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REQUIREMENT FOR THE DEGREE OF
BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

# Impact Loading and Recovery of Copper
# 100% Report


**GROUP No. 5**

Devon Barroso
Jorge Barrera
Guillermo Fernandez
Javier Seoane
Ernesto Vallejo

Advisor: Professor Ibrahim Nur Tansel
AFRL Advisor: Dr. Joel House


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## Ethics Statement and Signatures

The work submitted in this B.S. thesis is solely prepared by a team consisting of Devon Barroso, Jorge Barrera, Guillermo Fernandez, Javier Seoane, and Ernesto Vallejo and it is original. Excerpts from others' work have been clearly identified, their work acknowledged within the text and listed in the list of references. All of the engineering drawings, computer programs, formulations, design work, prototype development and testing reported in this document are also original and prepared by the same team of students.

| | | |
|---|---|---|
| Devon Barroso<br>Team Leader | Jorge Barrera<br>Team Member | Guillermo Fernandez<br>Team Member |

| | |
|---|---|
| Javier Seoane<br>Team Member | Ernesto Vallejo<br>Team Leader |

Dr. Ibrahim Nur Tansel
Faculty Advisor

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# Abstract

This work will focus on the research and development of five separate projectiles and targets that will be used to study the effects of impact and dynamic fractures in copper at several stress levels. At high velocity impact conditions, each projectile and target will experience shockwave propagation which will produce spallation if the tension created from the free surfaces' reflection of the shockwaves is greater than the spall strength of the material. The use of a soft recovery system will be implemented to study spallation of copper and the shock loading developed in the target after impact.

Due to the material specification, tolerances, precise surface finishes, and parallelism needed to conduct the experiments, the projectiles and targets will be designed using SolidWorks at Florida International University (FIU); the final design package will be sent to Eglin Air Force Base where it will be fabricated and tested. After the first test series is conducted at Air Force Research Laboratory (AFRL), a full analysis of the projectile/target package will be performed by the AFRL project mentor. The data and possible new requirements will be sent back to FIU in order to procure the next set of engineering drawings and design package. Once the designated team lead has analyzed the data and new constraint criteria's, new modifications will be made to the next projectile and target for the follow on test series. The pressures that the projectile and target will undergo are 1, 1.5, 2, 2.5, 3 GPa after impact. This work abides by AFRL standards and regulations.

# 1. Introduction

## 1.1 Problem Statement

The Air Force Research Laboratory's Munitions Directorate at Eglin Air Force Base (AFB) in Florida conducts research on material properties for use in air-delivered munitions. The Munitions Directorate is home to the High Pressure Particulate Physics Facility (HP3). As the name implies, this facility carries out experiments requiring the testing of high strain rates on materials. One of the methods available at the facility, and the one that this work will focus primarily on, is a 60 mm powder fired cannon used for shock loading experiments. The facility conducts experiments in many areas; the work presented in this thesis will focus on AFRL's ongoing research into the formation of spall. Spallation describes a process of void nucleation and growth that can lead to material failure. While this study focuses on the characterization of copper, the methods that will be developed from the experiments are also applicable to other materials.

The 60 mm gun will be firing projectiles tipped with an impactor plate into a target assembly to generate shock loading. The target assembly will hold the target plate which is surrounded by a momentum trap that protects the edges from deformation. After impact occurs, the target specimen is decelerated in a controlled way, or soft recovered, to prevent further deformation so that postmortem metallurgical analysis can be conducted. [1] A soft catch recovery test has not been conducted before at HP3 and it is the first time a momentum trap is applied. Previous uses of the gun involved a hard catch system. The hard catch experiment has traditionally focused on the first few microseconds of the experiment when the shock waves form in the material. No material is recovered from past shots since all elements are extensively deformed after impacting the hard catch system.

The objective of this project is to design five different target specimens with five corresponding impactors to produce a shock wave and subsequent spallation from the impacts. The soft catch recovery system is used to study the metallurgical effects of shock loading and spallation on the target material. The experiments will focus on the effects of shock loading on copper metal only. Each target and impactor combination must be designed to meet precise impact pressure and pressure wave propagation conditions specified by AFRL. This is to be accomplished by manipulating the projectile speed as well as the impactor's geometry (thickness) and materials (density). The ultimate goal is to find a correlation between the theoretical impact pressures, spallation plane location and pulse duration to the physical results.

## 1.2 Motivation

The AFRL's Munitions Directorate is interested in the study of incipient spall in copper through shock recovery experiments. The project is funded by AFRL and is being monitored by Dr. Joel House. Dr. House is the Branch Chief of the Damage Mechanisms Branch, of the Ordnance Division in the Munitions Directorate, at Eglin AFB.

In order for newer technology to mature, research and development on material response is tested through experiments conducted at the HP3 facility. As dynamic impact takes place, changes in the microstructure of the material occur; obtaining the microstructure change is one of the goals of this study [1]. These microstructure changes are preserved due to a previous FIU team's implementation of a "soft catch" system to recover the material with minimal damage created by any additional loads. The purpose and motivation of this project is to continue the research the soft catch team began and gather data that will help improve the predictive capability of finite element based continuum codes used in the development of air delivered munitions.

## 1.3 Literature Survey

Research into the high strain physics field began with the work of Dr. John Hopkinson and his son Bertram. John was the first to study the relation between the propagation of transient waves and the formation of brittle fractures in a material. His son Bertram was the first to document how shockwaves could induce a fracture in a ductile metal where the reflected wave from the rear surface of the sample collided with the tail of the release wave of the impactor. The phenomenon that he observed, where there occurs the formation of internal damage and cracking, but not complete separation or forming of scabs in the target specimen is called "incipient spall." Spallation is the term used to describe the creation of this internal damage, to the point that complete separation or scabbing of the specimen occurs. [3]

Shock loading experiments are undertaken in order to better understand the physical properties of different materials under exceedingly high strain rates. There are numerous ways in which to achieve the strain rates needed to produce shock loading in a material. The most commonly used experimental methods include explosive loading, gun-launched impactors, exploding foils, or direct radiation impingement. [3]

In order to study shock loading physics, understanding specific material behavior and how they react given certain parameters is essential. Shock loading physics is a specialized field of material engineering requiring a unique set of experimental and numerical capabilities. Shock loading deals with microstructural properties, but experimentally the parameters are macroscopic. Macroscopic parameters include the impact velocity, shock pressure, and surface spall velocity. [4] Since copper spallation is the main focal point of this research, this project will use known copper properties under shock loading conditions. Obtaining copper's properties the necessary geometry characteristics of the components can be defined (i.e. thickness, diameter) and the impactors' material can be selected in order to satisfy the experimental criteria.

In another aspect, spallation is dependent on the loading history as well as the loading rate of the material; changing these properties will change the result. [5] Once spallation occurs, there are certain properties that are obtained through shock loading testing; these properties include the strain rate ($\varepsilon$), the spall strength ($\sigma_{sp}$) and the temperature in the particular spallation area. [5] The only value obtained from the impact between the impactor and target is the particle velocity on the free surface ($u_{rs}(t)$). By using the acoustic method [7], the strain rate and spall strength can be found through the particle velocity recorded. [6] A way to define spall strength as a solid experiencing an elastic-plastic transition is through an equation that has been developed by G.I. Kanel and is expressed as:

$$\sigma_{sp} = \frac{1}{2}\rho_0 c_b(\Delta u_{fs} + \delta) \qquad \textbf{Equation 1}$$

where,

$$\begin{cases} \Delta u_{fs} = Pullback\ Velocity \\ \rho_0 = Initial\ Density \\ c_b = Bulk\ Sound\ Speed \end{cases}$$

The value of **δ** is merely a correction term for profile distortion, which can be defined from the plastic and elastic wave velocities, release and recompression waves, or as the spall layer thickness. [4] Despite **δ** is used in some applications to calculate the spall strength of copper, it cannot be used in all instance. In the case of this research, the formation of mobile stacking multidirectional spallation planes could cause problems in finding the elastic and plastic waves. [4] Several experiments have shown that pre-spall damage, spall damage, and spall strength are related to compression-tension-loading-pulse properties. [3]

The 60 mm gun at the HP3 facility qualifies as a gun-launched impactor and will be the method of shock delivery in this project. The gun's barrel has a diameter of 60 mm and a length of 13.7 m. The barrel is smooth as there is no need for the projectile to have a stable flight after leaving the barrel. The last 0.75 m of the barrel penetrate into the catch chamber and the very tip sits in close proximity to the target assembly. Such setup ensures that there is no space for the flight path of the impactor to be altered before coming in contact with the target assembly. The target assembly ensures proper positioning of the target up until the point of impact, after which the target specimen can be soft recovered. [1]

This work will aim to produce incipient spall in the target specimen while avoiding complete spallation. To achieve this goal, a single shockwave needs to be produced in the target specimen whose relieve wave magnitude can achieve incipient spall, but not cause complete spallation. For this reason, the first configuration will be shot at the lowest possible velocity the gun can achieve. Gradual increase of shot velocity will be adjusted to achieve the required impact pressures up until complete spallation is expected to occur.

One of the possible, readily available impactor materials is PMMA. PMMA, or Poly(methyl methacrylate), is the most common acrylic plastic. It is more commonly known by the brand names it is sold as, Plexiglas. PMMA is a tough, highly transparent material that can be molded, cut, drilled and formed. These properties make it ideal for applications where transparency is required but impact must be sustained. This impact resistance and toughness are apparent in applications such as airplane windshields or the roof of the Houston Astrodome, which is made up of hundreds of panels of PMMA. [8]

The interest in PMMA stems from the possible need for lower pressure impacts on copper. Since the spall strength of copper is located in the region of 2.6 GPa, a copper on copper impact at the minimum speed of the HP3 gun may generate pressures that are too high. Pressures over this threshold are likely to cause severe spallation of the target specimen. In order to achieve incipient spall, lower pressure impacts must be achieved without lowering the impact speed, as the gun cannot reliably fire below a specific speed. In this situation, a change in the material of the impactor can be used to change the impact pressure. Lower density materials will lower the impact pressure. While aluminum can also be considered for this purpose, PMMA is both economical to obtain and easier to machine than aluminum. PMMA has an average measured density of 1.183 g/cc which should allow for impact pressures covering the whole spall range of copper.

The properties of PMMA that will be of relevance to this work include the effects of strain rate in compression, tension, fracture and size. PMMA comes in various forms, but this project will be focusing on the use of sheets. PMMA exhibits a Hugoniot elastic limit of around 0.7 GPa; this means that impacts above this pressure will result in permanent deformation of the material. A meeting of the shock and release waves above this pressure within the material would indeed cause spall, but because the focus of this work is the study of copper, this situation will be neglected for PMMA. [9]

If any spall were to occur in a PMMA impactor, it would be immediately apparent. Unlike the case of metals, it would not require sectioning and preparation to discover the presence of spall. The damage could be observed using transmitted light on the clear acrylic. Spall in PMMA occurs differently than in metals, with the appearance of “penny-like” cracks rather than small voids. [10]

The Hugoniot curve of PMMA has been calculated using plate impact experiments performed in the past. The following figure shows these results [10]:

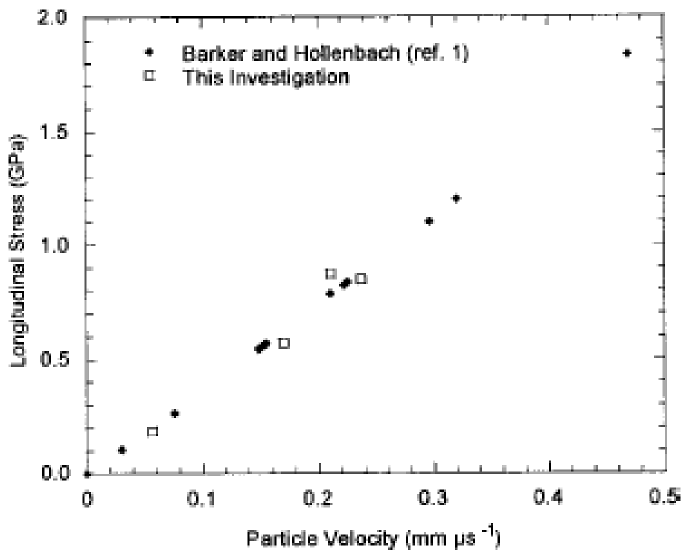


**Figure 1: Hugoniot of PMMA (stress-particle velocity) [10]**

## 1.4 Discussion

Initially, a copper-on-copper projectile target package was the desired combination, but the impact pressure was too high at minimum velocity; therefore, other materials had to be researched to satisfy the pressure criteria. After extensive research, the chosen material for the impactor on the first set of shots was Poly(methyl methacrylate) (PMMA).

