>
<tr>
<td>10</td>
<td>7.1</td>
<td>2163</td>
<td>2099</td>
<td>2101</td>
<td>2046</td>
<td>C</td>
<td>(b)</td>
</tr>
<tr>
<td>11</td>
<td>6.9</td>
<td>2073</td>
<td>2066</td>
<td>2070</td>
<td>2016</td>
<td>P</td>
<td>(b)</td>
</tr>
<tr>
<td>12</td>
<td>7.0</td>
<td>2071</td>
<td>2067</td>
<td>2069</td>
<td>2015</td>
<td>P</td>
<td>(b)</td>
</tr>
</tbody>
</table>

**Remarks:**

(a) 100727.03.CAW – 2029g, AVG THICKNESS: .673”

(b) 100727.04.CAW – 2093g, AVG THICKNESS: .675”

---

**Shots Included Partial: 3**

**Shots Included Complete: 3**

---

**V56r:** 2031

**High Partial:** 2016

**Low Complete:** 2023

**Req Range:** 125

**Range Of Results:** 62

**Range Of Mixed Results:** 7

---

All values out of tolerance must be clearly marked, product tagged for disposition and contained.
<table>
<thead>
<tr>
<th>Sample No:</th>
<th>SEE REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer:</td>
<td>COMPOSITE ONE</td>
</tr>
<tr>
<td>Part No:</td>
<td>ZYLEX</td>
</tr>
<tr>
<td>Size:</td>
<td>12&quot; x 12&quot;</td>
</tr>
<tr>
<td>Batch No:</td>
<td>SEE REMARKS</td>
</tr>
<tr>
<td>Manufacture Date:</td>
<td>SEE REMARKS</td>
</tr>
<tr>
<td>Weight:</td>
<td>SEE REMARKS</td>
</tr>
<tr>
<td>Avg Thickness:</td>
<td>SEE REMARKS</td>
</tr>
<tr>
<td>Caliber:</td>
<td>.36 cal FSP</td>
</tr>
<tr>
<td>Projectile Weight:</td>
<td>44g</td>
</tr>
<tr>
<td>Barrel Serial No:</td>
<td>7.62 x 39</td>
</tr>
<tr>
<td>Barrel Length:</td>
<td>16.5&quot;</td>
</tr>
<tr>
<td>Twist Range:</td>
<td>1.094</td>
</tr>
<tr>
<td>Specification:</td>
<td>MIL-STD-662F</td>
</tr>
<tr>
<td>Powder:</td>
<td>Accurate No.2</td>
</tr>
<tr>
<td>Temperature:</td>
<td>69.8</td>
</tr>
<tr>
<td>Witness Material:</td>
<td>2024 T3</td>
</tr>
<tr>
<td>Relative Humidity:</td>
<td>64%</td>
</tr>
<tr>
<td>Distance To Target:</td>
<td>16.4'</td>
</tr>
<tr>
<td>Conditioning:</td>
<td>AMBIENT</td>
</tr>
<tr>
<td>Visual Examination:</td>
<td></td>
</tr>
<tr>
<td>Round</td>
<td>Powder</td>
</tr>
<tr>
<td>-------</td>
<td>--------</td>
</tr>
<tr>
<td>1</td>
<td>7.1</td>
</tr>
<tr>
<td>2</td>
<td>6.9</td>
</tr>
<tr>
<td>3</td>
<td>7.0</td>
</tr>
<tr>
<td>5</td>
<td>6.9</td>
</tr>
<tr>
<td>6</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Remarks:
- Shots Included Partial: 3
- Shots Included Complete: 3

High Partial: 1998
Low Complete: 2032
Req Range: 128
Range Of Results: 122
Range Of Mixed Results: 35
## Laboratory Test Report

**Velocity Loss, Protection - Ballistic Limit V50**

**Job No:** 100727.03.CAW  
**Test Date:** 7/27/2010

### Sample Information

| Description 1: | CONTROL SAMPLE |
| Description 2: | AMCA 52-32 PLY |

### Manufacturer
- **Manufacturer:** COMPOSITE ONE
- **Part No:** YVEX
- **Size:** 12" X 12"
- **Caliber:** .36 cal FSP
- **Muzzle To Range:** 16.4'

### Specimen Details
- **Barrel Serial No:** 7.32 x 49
- **Barrel Length:** 16.5"  
  **MidPoint To Target:** 6.6
- **Twist Range:** 1.4-4.5