PMMA has desirable properties that will allow for this project's success. There has been prior research performed on PMMA such as wave propagation and spall fracture, a subject relevant for this project since the design of some components can be affected by the wave propagation of PMMA. As for general details regarding the target and projectile, they are described as follows:

# TARGET ASSEMBLY

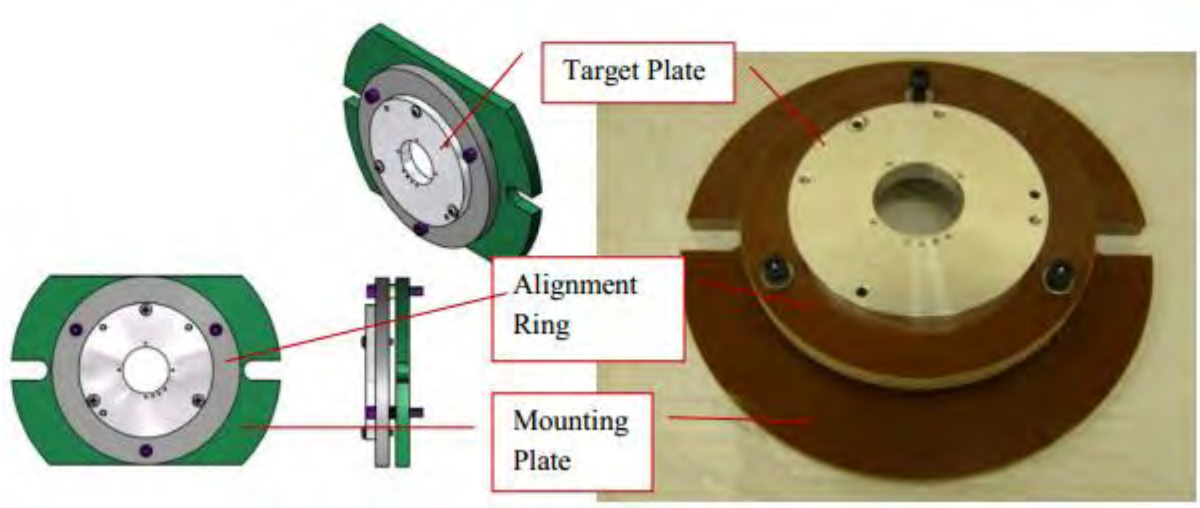


**Figure 2: Target Assembly Courtesy of AFRL, Munitions Directorate [1]**

## Alignment Ring or Phenolic Ring

The dimensions of the phenolic ring will be constant and its material will stay unchanged. The purpose of this ring is to hold the target in place upon impact. The phenolic ring will be destroyed upon impact.

## Mounting Plate or Target Ring

The target ring will have constant dimensions and it will be made of aluminum for all experiments. The purpose for the target ring is to hold the momentum trap in place for impact. This target ring will be destroyed upon impact.

## TARGET

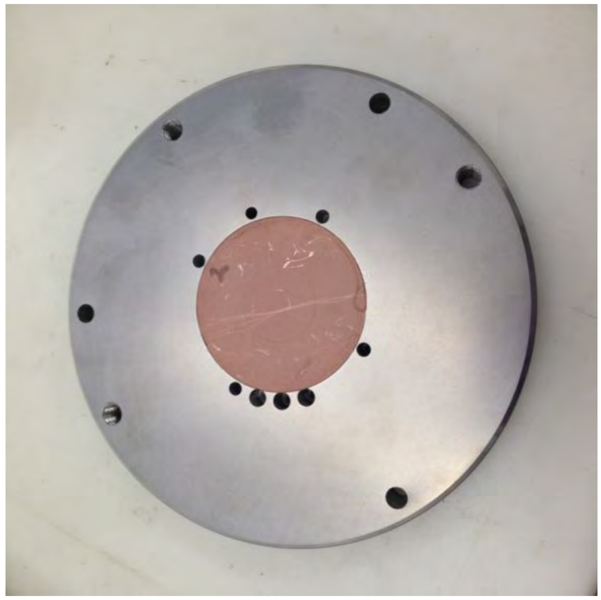

**Figure 3: Target and Alignment Ring**

The target is formed by two components, a momentum trap (Figure 4) and target plate (Figure 5). The target plate will be analyzed by the AFRL mentor. The momentum trap is made of copper with an outer diameter of 46 mm (1.810 in). The momentum trap is used to capture the release wave from impact and prevent any further changes to the microstructure of the sample. The inner disk material, or target plate, and design will be dependent on the researched performed by the members of the senior design team.

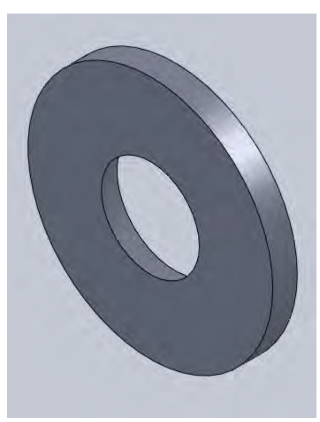

**Figure 4: Momentum Trap**

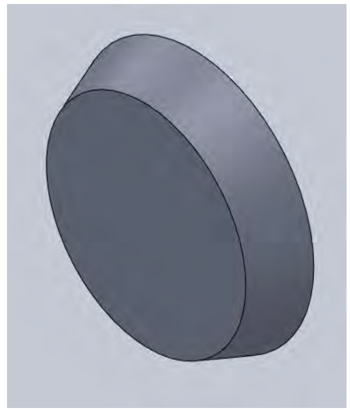

**Figure 5: Target Plate**

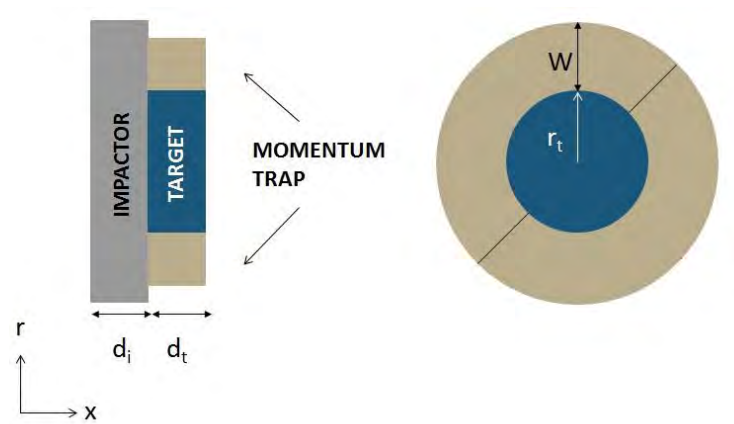


**Figure 6: Target Package**

## PROJECTILE

The portion of the projectile that will be designed by the members of the senior design group will be the impactor tip. The tip of the projectile is a disk which will be made from the chosen material. The dimensions will be dependent on the calculations and physical properties of each material proposed. As for the first projectile package, the team chose Poly(methyl methacrylate). Depending on the results of the tests, the team may or may not choose the same material for remaining tests. In order to facilitate the experiments, impactor dimensions were modified to meet HP3's most available projectile for the gun.

# 2. Project Formulation

## 2.1 Overview

Weekly conference calls with the AFRL mentor were scheduled once the senior design team was established. These meetings provided more in depth details on what the constraints of the design problems were and provided a better understanding of the physics and engineering design applied. Besides, during the first semester of senior design, a trip to Eglin Air Force Base was organized in order to meet the AFRL mentor and further understand the background and visualize the physical architecture of the HP3 gun and how it is set up. The physics and mathematics behind this project will be discussed in section 6, as well as further detail regarding the facilities that make this project possible.

## 2.2 Project Objectives

The objective of this project is to design five different target specimens with five corresponding impactors to study the spallation effects on copper. The experiments will focus on obtaining incipient spallation and void nucleation inside the target in order to characterize the effects of shock loading on copper. Each target and impactor combination must be designed to meet specific impact pressure and pressure wave propagation conditions specified by AFRL. The ultimate goal is to find a correlation between the predicted effects of impact and the experimental results. Application of a momentum trap will also be researched since this is the first time AFRL will use such a component in the target assembly. As research is being conducted, the slightest adjustment in the diameter of the impactor plate, in the millimeter range can change the pulse duration and spall plane location inside the target plate. As the different shots are being conducted, depending on the results of each, the material or diameter may change to satisfy the different parameters required (i.e. impact pressure, spall plane location, pulse duration).

## 2.3 Design Specifications

For the project, the following design specifications will be considered:

- Impact pressure range: 1.0 GPa - 3 GPa (increment of 0.5 GPa)
- Pulse duration: $t \approx 2.0$ μs
- Minimum momentum trap outer diameter: 46 mm (1.810 in)
- Minimum impactor diameter: 55 mm (2.165 in)

# 3. Engineering Design and Analysis

## 3.1 Kinematic Analysis

**Table 1: Nomenclature**

| Nomenclature | |
|---|---|
| **Symbol** | **Description** |
| $\rho$ | Density |
| $C_o$ | Bulk sound speed |
| s | Hugoniot slope |
| **Superscripts** | |
| T | Target |
| I | Impactor |
| **Subscripts** | |
| p | Pressure or particle |
| 0 | Initial |
| s | Shockwave |
| r | Release wave |

Wave propagation theory is a process in dynamic deformation that states that stress has to travel through a non-rigid body following specific laws. Simply put, when impact occurs, a stress wave is created. On one side of such wave the particles experience stress for the duration of the wave, while the particles on the other side have not felt the effect of the wave. [3] These waves are called shock waves and are measured using the Rankine-Hugoniot equation and equation of state, which will be later discussed. [3] The two main types of waves that occur most commonly are longitudinal and shear waves (transverse). For longitudinal waves, the oscillations happen in the direction of wave propagation, whereas in the shear wave, they occur at a right angle of the wave direction. [3] Several experiments are aimed at studying wave propagation, which include the Taylor test, Hopkinson split-bar test, and the pressure-shear test among others. [3]

As stated before, through impact stress shock waves are created, followed by release waves. The ideal goal of the project is to have the release waves of the impactor and the target intersects in the target to analyze the spallation in the material. To be able to do this, first a material must be selected for the projectile. Since AFRL is interested in copper, the target for every experiment will be made from copper. The equations used for analysis to find the normal shock wave relations are as follows:

$$\rho_0(u_s - u_0) = \rho(u_s - u) \qquad \textbf{Equation 2}$$

$$p - p_0 = \rho_0(u - u_0)(u_s - u_0) \qquad \textbf{Equation 3}$$

$$e - e_0 = \frac{1}{2}(p + p_0)\left(\frac{1}{\rho_0} - \frac{1}{\rho}\right) \qquad \textbf{Equation 4}$$

Where $u_0$ is the absolute initial velocity, p is pressure and the unknown is u, which is the local particle velocity at impact. From here, after finding the velocity at impact, the local particle velocity of the target and the projectile can be determined using the following equations:

$$u_p^T = u \qquad \textbf{Equation 5}$$

$$u_p^I = u_0 - u \qquad \textbf{Equation 6}$$

The particle velocity in the target is the derived from local particle velocity produced by impact. The particle velocity of the impactor is the absolute initial velocity minus the local particle velocity produced by impact.

The velocity at impact in Equation 2 can be used to find the pressure at impact. To determine if there is spallation, the pressure calculated must not exceed the spall strength of the material. If the pressure does exceed the material spall strength, then there will be no spallation and impactor thickness, initial velocity, or material must be changed. If the spall strength does exceed the pressure calculated, then the shock velocity can be found to find the spall plane location. Using the local particle velocity at impact for both target and impactor, the Shock Hugoniot equation of state can be applied (Equation 7, 8). [2]

$$u_s^T = c_0^T + s^T u_p^T$$ **Equation 7**

$$u_s^I = c_0^I + s^I u_p^I$$ **Equation 8**

## 3.2 Wave Analysis

When the shock compression wave, solid black line, reflects off the free surface of the material it is now a release wave in tension, dashed line (Figure 7). This wave is created in both projectile and target and their intersection will create a strong tensile pulse in the material, which is shown in the Figure 3. If the magnitude of the pulse is sufficiently high the material will undergo the nucleation of voids, and the possibility of the voids linking up to form a spall plane in the material.

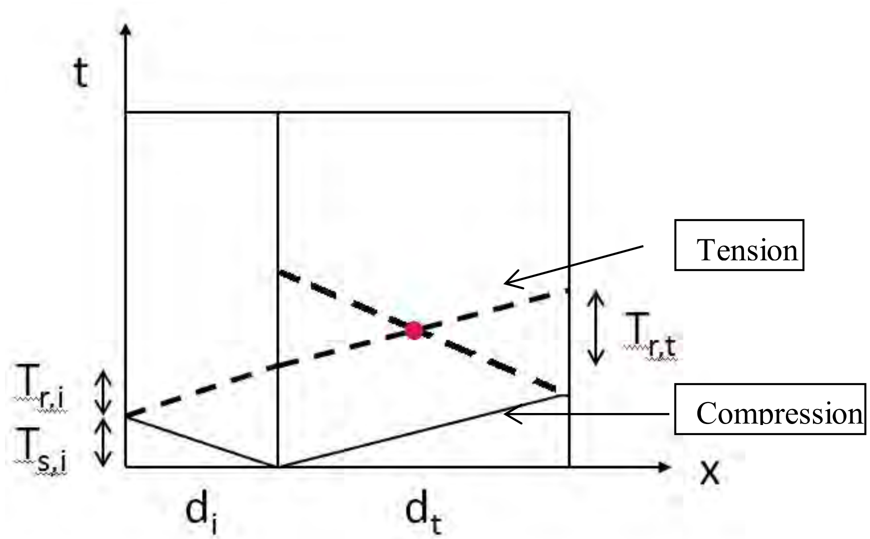


**Figure 7: x-t Diagram**

For the purpose of the experiments to calculate the release waves, the bulk sound speed at the impact pressure needs to be calculated using the following equations:

$$C_{0,p}^T = C_0^T + 2s^T u_p^T$$ **Equation 9**

$$C_{0,p}^{I} = C_{0}^{I} + 2s^{I}u_{p}^{I}$$ **Equation 10**

Once the bulk sound speed of the materials at impact is found, the release waves are determined. For these calculations, the release waves are considered to be longitudinal waves due to planar impact. The release waves' speed will be determined for the target and projectile.

$$u_r = C_{longitudinal} = C_{0,p} * \sqrt{\frac{3(1-\upsilon)}{1+\upsilon}}$$ **Equation 11**

Equations 2-11 will be used to later in this report to determine if spallation occurs and where the spall plane is located inside the target.

## 3.3 Structural Design

The main objective of this paper is to deliver five distinct projectile and target geometries that will be able to provide results demonstrating the behavior of material at impact conditions. The structural design of each of those components will be developed by using theory of wave propagation in solids, as stated in previous sections. The complex nature of wave propagation in solids suggests the use of finite element analysis. This paper will only provide mathematical models and predictions derived from the Rankine-Hugoniot Equations.

CAD software will be used to define the projectile/target assemblies and to establish the interface tolerances between components. In order to achieve the desired impact, velocity, and geometry requirements, the following parameters of the components will be analyzed:

- Density
- Pressure
- Particle velocity
- Shockwave velocity
- Elastic wave velocity

The theories that will be applied to perform the necessary mathematical calculations are the Rankine-Hugoniot relations, and the mass and momentum conservation equations. Thus, the application of the Rankine-Hugoniot relations to the shockwaves developed at impact in the target plate will allow the calculations of the mentioned parameters.

Figure 4 and 5 contain the target assembly which will be defined by the material chosen according to its density. The thickness of the target assembly will be chosen from the shockwave and elastic wave velocities approximated from the Rankine-Hugoniot relations. The draft angle of the target plate in Figure 5 will allow the target plate to separate from the momentum trap upon impact; this will allow the target plate to reach the soft-catch system safely. The projectile's thickness is also an important factor for the experiment and will be obtained from Equation 7 and 8. The impactor's diameter is limited by the projectile and the target's diameter by the alignment ring and mounting plate.

The structural design of the target assembly and projectile needs to ensure that the shockwave propagation and wave reflection reach a spallation point inside the target and that release waves from the outer diameter will not change the metallurgical conditions through the target. An optimal structural design of the target will result in voids being found inside the target plate after shock loading without complete fracture of the target. This condition is known as incipient spall and is the metallurgical condition of interest to AFRL's Munitions Directorate. AFRL's interest is pursuing the metallurgical analysis of the void growth phenomena resulting from shock loading, and how these voids influence the subsequent mechanical properties of the material when subjected to re-loading conditions. The investigation into the metallurgical conditions of the shock loaded and recovered specimens was not intended to be covered in this report. Ultimately, the data from the metallurgical investigation on incipient spall will feed algorithms to predict the properties of material in modeling and simulations, and these algorithms will be used in the design of air delivered munitions.

The final parameter to be calculated is $w$, which is the width of the momentum trap required to eliminate "edge" effect (Figure 7).

To find the minimum width of the copper ring in the target, the following formula was used:

$$w \geq u_{r,T}\left[\frac{d_I}{u_{s,I}} + \frac{d_I}{u_{r,I}} + \frac{d_T}{u_{r,T}}\right]$$

Once all calculations have been done and checked, the SolidWorks drawings are made for both target and projectile. A final set of dimensions will be sent to AFRL's Munitions Directorate for manufacturing. Each experiment will have different calculations because different testing pressures are required.

## 3.4 Force and Stress Analysis

Spallation in the target will occur when the impact pressure will exceed the spall strength ($\sigma_{spall}$) of copper. For the first set of shots, complete spallation will not occur. To focus on how the spall forms in the material, the majority of the tests will be at impact pressures under 2.6 GPa. [11] The magnitude of the tensile pulse above 2.6 GPa will be sufficient to exceed the incipient spall of the material and may cause complete separation in the target.

## 3.5 Impactor Material Selection

The material selection process for the projectile began with certain materials selected by Dr. House. The first two materials selected for analysis were copper and 2024 Aluminum. 2024 aluminum was selected because the Air Force has an abundant supply of the material ready to be used. Completing the calculations, it was found that neither of these materials can be used for the majority of the experiments due to the fact that at the lowest speed that the gun can fire, the impact pressure exceeds the maximum amount of pressure our advisor is interested in.

**Impactor: Copper**
**Copper Target Thickness: 7 mm**

**Table 2: Copper on Copper Calculations**

| Velocity (m/s) | Pulse Duration (µs) | Pressure (GPa) | Max. Impactor Thickness (mm) |
|---|---|---|---|
| 300 | 1.75 | 5.58 | 4 |
| 350 (min) | 1.75 | 6.59 | 4 |
| 400 | 1.74 | 7.57 | 4 |

**Impactor: 2024 Aluminum**
**Copper Target Thickness: 7 mm**

**Table 3: 2024 Aluminum on Copper**

| Velocity (m/s) | Pulse Duration (µs) | Pressure (GPa) | Max. Impactor Thickness (mm) |
|---|---|---|---|
| 300 | 2.05 | 3.25 | 6 |
| 350 (min) | 2.03 | 3.83 | 6 |
| 400 | 2.00 | 4.41 | 6 |

Selection of a compatible material was done by research of common materials that the Air Force has access to, Poly(methyl methacrylate) was found to achieve a pressure close enough to 1 GPa when fired at the lowest consistent speed achievable by the powder gun (350 meters per second). At this speed the pulse duration is at its maximum for what is needed for the experiments.

**Poly (methyl methacrylate) – PMMA**
**Copper Target Thickness: 7 mm**

**Table 4: PMMA Calculations**

| Velocity (m/s) | Pulse Duration (µs) | Pressure (GPa) | Max. Impactor Thickness (mm) |
|---|---|---|---|
| 300 | 2.09 | 0.97 | 3.3 |
| 350 (min) | 2.07 | 1.16 | 3.3 |
| 400 | 2.04 | 1.35 | 3.3 |

Another material that was selected for analysis was single-crystal Quartz. After completing the calculations it was concluded that Quartz could be used for experiments above

1.5 GPa. Although the pulse duration is above the maximum for the experiment, modifications to the target thickness can be performed to obtain a pulse duration that will satisfy the requirements. Changing the thickness of the impactor material will not affect the pressure upon impact. This change will affect the amount of time that it takes the shock and release waves to travel through the impactor.

**Quartz (Single-Crystal)**
**Target Thickness: 7 mm**

**Table 5: Quartz Calculations**

| Velocity (m/s) | Pulse Duration (µs) | Pressure (GPa) | Max. Impactor Thickness (mm) |
|---|---|---|---|
| 300 | 3.30 | 1.30 | 3 |
| 350 (min) | 3.24 | 1.58 | 3 |
| 400 | 3.18 | 1.86 | 3 |

# 4. Design Alternatives

## 4.1 Overview of Designs

Figure 2 displays the design of the current mounting setup to be used for the target in the testing of the five different configurations. Some dimensions for this mount will stay constant throughout the different shot series. The constant dimensions include the outer diameter of the ring which is set at $D_o$ = 120 mm, and the outer diameter of the momentum trap will remain the same (set at $D_c$ = 46 mm). [1]

Inversely, there are variables that may or may not change throughout the five different shots depending on different factors such as data retrieved from previous shots. Variables that are likely to change include the thickness of the target, as well as the size of the target due to possible edge effects.

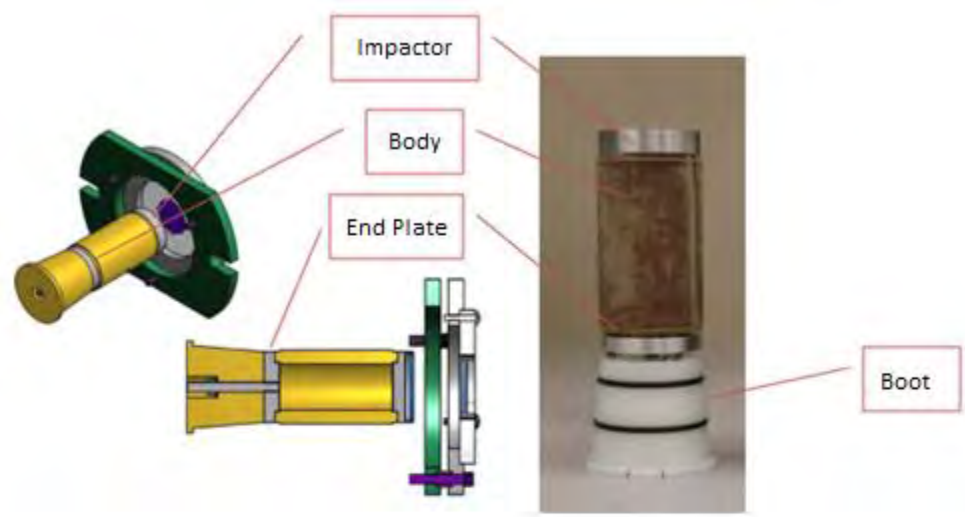


**Figure 8: Projectile Courtesy of AFRL, Munitions Directorate [1]**

Figure 8 presents the complete conceptual assembly of the components that could be used for the project. Similarly to the target, there are several variables that will remain constant throughout each of the five shots for the projectile assembly in order to maintain ease of manufacturing and availability of the projectile types. The main variables that will be expected to change throughout each experiment will be the thickness and the material of the projectile impactor.

## 4.2 Proposed Conceptual Design

The factors that will be re-designed for the purposes of a soft catch recovery system are the target geometry, momentum trap inside geometry, impactor thickness, and the area on the projectile where the impactor resides. Figure 9 resents a drawing of the proposed set up that includes the re-designed target along with the projectile and the changes that will be made.