### Material Details
- **Relative Humidity:** 63%
- **Temperature:** 70.7

### Test Conditions
- **Conditioning:** Ambient
- **Witness Material:** 2024 T3
- **Distance To Target:** 16.4'

### Test Results

<table>
<thead>
<tr>
<th>Round</th>
<th>Powder</th>
<th>Striking Velocity 1</th>
<th>Striking Velocity 2</th>
<th>Avg Striking Velocity</th>
<th>Striking Velocity</th>
<th>Observation PC</th>
<th>Included Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>2605</td>
<td>2599</td>
<td>2602</td>
<td>2534</td>
<td>C</td>
<td>0 (a)</td>
</tr>
<tr>
<td>2</td>
<td>9.0</td>
<td>2419</td>
<td>2415</td>
<td>2417</td>
<td>2347</td>
<td>C</td>
<td>0 (a)</td>
</tr>
<tr>
<td>3</td>
<td>7.0</td>
<td>2079</td>
<td>2075</td>
<td>2077</td>
<td>2032</td>
<td>C</td>
<td>0 (a)</td>
</tr>
<tr>
<td>4</td>
<td>5.0</td>
<td>1819</td>
<td>1816</td>
<td>1818</td>
<td>1479</td>
<td>P</td>
<td>0 (a)</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>1814</td>
<td>1810</td>
<td>1812</td>
<td>1765</td>
<td>P</td>
<td>0 (a)</td>
</tr>
<tr>
<td>6</td>
<td>6.5</td>
<td>1977</td>
<td>1973</td>
<td>1975</td>
<td>1924</td>
<td>P</td>
<td>0 (a)</td>
</tr>
<tr>
<td>7</td>
<td>6.9</td>
<td>1989</td>
<td>1984</td>
<td>1986</td>
<td>1934</td>
<td>P</td>
<td>0 (b)</td>
</tr>
<tr>
<td>8</td>
<td>7.2</td>
<td>2131</td>
<td>2126</td>
<td>2128</td>
<td>2073</td>
<td>C</td>
<td>0 (b)</td>
</tr>
<tr>
<td>9</td>
<td>7.0</td>
<td>2068</td>
<td>2062</td>
<td>2065</td>
<td>2011</td>
<td>P</td>
<td>0 (b)</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>2103</td>
<td>2099</td>
<td>2101</td>
<td>2046</td>
<td>C</td>
<td>0 (b)</td>
</tr>
<tr>
<td>11</td>
<td>6.9</td>
<td>2073</td>
<td>2068</td>
<td>2070</td>
<td>2016</td>
<td>P</td>
<td>0 (b)</td>
</tr>
<tr>
<td>12</td>
<td>7.0</td>
<td>2071</td>
<td>2067</td>
<td>2069</td>
<td>2015</td>
<td>P</td>
<td>0 (b)</td>
</tr>
</tbody>
</table>

### Remarks
- **Remarks:** All values out of tolerance must be clearly marked, product tagged for disposition and contained.
- **Shots Included Partial:** 3  
  **Shots Included Complete:** 3

**V50:** 2031  
**High Partial:** 2016  
**Low Complete:** 2023  
**Range:** 128  
**Range Of Results:** 62  
**Range Of Mixed Results:** 7

---

All values out of tolerance must be clearly marked, product tagged for disposition and contained.