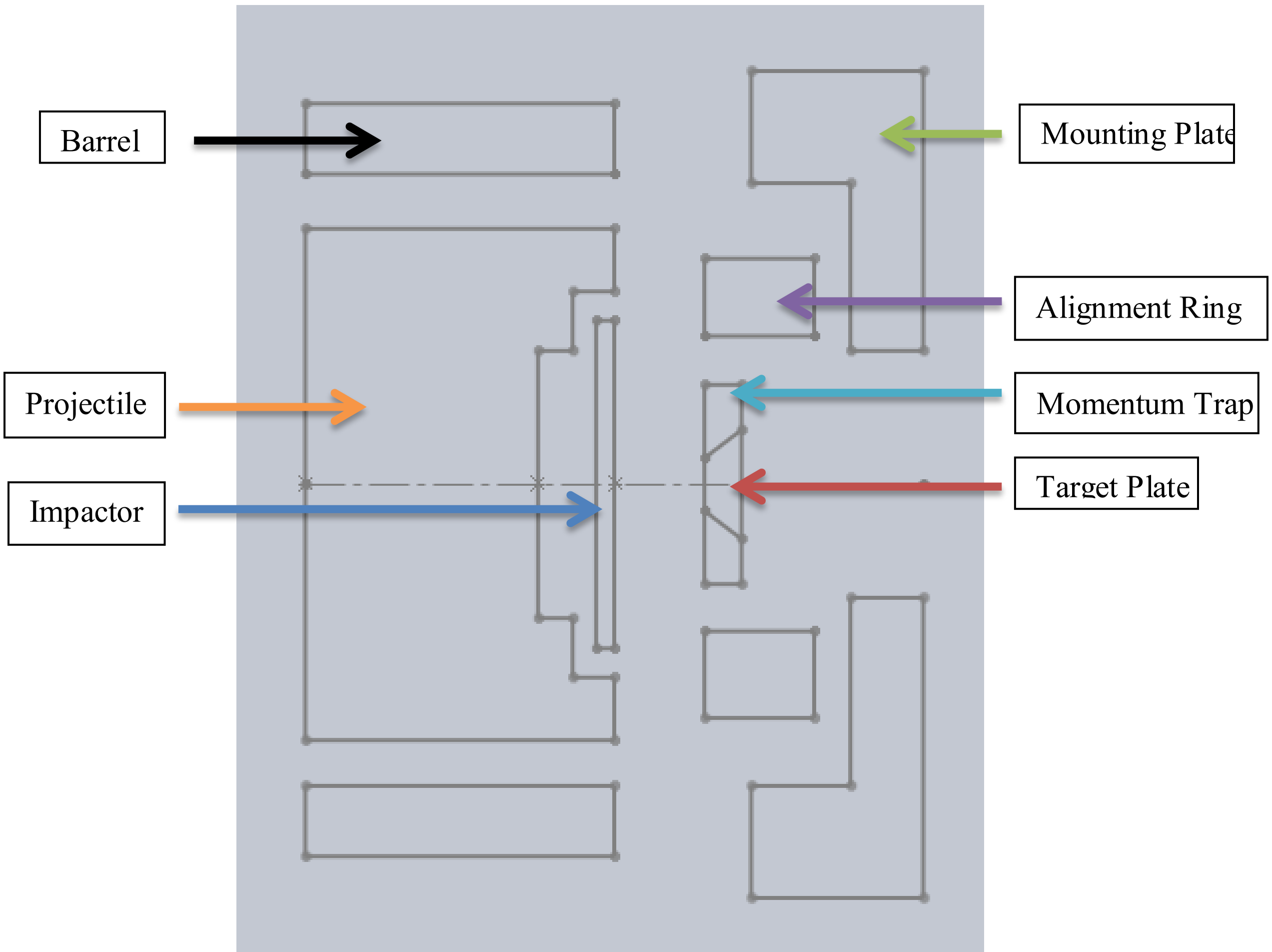


**Figure 9: Experiment Overview**

As shown in Figure 9 and 10, the area around the target plate is the momentum trap where the target will be placed for testing. The projectile will be coming from the left side of the drawing and come out to the right and into a soft catch recovery system.

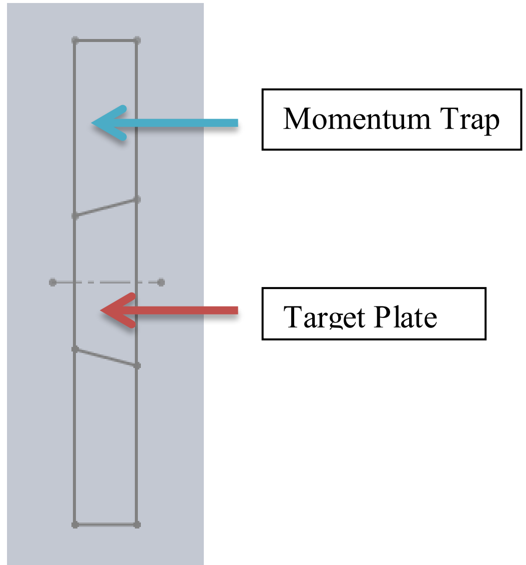


**Figure 10: Target Assembly**

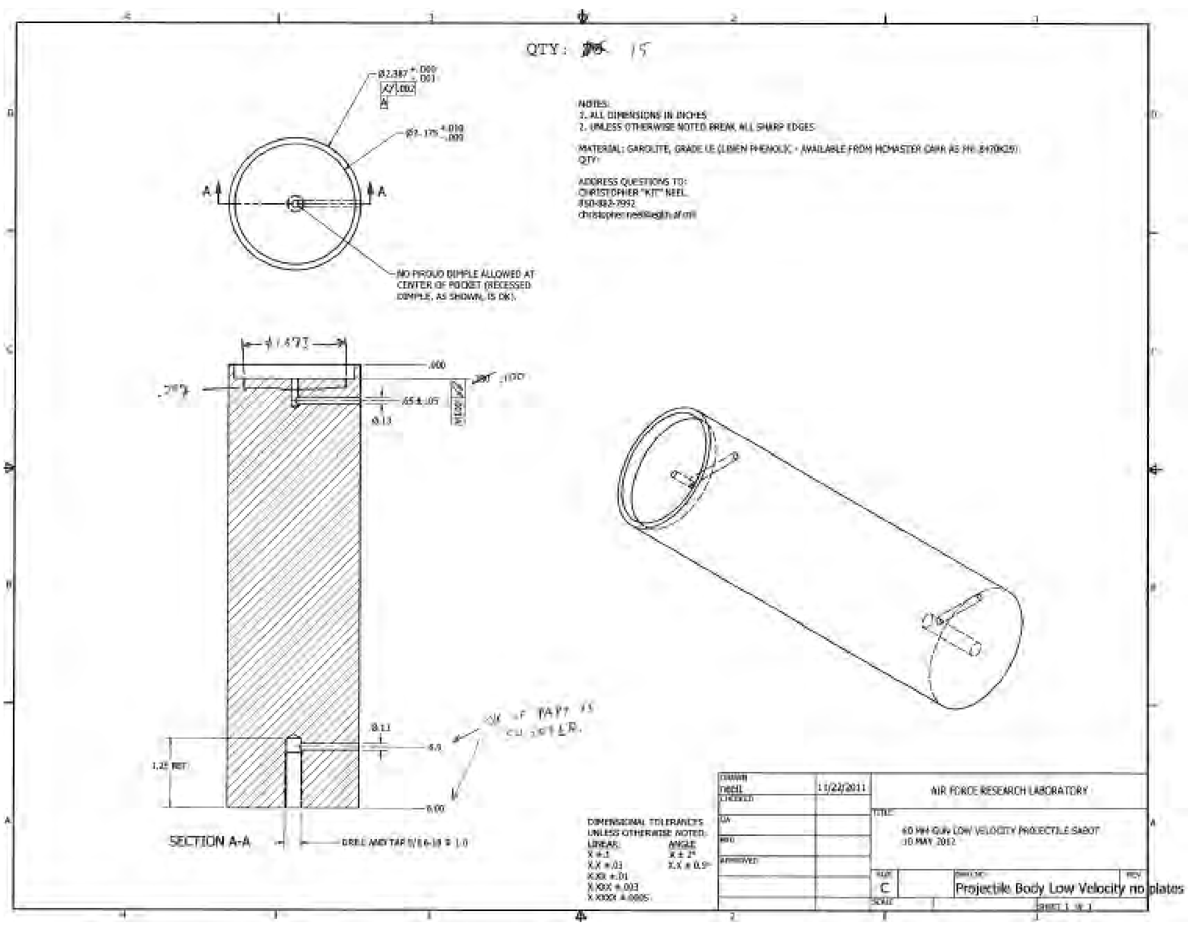


**Figure 11: Projectile Courtesy of AFRL, Munitions Directorate [1]**

Figure 11 is a drawing of the projectile that is currently being used for testing in AFRL. The geometry of the projectile will remain constant to fit into the gun and will have a re-design on the front face where the impactor sits inside.

## 4.3 Proposed Conceptual Design First Calculations

For the design of the projectile impactor and target components, the dynamic properties of PMMA and OFHC Copper were obtained through literature survey. The design criteria for the first shot are the following:

i. The impactor and target behave as non-rigid bodies.

ii. Achieve impact pressure **P ≈ 1.0 GPa**

iii. Pulse duration **t ≈ 2µs**

iv. Incipient spallation plane inside target

v. Reduce edge effects inside the target

**Table 6: Dynamic Properties of PMMA & OFHC Cu [3] [12]**

| Impactor (PMMA) | Target (OFHC Cu) |
|---|---|
| $\rho_o = 1.19$ g/cc | $\rho_o = 8.93$ g/cc |
| $C_{b,o} = 2.23$ km/s | $C_{b,o} = 3.94$ km/s |
| S = 1.52 | s = 1.489 |
| v = 0.327 | v = 0.343 |
| L = 3.3 mm | L = 7 mm |
| D = 50 mm | D = 15 mm |
| | $\sigma_{spall} = 2.6$ GPa |

**NOTE:** Table 6 presents the information that will be utilized throughout the calculations later in this section. The reader is welcomed to check the results of the calculations at his/her own leisure.

In order to ensure that the design criteria are met, the following dynamic factors were calculated:

a. Particle velocity
b. Shock pressure
c. Shock speed
d. Release wave speed
e. Spall place location & spallation time
f. Radial wave propagation (edge effects)

The equation governing the design of the components is shown below in **Eq.12**. This equation represents the pressure that a solid material experiences after high velocity impact as a function of its density, bulk sound speed, Hugoniot slope, and initial and final particle velocities.

$$P - P_o = \rho_o c_o (u_i - u_o) + \rho_o s (u_i - u_o)^2$$ **Equation 12** [3]**: Pressure difference**

Important assumptions applied to utilize **Eq. 12-14** are the following:

a. Projectile and target material undergo large deformation.
b. One-dimensional deformation of the components upon impact due to planar contact.
c. Edge effects are not present within target plate due to momentum trap proposed.
d. Edge effects are negligible as long as spallation plane occurs inside target and contact between target plate and momentum trap occurs in a period of time sooner than radial waves from momentum trap can reach target plate.
e. Uniform density in all components.
f. Edge effects from target plate and momentum trap contact plane are negligible.
g. Pressure experienced by projectile and target plate is the same at contact.
h. $u_{initial}^{Target} = 0, u_{initial}^{Impactor} = shot\ velocity = 350\ \frac{m}{s}$

Additional dynamic behavior equations:

$u_s = C_{b,0} + su_p$ **Equation 13** [3]**: Shock wave speed**

$C_{b,p} = C_{b,0} + 2su_p$ **Equation 14** [3]**: Bulk sound speed at impact pressure**

$u_{r=} C_L = C_{b,p} * \sqrt{\frac{3(1-\upsilon)}{(1+\upsilon)}}$ **Equation 15** [3]**: Longitudinal sound wave speed**

CALCULATIONS

**Step 1: Solve for particle velocity upon impact**

$$\boldsymbol{P - P_o = \rho_o c_o (u_i - u_o) + \rho_o s (u_i - u_o)^2}$$

Target: $\boldsymbol{P^T = \rho_o^T c_{b,o}^T u^* + \rho_o^T s^T (u^*)^2}$

Impactor: $\boldsymbol{P^I = \rho_o^I c_{b,o}^I (u_i - u^*) + \rho_o^I s^I (u_i - u^*)^2}$

Upon impact $\boldsymbol{P^T = P^I}$, solving for **u*** and applying the quadratic equation, **u*= 0.0288 km/s**

$\boldsymbol{u_p^T = u^* - \cancel{u}_o^T = 0.0288\ km/s}$

$\boldsymbol{u_p^I = u_o^I - u^* = 0.321\ km/s}$

**Step 2: Solve for impact pressure *P***

$\boldsymbol{P^T = (8.93)(3.94)(0.0288) + (8.93)(1.489)(0.0288)^2 = 1.039\ GPa}$

$\boldsymbol{P^I = (1.19)(2.23)(0.321) + (2.785)(1.338)(0.321)^2 = 1.023\ GPa}$

**Step 3: Solve for shock wave speed**

$\boldsymbol{u_s^T = c_{b,o}^T + s^T u_p^T = (3.94) + (1.489)(0.0288) = 3.982\ km/s}$

$\boldsymbol{u_s^I = c_{b,o}^I + s^I u_p^I = (5.328) + (1.338)(0.3487) = 2.719\ km/s}$

**Step 4: Solve for bulk sound speed at impact & release wave speed**

$$c_{b,p>0} = \frac{1}{\rho_o}\frac{\partial P}{\partial u}|_{u=u_p} \rightarrow \ c_{b,o} + \ 2su_p$$

$C_{b,p}{}^{T}$ = (3.94) + 2(1.489)(0.0288) = 4.026 km/s

$C_{b,p}{}^{I}$ = (2.23) + 2(1.52)(0.321) = 3.207 km/s

$$C_L = C_{b,p} * \sqrt{\frac{3(1-v)}{1+v}}$$

$C_L^T = 4.877$ km/s

$C_L^I = 3.955$ km/s

**Step 5: Solve for spallation plane location**

$$Pulse\ duration = t = \frac{L}{u_s^I} + \frac{L}{u_r^I} = 2.04\mu$$

$t_1 = \frac{L}{u_s^T} = 1.757\ \mu s$, $t_1$ = time it takes for shock wave to reach free surface in target

Since $t_1 < t$, ***x ranges from 0 to 7 mm***

$$x\ = \frac{L - u_r^T(t - t_1)}{2}\ = 2.79\ mm\ @\ t_{spall} = t + \frac{x}{u_r^T} = 2.32\mu s$$

**Step 6: Calculate time for edge effects to reach target ($t_e$)**

Due to geometry of the momentum trap, the shortest distance between the edge of the momentum trap to the target is:

$$d = (R_o - R_i) * \sin(90 - \theta)$$

where,

$$\begin{cases} R_o = Momentum\ Outer\ Radius\ (Front\ \ Face) \\ R_i = Momentum\ Inner\ Radius\ (Front\ Face) \\ \theta = Momentum\ Draft\ Angle \end{cases}$$

Then, since edge effects do not act in the longitudinal direction, bulk sound speed at impact pressure will be used to calculate the time $t_e$.

$$\boldsymbol{t_e = \frac{d}{C_{b,p}^{T}} = 2.99\mu}$$

## SUMMARY OF RESULTS

**Table 7: Design Criteria & Results**

| Design Criteria & Results | |
|---|---|
| Impact Pressure | **1.03 GPa (≈1.0 GPa)** |
| Pulse Duration | **2.04 μs (≈2.0 μs)** |
| Spallation plane location | **2.79 mm (inside target plate)** |
| Edge effects time | **Negligible (2.32 < 2.39 μs)** |

From Table 7, it can be observed that the first desired impact pressure has been achieved with the use of PMMA as the impactor at a speed of 350 meters per second. The pulse duration, which affects the metallurgical properties of the materials, has also matched the optimal desired time of two microseconds. Moreover, Spallation has been achieved at a depth of 2.79 millimeters which falls within an acceptable percentage (20%) from the mid-plane of the target (3.5 mm). Thus, through the first iteration, the prediction values are reasonable. It is important to mention that the edge effects formed at the outer radius of the momentum trap during the shot do not reach the target in time to affect the spallation plane. Therefore, the release waves created at the edges of the momentum trap do not distort the desired one dimensional spall plane inside the target. It is important to acknowledge the interface between the target plate and the momentum trap since the epoxy used to hold both components together before impact might serve as a free surface where release waves may be produced.

## 4.4 Original Proposed Design Drawings

Figures 12 through 17 present engineering drawings of the final design package that will be used for the first series of shots.

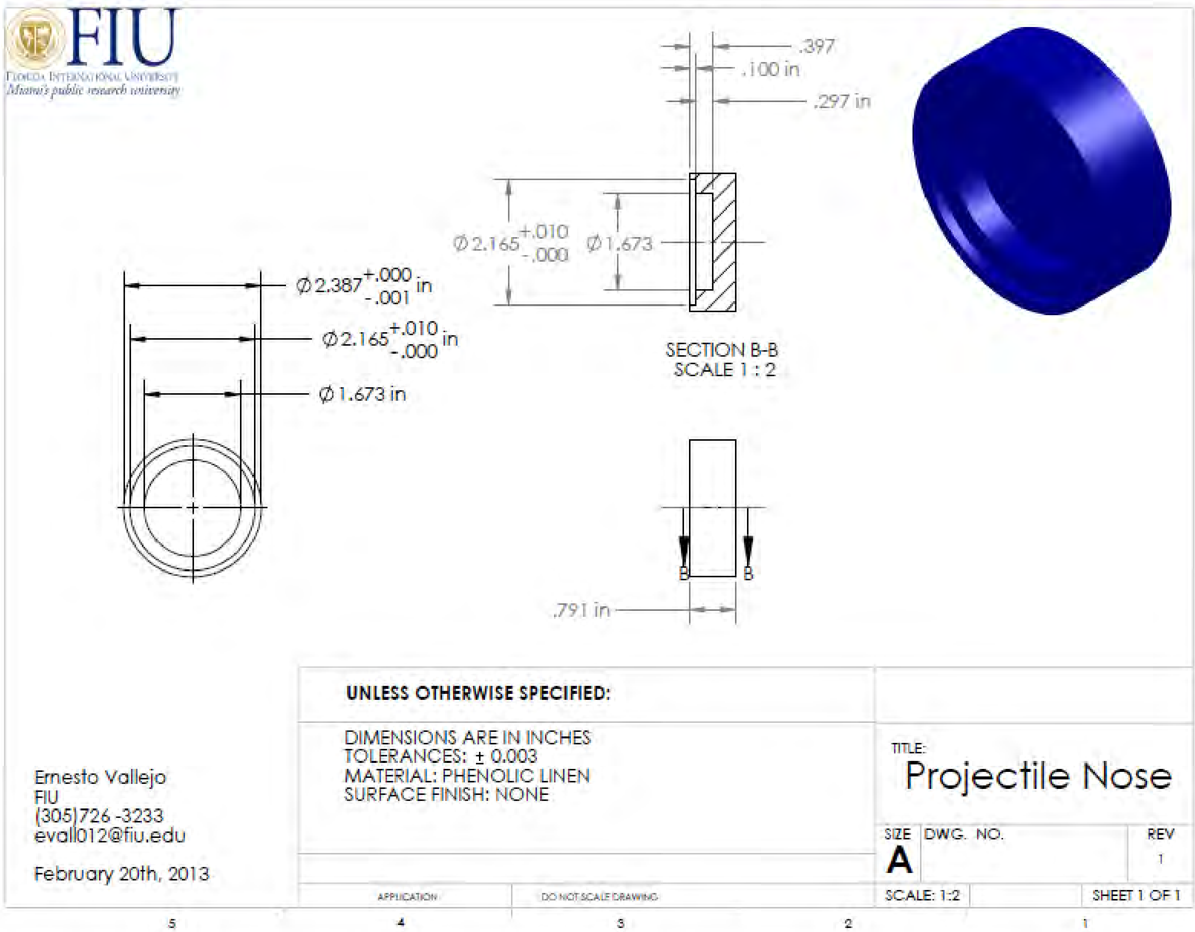


**Figure 12: Projectile Design**

Figure 12 presents the projectile nose dimensions since this part of the projectile that is going to be utilized has been adjusted to the FIU team's research and calculations.

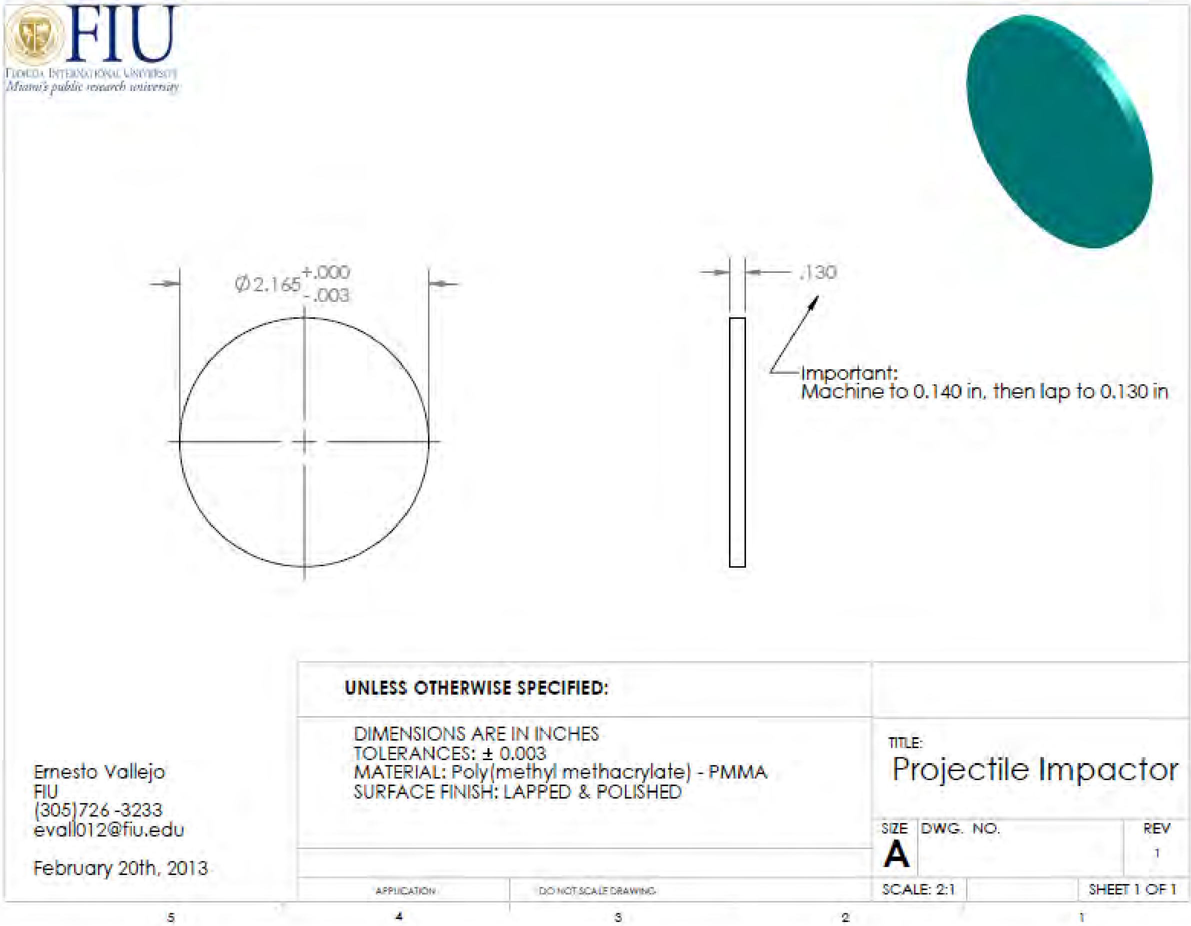


**Figure 13: Projectile Impactor Design**

The projectile impactor design can be observed in Figure 13. The thickness for this component is critical in achieving the desired spall location inside the target plate as well as the desired pulse duration for the impact. The lap finish in the impactor and target assembly will increase the probability of planar contact.