---

Page 1 of 1  
4-27-2009
<table>
<thead>
<tr>
<th>Date Received:</th>
<th>Job No: 100727.07.CAW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Courier:</td>
<td>Test Date: 7/27/2010</td>
</tr>
<tr>
<td>Comp File:</td>
<td></td>
</tr>
<tr>
<td>Description 1:</td>
<td>Client:</td>
</tr>
<tr>
<td>Description 2:</td>
<td>Report No:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample No:</th>
<th>SEE REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer:</td>
<td>COMPOSITE ONE</td>
</tr>
<tr>
<td>Part No:</td>
<td>ZVY/EX</td>
</tr>
<tr>
<td>Size:</td>
<td>12” X 12”</td>
</tr>
<tr>
<td>Batch No:</td>
<td></td>
</tr>
<tr>
<td>Manufacture Date:</td>
<td></td>
</tr>
<tr>
<td>Weight:</td>
<td>SEE REMARKS</td>
</tr>
<tr>
<td>Avg Thickness:</td>
<td>SEE REMARKS</td>
</tr>
<tr>
<td>Caliber:</td>
<td>.36 cal FSP</td>
</tr>
<tr>
<td>Projectile Weight:</td>
<td>44g</td>
</tr>
<tr>
<td>Barrel Serial No:</td>
<td>7.62 x 39</td>
</tr>
<tr>
<td>Barrel Length:</td>
<td>16.5&quot;</td>
</tr>
<tr>
<td>Twist Range:</td>
<td>1.946</td>
</tr>
<tr>
<td>Specification:</td>
<td>MIL-STD-662F</td>
</tr>
<tr>
<td>Powder:</td>
<td>Accurate No.2</td>
</tr>
<tr>
<td>Temperature:</td>
<td>69.8</td>
</tr>
<tr>
<td>Witness Material:</td>
<td>2024 T3</td>
</tr>
<tr>
<td>Relative Humidity:</td>
<td>64%</td>
</tr>
<tr>
<td>Distance To Target:</td>
<td>16.4’</td>
</tr>
<tr>
<td>Conditioning:</td>
<td>AMBIENT</td>
</tr>
<tr>
<td>Visual Examination:</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Round</th>
<th>Powder</th>
<th>Striking Velocity 1</th>
<th>Striking Velocity 2</th>
<th>Avg Striking Velocity</th>
<th>Striking Velocity</th>
<th>Observation PC</th>
<th>Included</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.1</td>
<td>2092</td>
<td>2088</td>
<td>2090</td>
<td>2036</td>
<td>C</td>
<td>✓</td>
<td>(a)</td>
</tr>
<tr>
<td>2</td>
<td>6.9</td>
<td>2053</td>
<td>2048</td>
<td>2050</td>
<td>1987</td>
<td>P</td>
<td>✓</td>
<td>(a)</td>
</tr>
<tr>
<td>3</td>
<td>7.6</td>
<td>2088</td>
<td>2084</td>
<td>2086</td>
<td>2032</td>
<td>C</td>
<td>✓</td>
<td>(a)</td>
</tr>
<tr>
<td>5</td>
<td>6.9</td>
<td>2024</td>
<td>2020</td>
<td>2022</td>
<td>1989</td>
<td>P</td>
<td>✓</td>
<td>(a)</td>
</tr>
<tr>
<td>6</td>
<td>7.2</td>
<td>2131</td>
<td>2126</td>
<td>2128</td>
<td>2073</td>
<td>C</td>
<td>✓</td>
<td>(a)</td>
</tr>
</tbody>
</table>

Remarks:

- Shots Included Partial: 3
- Shots Included Complete: 3
- V50: 2010
- High Partial: 1998
- Low Complete: 2032
- Req Range: 128
- Range Of Results: 122
- Range Of Mixed Results: 35

All values out of tolerance must be clearly marked, product tagged for disposition and contained.
### High Com Test Report – 3/04/2010 Shoot

**Date Received:**

**Courier:**

**Comp File:**

**Description 1:** HJ1 CRTL S3

**Description 2:** 8 PLY

**Sample No:** HJ1 CRTL S3

**Manufacturer:** COMPOSITE ONE

**Part No:** ZEON

**Size:** 18” x 18”

**Batch No:**

**Manufacture Date:**

**Weight:** 1664g

**Avg Thickness:** .98"

**Temperature:** 63.5

**Relative Humidity:** 32%

**Conditioning:** AMBIENT

**Caliber:** 22 cal FSP

**Projectile Weight:** 17gr

**Barrel Serial No:** 6.56 x 46

**Barrel Length:** 25"

**Twist Range:** 1-7

**Specification:** MIL-STD-602F

**Powder:** Accurate No.2

**Muzzle To Range:** 16.4’

**No Of Screens:** 4

**Screen Spacing:** 6’

**MidPoint To Target:** 6.56

**Witness Material:** 2024 T3

**Distance To Target:** 16.4’

**Gunner:** GRiffin

**Inspector:** WRIGHT

<table>
<thead>
<tr>
<th>Round</th>
<th>Powder</th>
<th>Striking Velocity 1</th>
<th>Striking Velocity 2</th>
<th>Avg Striking Velocity</th>
<th>Striking Velocity 50</th>
<th>Observation PC</th>
<th>Included</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.9</td>
<td>1152</td>
<td>1159</td>
<td>1151</td>
<td>1127</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.8</td>
<td>10.48</td>
<td>1045</td>
<td>1046</td>
<td>1034</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.9</td>
<td>984</td>
<td>982</td>
<td>983</td>
<td>963</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.1</td>
<td>1224</td>
<td>1221</td>
<td>1222</td>
<td>1197</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2.0</td>
<td>1061</td>
<td>1059</td>
<td>1060</td>
<td>1038</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2.1</td>
<td>1135</td>
<td>1134</td>
<td>1134</td>
<td>1110</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2.0</td>
<td>1026</td>
<td>1024</td>
<td>1025</td>
<td>1004</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2.1</td>
<td>957</td>
<td>955</td>
<td>956</td>
<td>936</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2.2</td>
<td>1190</td>
<td>1188</td>
<td>1189</td>
<td>1184</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2.0</td>
<td>1166</td>
<td>1166</td>
<td>1166</td>
<td>1142</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>2.0</td>
<td>1023</td>
<td>1020</td>
<td>1022</td>
<td>1001</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>2.0</td>
<td>996</td>
<td>994</td>
<td>995</td>
<td>974</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2.1</td>
<td>1131</td>
<td>1130</td>
<td>1130</td>
<td>1106</td>
<td>P</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Remarks:**