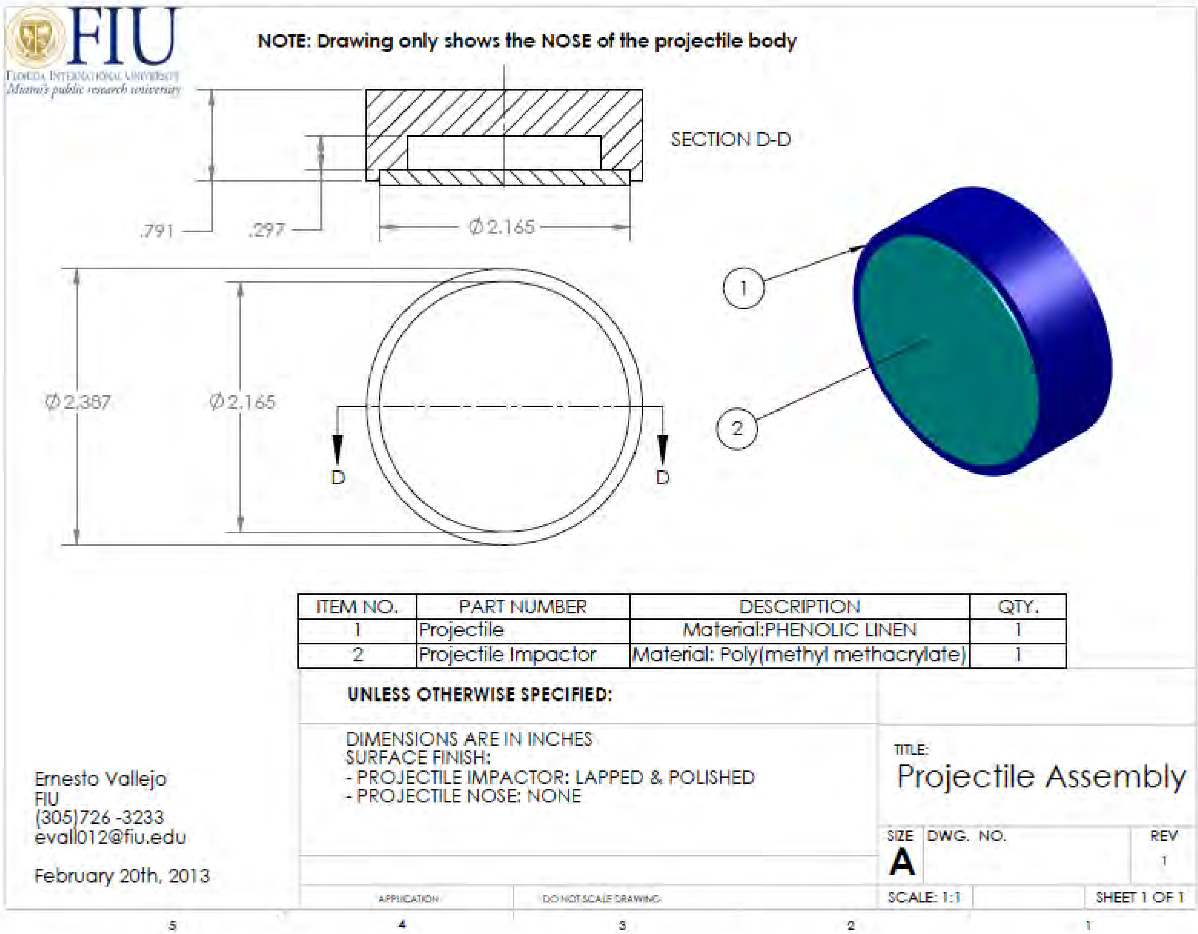


**Figure 14: Projectile Assembly**

Figure 14 represents the assembly view of the projectile and projectile impactor. The lead time to manufacture the projectile assembly is approximately four to six weeks. The desire to study the effects of planar shock drives the requirement to have flat and parallel surfaces on the impactor face, and the target face. A small deviation from complete flatness can cause a different outcome for the experimental results.

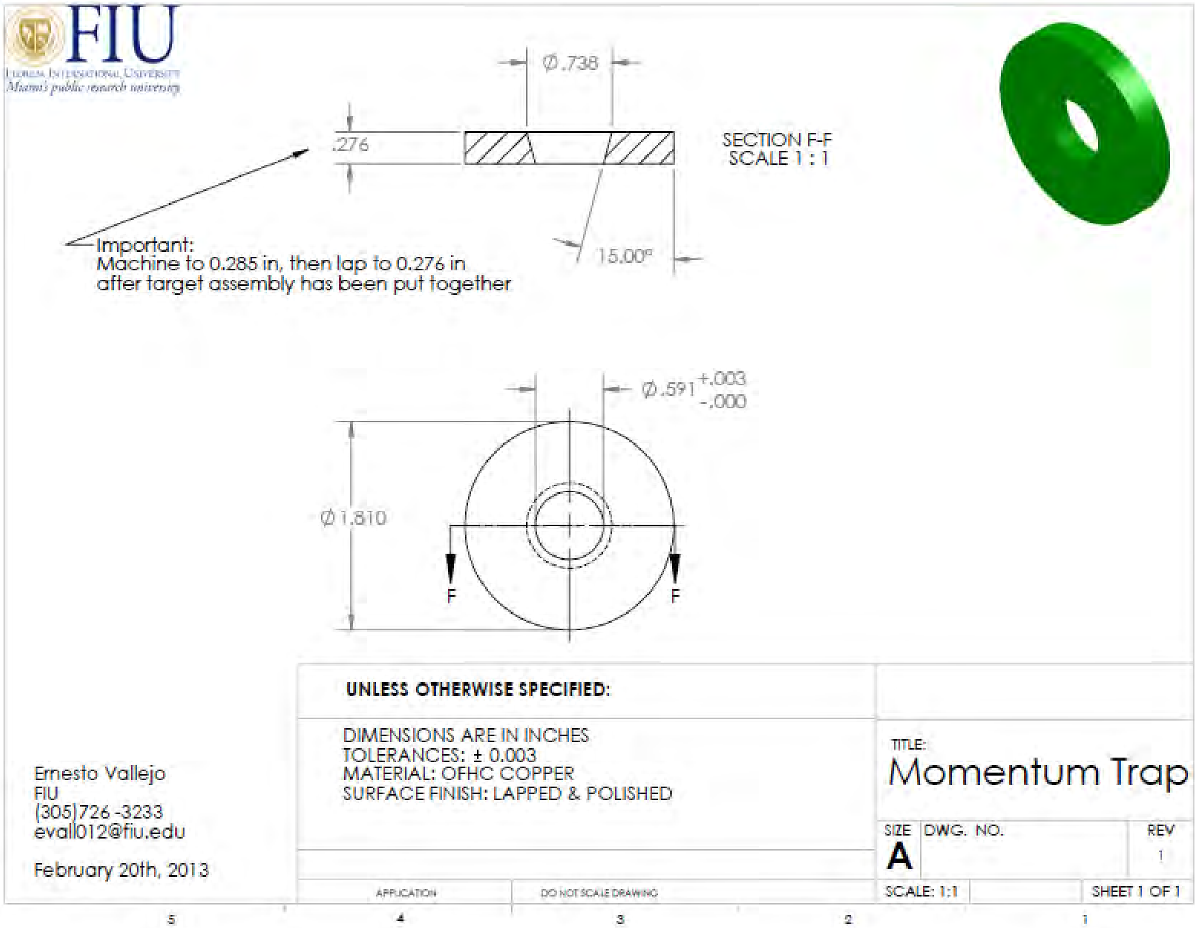


**Figure 15: Momentum Trap Design**

The momentum trap design, presented in Figure 15, has undergone a variety of changes due to its function in preventing edge effects and enabling clean separation from the target plate. The separation angle of fifteen degrees has been used to allow the latter condition.

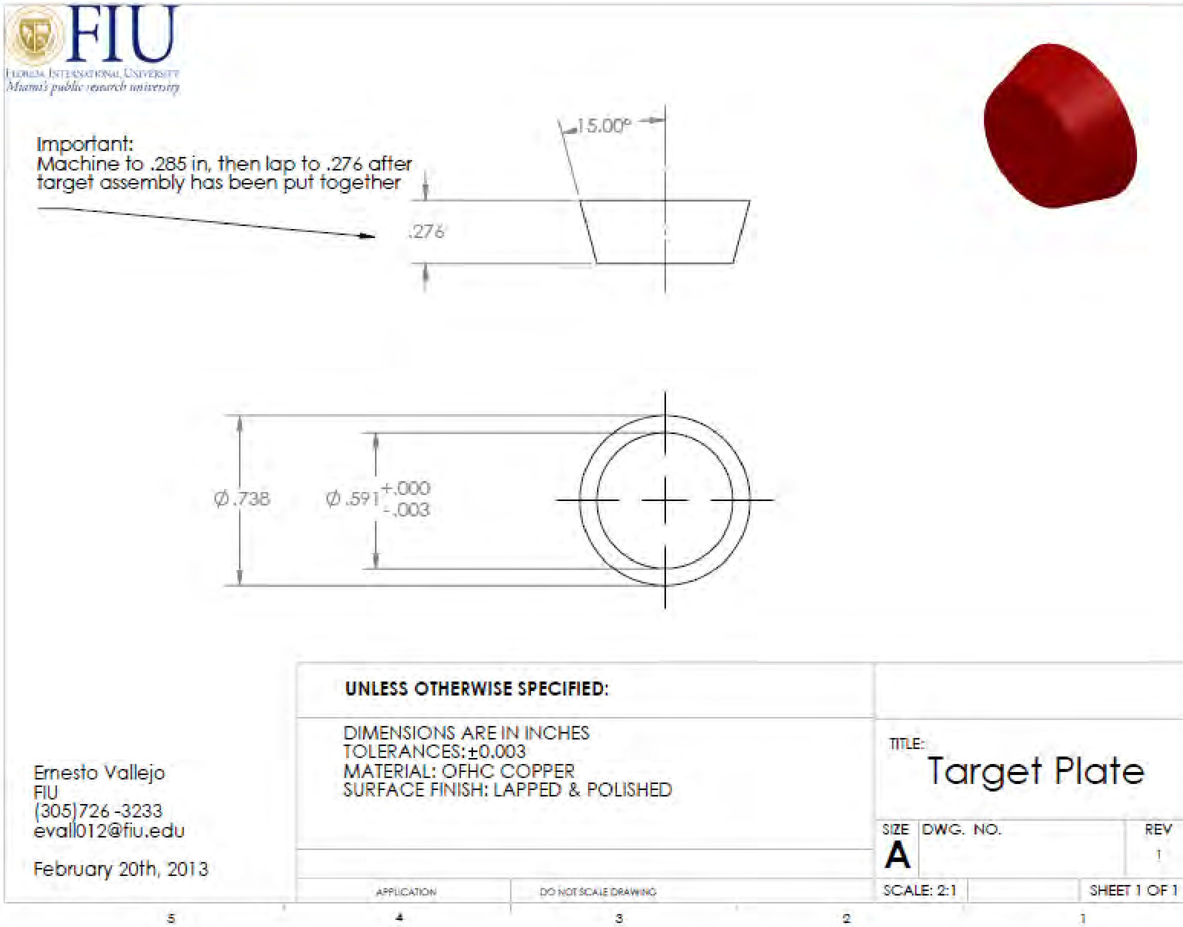


**Figure 16: Target Plate Design**

Figure 16 presents the target plate design that will be used for the first series of shots. When the results from the experiments come back to FIU, the senior design team will make the necessary decisions to change the dimensions of this component to achieve cleaner spallation planes. The decisions driving the dimensions will be based on iterative analysis of the calculations, as well as, physical evidence of spallation inside target. A "clean" spallation plane will be of one dimensional character. A "dirty" spallation plane would contain voids in more than one dimension over a large area.

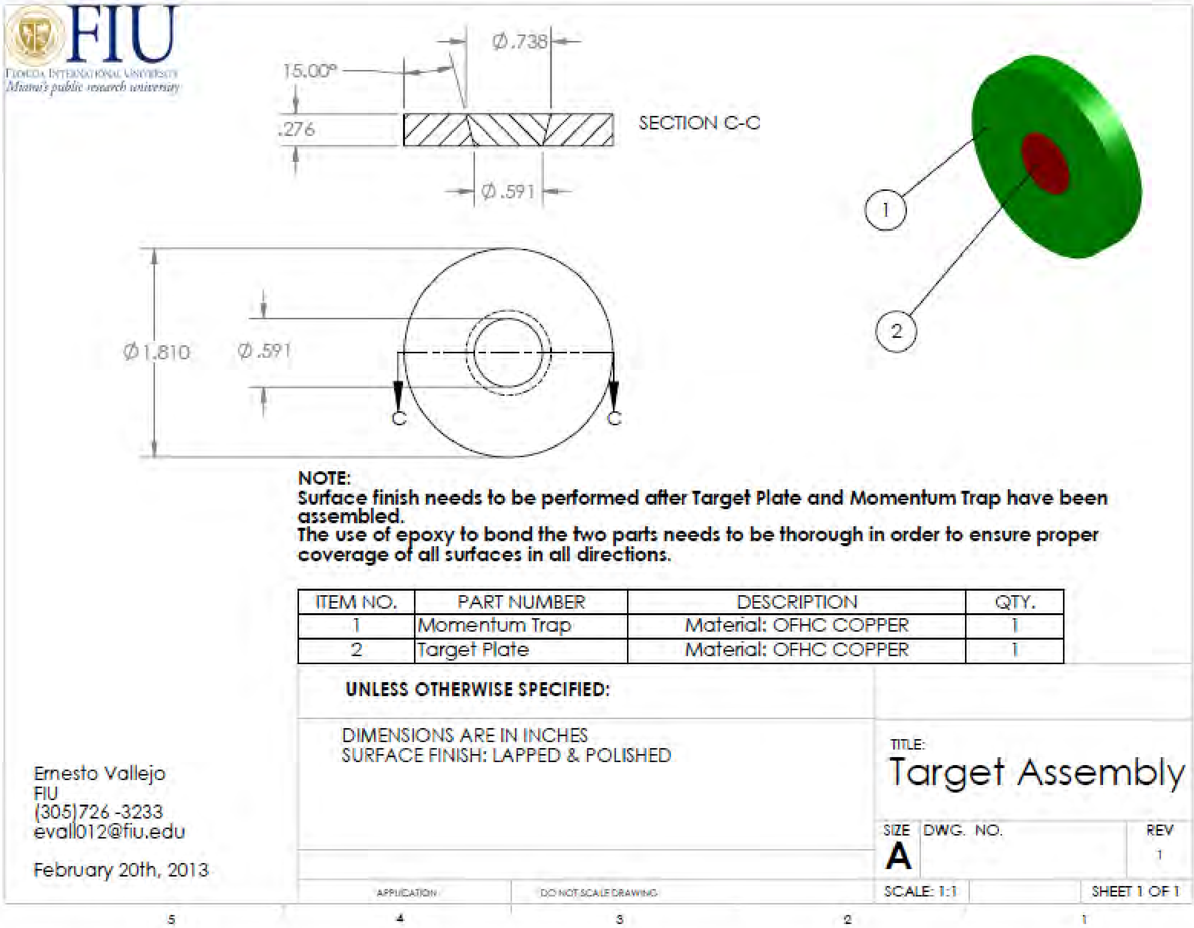


**Figure 17: Target Assembly**

Figure 17 provides a representation of the final target assembly and its properties for the first shot.

## 4.5 Proposed Design Alternative A: Constant Impactor Thickness

In order to provide greater flexibility to AFRL, the FIU senior design team decided to perform two additional studies to what will now be known as the original proposed design. The studies are based on a PMMA impactor and a copper target. The decision to invest time into such endeavors was to enhance the probability of success of the project and ensure that the costumer is satisfied with the results from the experiments. Also, since time is a constraint for the project, it was desirable to enable AFRL to continue with this project's research even after finalizing the senior design team's involvement.

Finally, in order to establish a general method to perform shock loading analysis on other materials, the alternatives seek to provide more evidence supporting the predictions' accuracy and validity. Tables 8 through 10 present the spall plane location, pulse duration, spallation time, and edge effects time for impactor thicknesses of 3, 3.3, and 3.5 millimeters. Figures 18 through 20 provide a graphical representation of the shoot speed versus the spall plane location inside the target for each respective case.

**Table 8: Impactor Thickness = 3 mm**

| Impactor thickness = 3 mm (0.118 in) | | | | | |
|---|---|---|---|---|---|
| Shot speed (m/s) | Impact Pressure (GPa) | Spall plane location (mm) | Pulse duration (µs) | Spall plane occurrence time (µs) | Edge effects time (µs) |
| 350 | 1.0235 | 3.245 | 1.8621 | 2.423 | 3.000 |
| 500 | 1.585 | 3.620 | 1.700 | 2.481 | 2.965 |
| 600 | 1.980 | 3.830 | 1.607 | 2.510 | 2.940 |
| 700 | 2.400 | 4.017 | 1.526 | 2.533 | 2.915 |
| 750 | 2.619 | 4.103 | 1.489 | 2.542 | 2.902 |
| 800 | 2.844 | 4.185 | 1.454 | 2.550 | 2.879 |
| 850 | 3.07 | 4.262 | 1.420 | 2.557 | 2.874 |

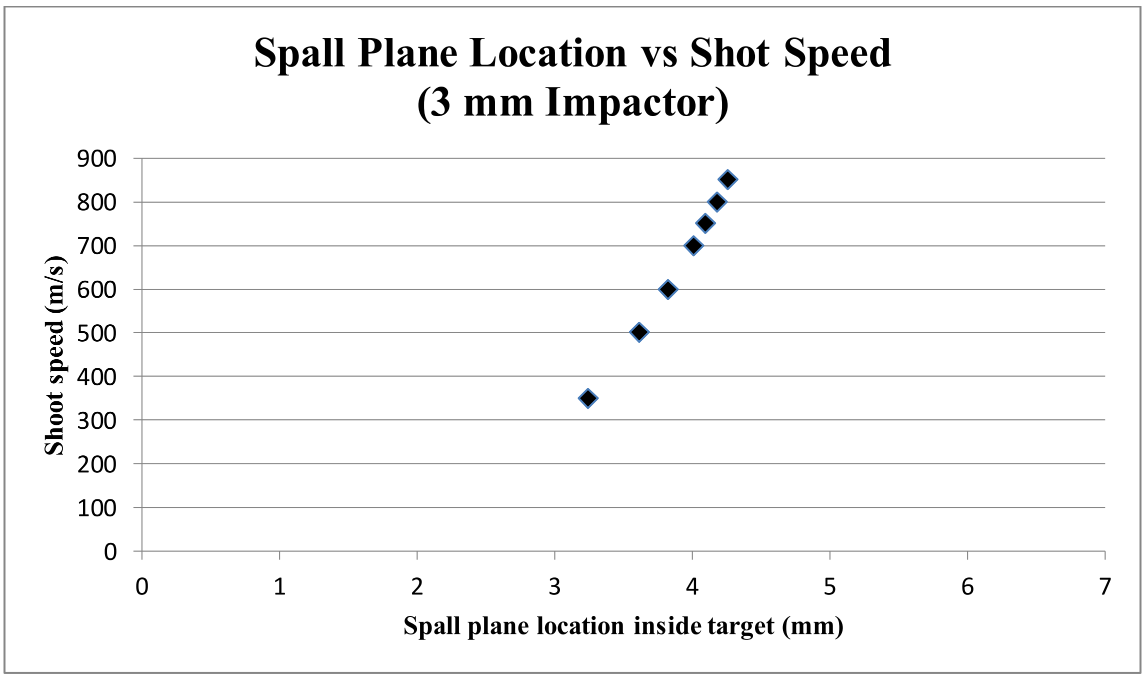


**Figure 18: Spall Plane Location vs. Shot Speed (3 mm Impactor)**

**Table 9: Impactor Thickness = 3.3 mm**

| Impactor thickness = 3.3 mm (0.130 in) | | | | | |
|---|---|---|---|---|---|
| Shot speed (m/s) | Impact Pressure (GPa) | Spall plane location (mm) | Pulse duration (µs) | Spall plane occurrence time (µs) | Edge effects time (µs) |
| 350 | 1.0235 | 2.971 | 2.048 | 2.330 | 3.000 |
| 500 | 1.585 | 3.200 | 1.870 | 2.400 | 2.970 |
| 600 | 1.980 | 3.430 | 1.768 | 2.430 | 2.941 |
| 700 | 2.400 | 3.634 | 1.679 | 2.457 | 2.915 |
| 750 | 2.619 | 3.728 | 1.638 | 2.468 | 2.901 |
| 800 | 2.844 | 3.817 | 1.600 | 2.478 | 2.888 |
| 850 | 3.07 | 3.901 | 1.562 | 2.486 | 2.874 |

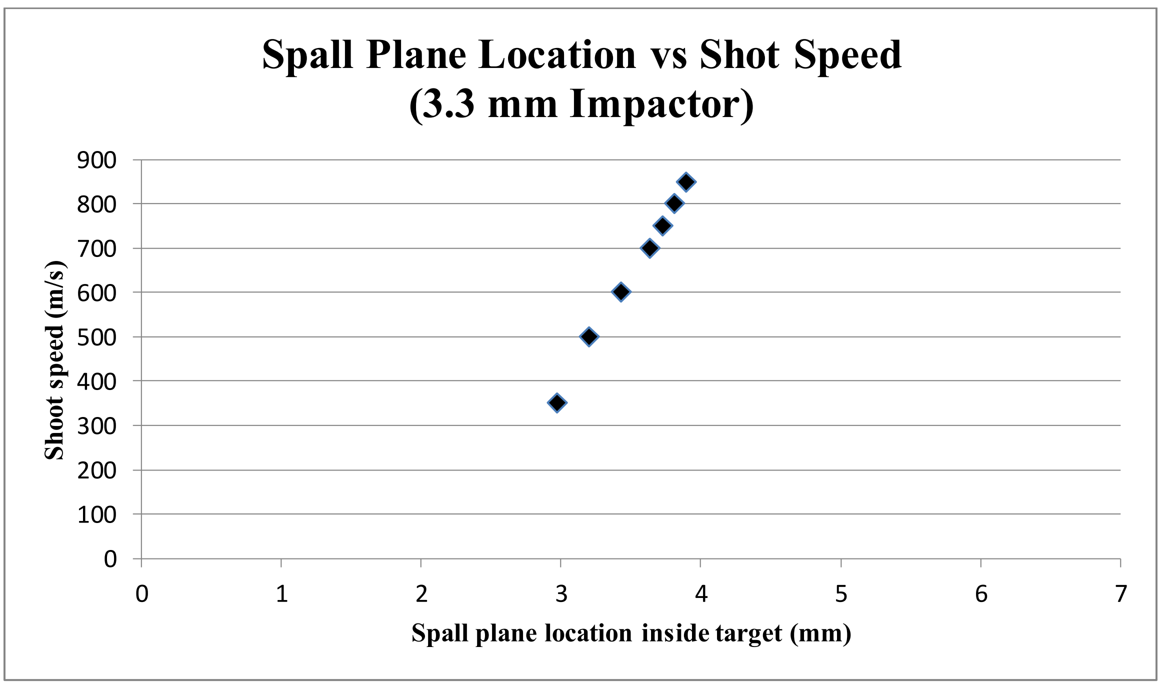


**Figure 19: Spall Plane Location vs. Shot Speed (3.3 mm Impactor)**

**Table 10: Impactor Thickness = 3.5 mm**

| Impactor thickness = 3.5 mm (0.138 in) | | | | | |
|---|---|---|---|---|---|
| Shot speed (m/s) | Impact Pressure (GPa) | Spall plane location (mm) | Pulse duration (µs) | Spall plane occurrence time (µs) | Edge effects time (µs) |
| 350 | 1.0235 | 2.488 | 2.172 | 2.268 | 3.000 |
| 500 | 1.585 | 2.920 | 1.982 | 2.340 | 2.965 |
| 600 | 1.980 | 3.164 | 1.8752 | 2.376 | 2.941 |
| 700 | 2.400 | 3.379 | 1.780 | 2.406 | 2.915 |
| 750 | 2.619 | 3.478 | 1.737 | 2.418 | 2.902 |
| 800 | 2.844 | 3.5714 | 1.696 | 2.429 | 2.887 |
| 850 | 3.07 | 3.660 | 1.657 | 2.439 | 2.874 |