**Shots Included Partial:** 3

**Shots Included Complete:** 3

**V50:** 1091

**High Partial:** 1106

**Low Complete:** 1110

**Range Of Results:** 118

**Range Of Mixed Results:**

All values out of tolerance must be clearly marked, product tagged for disposition and contained.

4-27-2009
<table>
<thead>
<tr>
<th>Date Received:</th>
<th>Job No: 100304.07.BRV.A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date: 3/4/2010</td>
<td>Test Date: 3/4/2010</td>
</tr>
<tr>
<td>Client:</td>
<td>Report No:</td>
</tr>
</tbody>
</table>

**Sample Description:**
1. HJ1 CRTL PPR C1
2. 4 PLY, 1 PLY CARBON NANO TUBE PAPER

**Sample No:** A, C1, 1 PLY CNT PAPER

**Manufacturer:** COMPOSITE ONE

**Caliber:** 22 cal FSP

**Muzzle To Range:** 16.4'

**Part No:** ZEON

**Projectile Weight:** 17.3gr

**No Of Screens:** 4

**Size:** 18’’ x 18’’

**Screen Spacing:** 5'

**Batch No:**
- **Barrel Serial No:** 5.56 x 45
- **Barrel Length:** 25’’
- **MidPoint To Target:** 6.56

**Manufacture Date:**
- **Twist Range:** 1.7
- **Weight:** 970g
- **Specification:** MIL-STD-662F
- **Avg Thickness:** .101’’
- **Powder:** Accurate No.2

**Temperature:** 64.4

**Witness Material:** 2024 T3

**Inspector:** WRIGHT

**Relative Humidity:** 32%

**Distance To Target:** 16.4’’

**Gunner:** GRIFFIN

**Conditioning:** AMBIENT

**Visual Examination:**

<table>
<thead>
<tr>
<th>Round</th>
<th>Powder</th>
<th>Striking Velocity 1</th>
<th>Striking Velocity 2</th>
<th>Striking Velocity 3</th>
<th>Observed PC Included</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.0</td>
<td>922</td>
<td>920</td>
<td>921</td>
<td>902</td>
<td>P</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>1212</td>
<td>1209</td>
<td>1210</td>
<td>1185</td>
<td>C</td>
</tr>
<tr>
<td>3</td>
<td>2.2</td>
<td>1217</td>
<td>1214</td>
<td>1216</td>
<td>1191</td>
<td>C</td>
</tr>
<tr>
<td>4</td>
<td>2.2</td>
<td>1217</td>
<td>1214</td>
<td>1216</td>
<td>1191</td>
<td>C</td>
</tr>
<tr>
<td>5</td>
<td>2.3</td>
<td>1423</td>
<td>1427</td>
<td>1429</td>
<td>1399</td>
<td>C</td>
</tr>
<tr>
<td>6</td>
<td>2.3</td>
<td>1156</td>
<td>1154</td>
<td>1156</td>
<td>1131</td>
<td>C</td>
</tr>
<tr>
<td>7</td>
<td>2.2</td>
<td>1048</td>
<td>1046</td>
<td>1047</td>
<td>1025</td>
<td>P</td>
</tr>
<tr>
<td>8</td>
<td>2.3</td>
<td>1329</td>
<td>1327</td>
<td>1328</td>
<td>1300</td>
<td>C</td>
</tr>
<tr>
<td>9</td>
<td>2.3</td>
<td>1142</td>
<td>1141</td>
<td>1142</td>
<td>1118</td>
<td>C</td>
</tr>
<tr>
<td>10</td>
<td>2.2</td>
<td>1065</td>
<td>1062</td>
<td>1064</td>
<td>1042</td>
<td>P</td>
</tr>
<tr>
<td>11</td>
<td>2.3</td>
<td>1326</td>
<td>1323</td>
<td>1324</td>
<td>1296</td>
<td>C</td>
</tr>
<tr>
<td>12</td>
<td>2.2</td>
<td>1154</td>
<td>1152</td>
<td>1153</td>
<td>1129</td>
<td>C</td>
</tr>
<tr>
<td>13</td>
<td>2.1</td>
<td>1130</td>
<td>1129</td>
<td>1130</td>
<td>1106</td>
<td>C</td>
</tr>
<tr>
<td>14</td>
<td>2.0</td>
<td>1243</td>
<td>1239</td>
<td>1241</td>
<td>1215</td>
<td>C</td>
</tr>
<tr>
<td>15</td>
<td>2.0</td>
<td>1156</td>
<td>1154</td>
<td>1155</td>
<td>1131</td>
<td>C</td>
</tr>
<tr>
<td>16</td>
<td>1.9</td>
<td>1008</td>
<td>1006</td>
<td>1006</td>
<td>1044</td>
<td>P</td>
</tr>
</tbody>
</table>

All values out of tolerance must be clearly marked, product tagged for disposition and contained.

4-27-2009
**Date Received:**

**Job No:** 100304.07.BRV.B

**Courier:**

**Test Date:** 3/4/2010

**Comp File:**

**Client:**

**Report No:**

---

**Sample No:** B, C1 2 PLY CNT PAPER

**Description 1:** HJ1 CRTL PPR C1

**Description 2:** 4 PLY, 2 PLY CARBON NANO TUBE PAPER

---

**Manufacturer:** COMPOSITE ONE

**Caliber:** 22 cal FSP

**Muzzle To Range:** 16.4'

**Part No:** ZEON

**Projectile Weight:** 17gr

**No Of Screens:** 4

**Size:** 18" x 18"

**Barrel Serial No:** 5.56 x 45

**Screen Spacing:** 5'

**Batch No:**

**Barrel Length:** 25"

**MidPoint To Target:** 6.56

**Manufacture Date:**

**Weight:** 970g

**Specification:** MIL-STD-662F

**Avg Thickness:** .101"

**Powder:** Accurate No.2

**Temperature:** 62.6

**Witness Material:** 2024 T3

**Gunner:** GRIFFIN

**Relative Humidity:** 32%

**Distance To Target:** 16.4'

**Inspector:** WRIGHT

**Conditioning:** AMBIENT

**Visual Examination:**

---

**Round**

<table>
<thead>
<tr>
<th>Powder</th>
<th>Striking Velocity 1</th>
<th>Striking Velocity 2</th>
<th>Avg Striking Velocity</th>
<th>Striking Velocity</th>
<th>Observation PC</th>
<th>Included</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2.0</td>
<td>931</td>
<td>929</td>
<td>930</td>
<td>911</td>
<td>P</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>2 2.2</td>
<td>1279</td>
<td>1275</td>
<td>1277</td>
<td>1260</td>
<td>C</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>3 2.1</td>
<td>1165</td>
<td>1165</td>
<td>1165</td>
<td>1141</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 2.0</td>
<td>1140</td>
<td>1138</td>
<td>1139</td>
<td>1115</td>
<td>C</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>5 1.9</td>
<td>1045</td>
<td>1042</td>
<td>1044</td>
<td>1022</td>
<td>P</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>6 2.0</td>
<td>1060</td>
<td>1058</td>
<td>1059</td>
<td>1037</td>
<td>C</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>7 1.9</td>
<td>1015</td>
<td>1012</td>
<td>1014</td>
<td>993</td>
<td>P</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>8 2.0</td>
<td>972</td>
<td>970</td>
<td>971</td>
<td>951</td>
<td>P</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

**Remarks:** PREVIOUSLY SHOT WITH 22 cal FSP, SEE JOB# 100304.07.BRV.A, 100304.07.BRV.C

**Shots Included Partial:** 2

**Shots Included Complete:** 2

**Remarks:**

**V50:** 1042

**High Partial:** 1022

**Low Complete:** 1037

**Req Range:** 125

**Range Of Results:** 122

**Range Of Mixed Results:** 0

---

**All values out of tolerance must be clearly marked, product tagged for disposition and contained.**

---

**Page 1 of 1**

---

**4-27-2009**
**Date Received:**

**Job No.:** 100304.07.BRV.C

**Courier:**

**Test Date:** 3/4/2010

**Comp File:**

**Client:**

**Description 1:** HJ1 CRTL PPR C1

**Report No.:**

**Description 2:** 4 PLY, 4 PLY CARBON NANO TUBE PAPER

**Sample No.:** C, CT CNT PAPER

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Caliber</th>
<th>Muzzle To Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPOSITE ONE</td>
<td>22 cal FSP</td>
<td>16.4'</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Projectile Weight</th>
<th>No Of Screens</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEON</td>
<td>17 gr</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Size:</th>
<th>Barrel Serial No:</th>
</tr>
</thead>
<tbody>
<tr>
<td>18&quot; x 18&quot;</td>
<td>5.56 x 45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Batch No.</th>
<th>Barrel Length:</th>
<th>Screen Spacing:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25&quot;</td>
<td>5'</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manufacture Date:</th>
<th>Twist Range:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weight:</th>
<th>Specification:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MIL-STD-662F</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Avg Thickness:</th>
<th>Powder:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accurate No.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature:</th>
<th>Witness Material:</th>
<th>Gunner:</th>
</tr>
</thead>
<tbody>
<tr>
<td>62.6</td>
<td>2024 T3</td>
<td>GRIFFIN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative Humidity:</th>
<th>Distance To Target:</th>
<th>Inspector:</th>
</tr>
</thead>
<tbody>
<tr>
<td>32%</td>
<td>16.4'</td>
<td>WRIGHT</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conditioning:</th>
<th>Visual Examination:</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMBIENT</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Round</th>
<th>Powder</th>
<th>Striking Velocity 1</th>
<th>Striking Velocity 2</th>
<th>Avg Striking Velocity</th>
<th>Striking Velocity</th>
<th>Observation PC</th>
<th>Included</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.4</td>
<td>1204</td>
<td>1201</td>
<td>1202</td>
<td>1177</td>
<td>C</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>1013</td>
<td>1011</td>
<td>1012</td>
<td>981</td>
<td>P</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

**Remarks:** PREVIOUSLY SHOT WITH 22 cal FSP, SEE JOB# 100304.07.BRV.A

**Shots Included Partial:**

<table>
<thead>
<tr>
<th>V50:</th>
<th>High Partial:</th>
<th>Low Complete:</th>
<th>Req Range:</th>
<th>Range Of Results:</th>
<th>Range Of Mixed Results:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1084</td>
<td>992</td>
<td>1177</td>
<td>125</td>
<td>106</td>
<td>0</td>
</tr>
</tbody>
</table>

**Shots Included Complete:**

PREVIOUSLY SHOT WITH 22 cal FSP, SEE JOB# 100304.07.BRV.A

All values out of tolerance must be clearly marked, product tagged for disposition and contained.
4.16 Raman Fitted Peak Data for Baseline-1,611 cm\(^{-1}\) Band–4/16/13 Shoot

![Fitted Spectrum, Baseline Removed](image)

1,611 cm\(^{-1}\) Band Raman Data Baseline Point 1
**1,611 cm\(^{-1}\) Band Raman Data Baseline Point 2**
Fitted Spectrum, Baseline Removed

1,611 cm\(^{-1}\) Band Raman Data Baseline Point 3
1,611 cm⁻¹ Band Raman Data Baseline Point 4
1,611 cm\(^{-1}\) Band Raman Data Baseline Point 5
1,611 cm$^{-1}$ Band Raman Data Baseline Point 6
1,611 cm\(^{-1}\) Band Raman Data Baseline Point 7
1,611 cm⁻¹ Band Raman Data Baseline Point 8
1,611 cm$^{-1}$ Band Raman Data Baseline Point 9
1,611 cm$^{-1}$ Band Raman Data Baseline Point 10
1,611 cm\(^{-1}\) Band Raman Data Baseline Point 11
1,611 cm$^{-1}$ Band Raman Data Baseline Point 12
1,611 cm\(^{-1}\) Band Raman Data Baseline Point 13
1,611 cm$^{-1}$ Band Raman Data Baseline Point 14
1,611 cm\(^{-1}\) Band Raman Data Baseline Point 15
Fitted Spectrum, Baseline Removed

1,611 cm\(^{-1}\) Band Raman Data Baseline Point 16
Fitted Spectrum, Baseline Removed

1,611 cm⁻¹ Band Raman Data Baseline Point 17
1,611 cm$^{-1}$ Band Raman Data Baseline Point 18
1,611 cm\(^{-1}\) Band Raman Data Baseline Point 19
1,611 cm$^{-1}$ Band Raman Data Baseline Point 20
1,611 cm$^{-1}$ Band Raman Data Baseline Point 21
1,611 cm$^{-1}$ Band Raman Data Baseline Point 22
Fitted Spectrum, Baseline Removed

1,611 cm\(^{-1}\) Band Raman Data Baseline Point 23
1,611 cm$^{-1}$ Band Raman Data Baseline Point 24
1,611 cm\(^{-1}\) Band Raman Data Baseline Point 25
1,611 cm$^{-1}$ Band Raman Data Baseline Point 26
1,611 cm⁻¹ Band Raman Data Baseline Point 27
1,611 cm$^{-1}$ Band Raman Data Baseline Point 28
1,611 cm\(^{-1}\) Band Raman Data Baseline Point 29
1,611 cm\(^{-1}\) Band Raman Data Baseline Point 30
$1,611 \text{ cm}^{-1}$ Band Raman Data Baseline Point 31
1,611 cm\(^{-1}\) Band Raman Data Baseline Point 32
1,611 cm$^{-1}$ Band Raman Data Baseline Point 33
1,611 cm\(^{-1}\) Band Raman Data Baseline Point 34
1,611 cm$^{-1}$ Band Raman Data Baseline Point 35
Fitted Spectrum, Baseline Removed

1,611 cm\(^{-1}\) Band Raman Data Baseline Point 36
4.17 Raman Fitted Peak Data for CNT 1-1 - 1,611 cm\(^{-1}\) Band – 4/16/13 Shoot

1,611 cm\(^{-1}\) Band Raman Data CNT 1-1 Point 1
1,611 cm\(^{-1}\) Band Raman Data CNT 1-1 Point 2
1,611 cm\(^{-1}\) Band Raman Data CNT 1-1 Point 3
1,611 cm$^{-1}$ Band Raman Data CNT 1-1 Point 4
1,611 cm⁻¹ Band Raman Data CNT 1-1 Point 5
$1,611 \text{ cm}^{-1}$ Band Raman Data CNT 1-1 Point 6
$1,611 \text{ cm}^{-1}$ Band Raman Data CNT 1-1 Point 7
Fitted Spectrum, Baseline Removed

1,611 cm\(^{-1}\) Band Raman Data CNT 1-1 Point 8
4.18 Raman Fitted Peak Data for CSR 1-1 - 1,611 cm\(^{-1}\) Band – 4/16/13 Shoot

1,611 cm\(^{-1}\) Band Raman Data CSR 1-1 Point 1
1,611 cm⁻¹ Band Raman Data CSR 1-1 Point 2
1,611 cm$^{-1}$ Band Raman Data CSR 1-1 Point 3
1,611 cm\(^{-1}\) Band Raman Data CSR 1-1 Point 4
1,611 cm$^{-1}$ Band Raman Data CSR 1-1 Point 5
$1,611 \text{ cm}^{-1}$ Band Raman Data CSR 1-1 Point 6
1,611 cm\(^{-1}\) Band Raman Data CSR 1-1 Point 7
1,611 cm⁻¹ Band Raman Data CSR 1-1 Point 8
$1,611 \text{ cm}^{-1}$ Band Raman Data CSR 1-1 Point 9
1,611 cm\(^{-1}\) Band Raman Data CSR 1-1 Point 10
Fitted Spectrum, Baseline Removed

1,611 cm⁻¹ Band Raman Data CSR 1-1 Point 11
Fitted Spectrum, Baseline Removed

1,611 cm\(^{-1}\) Band Raman Data CSR 1-1 Point 12
Fitted Spectrum, Baseline Removed

1,611 cm\(^{-1}\) Band Raman Data CSR 1-1 Point 13
Raman Fitted Peak Data for Baseline-1,651 cm\(^{-1}\) Band – 4/16/13 Shoot

Fitted Spectrum, Baseline Removed

1,651 cm\(^{-1}\) Band Raman Data Baseline Point 1
1,651 cm$^{-1}$ Band Raman Data Baseline Point 2
1,651 cm$^{-1}$ Band Raman Data Baseline Point 3
1,651 cm$^{-1}$ Band Raman Data Baseline Point 4
$1,651 \text{ cm}^{-1}$ Band Raman Data Baseline Point 5
1,651 cm$^{-1}$ Band Raman Data Baseline Point 6
1,651 cm$^{-1}$ Band Raman Data Baseline Point 7
Fitted Spectrum, Baseline Removed

1,651 cm$^{-1}$ Band Raman Data Baseline Point 8
1,651 cm$^{-1}$ Band Raman Data Baseline Point 9
1,651 cm\(^{-1}\) Band Raman Data Baseline Point 10
1,651 cm$^{-1}$ Band Raman Data Baseline Point 11
Fitted Spectrum, Baseline Removed

1,651 cm$^{-1}$ Band Raman Data Baseline Point 12
1,651 cm\(^{-1}\) Band Raman Data Baseline Point 13
Fitted Spectrum, Baseline Removed

1,651 cm\(^{-1}\) Band Raman Data Baseline Point 14
1,651 cm$^{-1}$ Band Raman Data Baseline Point 15
1,651 cm\(^{-1}\) Band Raman Data Baseline Point 16
1,651 cm⁻¹ Band Raman Data Baseline Point 17
1,651 cm$^{-1}$ Band Raman Data Baseline Point 18
1,651 cm⁻¹ Band Raman Data Baseline Point 19
Fitted Spectrum, Baseline Removed

1,651 cm$^{-1}$ Band Raman Data Baseline Point 20
Fitted Spectrum, Baseline Removed

1,651 cm\(^{-1}\) Band Raman Data Baseline Point 21
Fitted Spectrum, Baseline Removed

Relative Intensity

Relative Wavenumber

1,651 cm\(^{-1}\) Band Raman Data Baseline Point 22
Fitted Spectrum, Baseline Removed

1,651 cm\(^{-1}\) Band Raman Data Baseline Point 23
Fitted Spectrum, Baseline Removed

1,651 cm$^{-1}$ Band Raman Data Baseline Point 24
1,651 cm\(^{-1}\) Band Raman Data Baseline Point 25
1,651 cm\(^{-1}\) Band Raman Data Baseline Point 26
1,651 cm\(^{-1}\) Band Raman Data Baseline Point 27
1,651 cm$^{-1}$ Band Raman Data Baseline Point 28
1,651 cm$^{-1}$ Band Raman Data Baseline Point 29
1,651 cm\(^{-1}\) Band Raman Data Baseline Point 30
1,651 cm$^{-1}$ Band Raman Data Baseline Point 31
1,651 cm$^{-1}$ Band Raman Data Baseline Point 32
1,651 cm$^{-1}$ Band Raman Data Baseline Point 33
1,651 cm⁻¹ Band Raman Data Baseline Point 34
1,651 cm$^{-1}$ Band Raman Data Baseline Point 35
1,651 cm\(^{-1}\) Band Raman Data Baseline Point 36
4.20 Raman Fitted Peak Data for CNT 1-1 - 1,651 cm\(^{-1}\) Band-4/16/13 Shoot

Fitted Spectrum, Baseline Removed

1,651 cm\(^{-1}\) Band Raman Data CNT 1-1 Point 1
1,651 cm$^{-1}$ Band Raman Data CNT 1-1 Point 2
$1,651 \text{ cm}^{-1}$ Band Raman Data CNT 1-1 Point 3
1,651 cm$^{-1}$ Band Raman Data CNT 1-1 Point 4
225 cm$^{-1}$ Band Raman Data CNT 1-1 Point 5
$1,651 \text{ cm}^{-1}$ Band Raman Data CNT 1-1 Point 6
1,651 cm\(^{-1}\) Band Raman Data CNT 1-1 Point 7
1,651 cm$^{-1}$ Band Raman Data CNT 1-1 Point 8
4.21  Raman Fitted Peak Data for CSR 1-1 – 1,651 cm\(^{-1}\) Band-4/16/13 Shoot

1,651 cm\(^{-1}\) Band Raman Data CSR 1-1 Point 1
1,651 cm$^{-1}$ Band Raman Data CSR 1-1 Point 2
1,651 cm\(^{-1}\) Band Raman Data CSR 1-1 Point 3
$1,651 \text{ cm}^{-1}$ Band Raman Data CSR 1-1 Point 4
1,651 cm$^{-1}$ Band Raman Data CSR 1-1 Point 5
$1,651 \text{ cm}^{-1} \text{ Band Raman Data CSR 1-1 Point 6}$
$1,651 \text{ cm}^{-1}$ Band Raman Data CSR 1-1 Point 7
1,651 cm\(^{-1}\) Band Raman Data CSR 1-1 Point 8
1,651 cm^{-1} Band Raman Data CSR 1-1 Point 9
1,651 cm$^{-1}$ Band Raman Data CSR 1-1 Point 10
1,651 cm$^{-1}$ Band Raman Data CSR 1-1 Point 11
1,651 cm$^{-1}$ Band Raman Data CSR 1-1 Point 12
1,651 cm$^{-1}$ Band Raman Data CSR 1-1 Point 13
REFERENCES