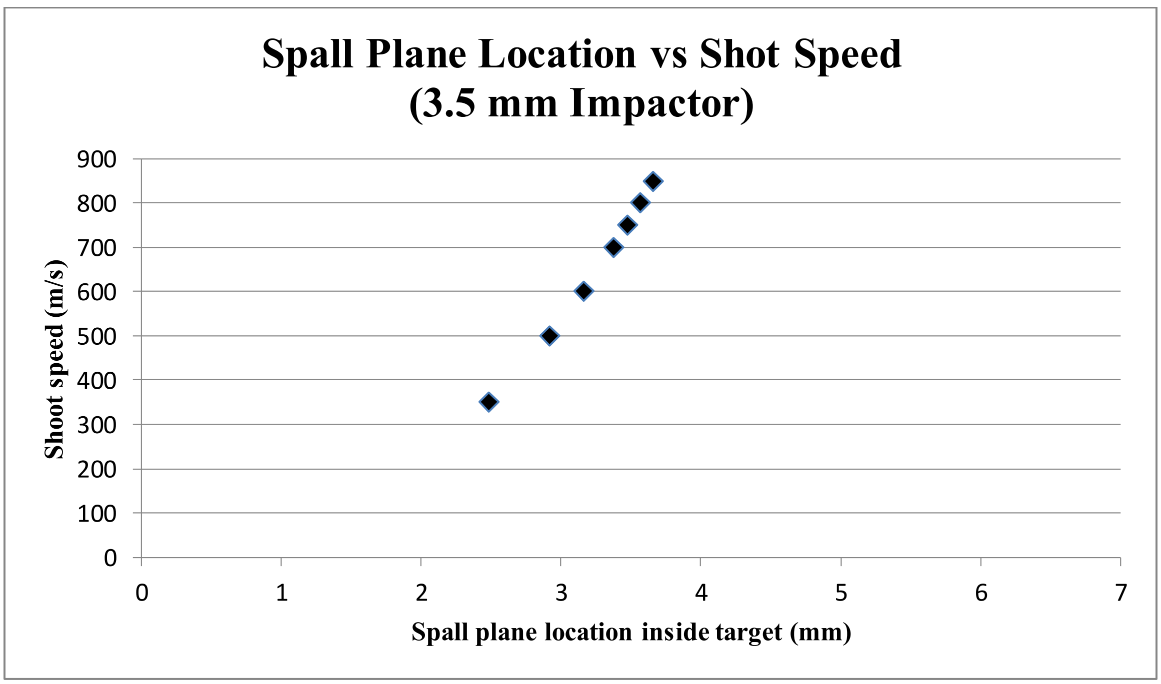


**Figure 20: Spall Plane Location vs. Shot Speed (3.5 mm Impactor)**

## Summary of Results

The chosen speeds for the shots are: 350, 500, 600, 700, and 850 meters per second. These shot speeds were chosen since they achieve the required impact pressures within an acceptable range of accuracy.

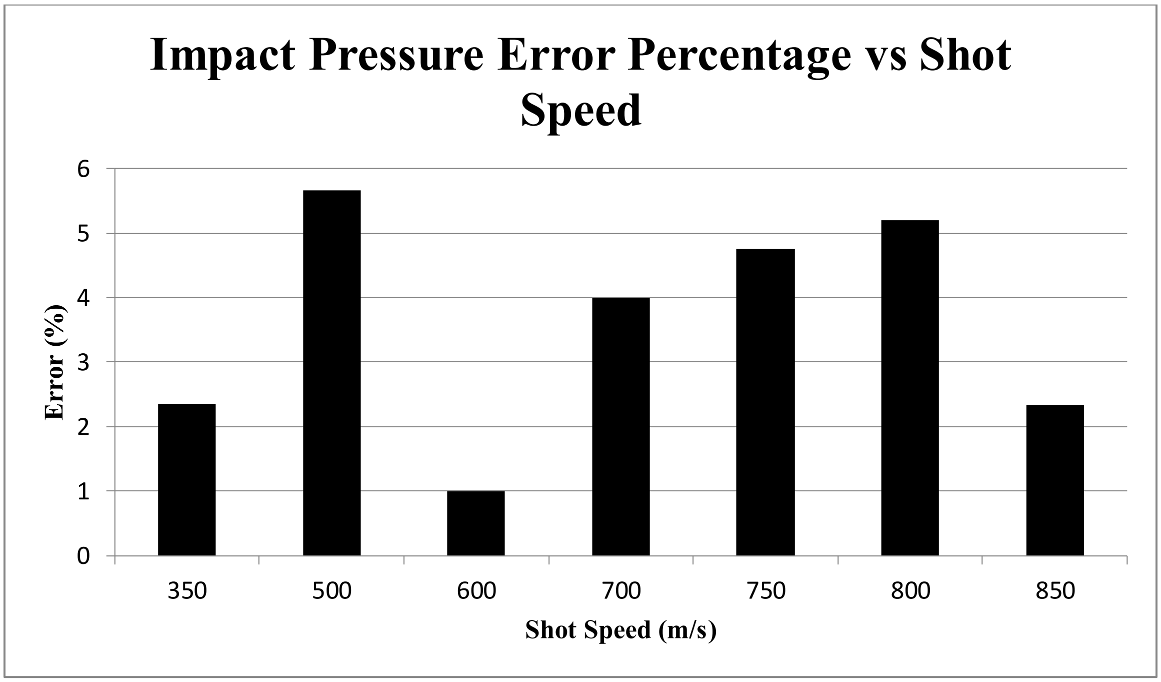


**Figure 21: Impact Pressure Error Percentage vs. Shot Speed**

From the results for the different impactor thicknesses, it is strongly advised to use 3.3 millimeter as the thickness of the impactor. A 3.3 millimeter impactor is predicted to achieve better localized spall planes inside the target.

## 4.6 Proposed Design Alternative B: Variable Impactor Thickness

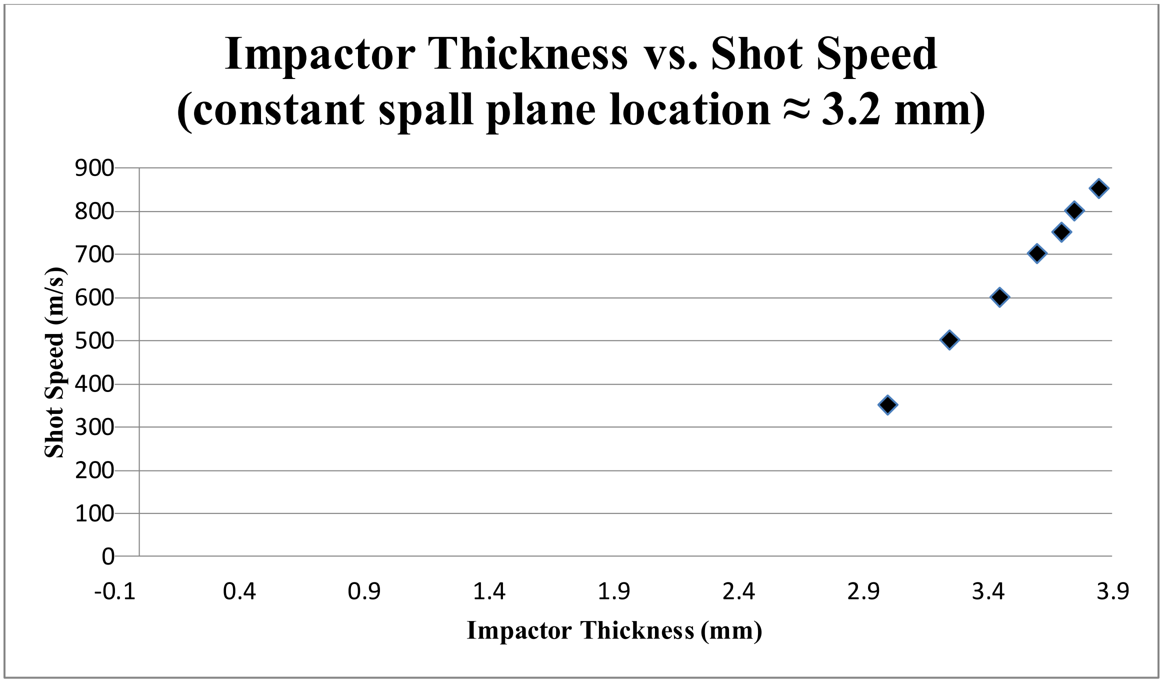


**Figure 22: Impactor Thickness vs. Shot Speed**

<u>Summary of Results</u>

The team strongly suggests avoiding the manufacturing of multiple impactors for the different thicknesses due to the time constraint of the project. Given enough time, it would be beneficial to use the criteria of constant spall plane location, since the spall plane location can be calculated to achieve the pulse duration criteria of two microseconds.

**NOTE:** The complete set of engineering drawings for the design packages can be found in the appendix of this report.

## 4.7 Feasibility Assessment

The impactor for the tip of the projectile as well as the target assembly will be manufactured at AFRL using the design package specifications. This ensures that the manufacturing process will meet AFRL standard requirements for HP3 shots. Tolerances, surface finish, and parallelism are crucial to every test shot. This serves to alleviate a lot of the feasibility challenges that would have to be surmounted if the team were responsible for the manufacturing of all of the components. Meeting the standard requirements would be impossible using the equipment available to students and would render our results unusable. Therefore, AFRL has provided very precise requests for the layout and content of the engineering drawings of the components that are being designed. This decision will be mutually beneficial in guaranteeing the credibility of the results.

# 5. Project management

## 5.1 Overview

During the design of these projectiles, time management and work distribution will be key to the success of this project. Time management was planned out in the beginning of the fall 2012 semester. Group meetings at specific times in which all group members could meet was established and contingency plans were put into action. Meeting dates were setup to be every Wednesday of the week from 12:00 P.M. through 3:00 P.M. In this three hour span, everyone agreed to meet and work on future assignments for the design project. Work was distributed depending on topics. If a team member worked on cost analysis topics, those topics involving the same genre were then assigned to that team member. All decisions made for the design project are voted for by all team members to assure a positive outcome. Every team member has a specific task within the group from team leader to time management leader. With this action, every team member has equal responsibility and work load throughout the design.

## 5.2 Breakdown of Work into Specific Tasks

**Table 11: Breakdown of Work into Specific Tasks**

| *JORGE* | *JAVIER* | *GUILLERMO* | *DEVON* | *ERNESTO* |
|---|---|---|---|---|
| Problem Statement | Overview of Conceptual Designs Developed | Description of Prototype | Kinematic Analysis and Animation | Assembly and Disassembly |
| Motivation | Proposed Conceptual Design | Prototype Design | Dynamic/Vibration Analysis of the System | Maintenance of the System |
| Literature Survey | Fist Calculations | Parts List | Structural Design | Regular Maintenance |
| Discussion | Original Proposed Design Drawings | Construction | Force Analysis | Major Maintenance |
| Overview | Design Alternative 1 | Prototype Cost Analysis | Stress Analysis | Environmental Impact |
| Project Objectives | Design Alternative 2 | Discussion | Material Selection | Risk Assessment |
| Design Specifications | Feasibility Assessment | Breakdown of Work | Failure Design Theories | Conclusion and Discussion |
| Constraints and Other Considerations | | Organization of Work | Deflection Analysis | Patent/Copyright Application |
| Discussion | | Breakdown of Responsibilities | Component Design/Selection | Commercialization Prospects of the Product |
| | | Patent/Copyright Application | Finite Element Analysis | Future Work |
| | | Commercialization of the Final Product | Design Overview | |
| | | Discussion | Discussion | |

## 5.3 Organization of Work and Timeline

**Table 12: Timeline**

| Tasks | Start Date | Duration (days) | End Date |
|---|---|---|---|
| **FALL 2012** | | | |
| Literature Survey | 23-Aug | 100 | 16-Oct |
| Conceptual Design | 16-Sep | 34 | 20-Oct |
| Solidworks Simulation | 25-Oct | 124 | 26-Feb |
| Formal PP Presentation: Intro to Senior Design | 10-Sep | 17 | 27-Sep |
| Analytical Structure and Analysis | 8-Jan | 93 | 10-Apr |
| One Page Synopsis (IAB Report) | 1-Oct | 8 | 9-Oct |
| Formal PP Presentation: GL Components | 1-Oct | 8 | 9-Oct |
| 10% Final Report | 9-Oct | 22 | 31-Oct |
| Team Poster - Soft Copy | 15-Oct | 10 | 25-Oct |
| 25% Final Report | 25-Oct | 13 | 7-Nov |
| Poster Design | 26-Oct | 13 | 8-Nov |
| Rehearsal Presentation, EC 2300 | 14-Nov | 4 | 14-Nov |
| Final Team Presentation to IAB, EC 2300 | 28-Nov | 4 | 28-Nov |
| **SPRING 2013** | | | |
| Testing | 8-Jan | 92 | 10-Apr |
| 50% Final Report | 10-Jan | 63 | 11-Feb |
| 75% Final Report | 11-Feb | 28 | 11-Mar |
| 100% Final Report | 11-Mar | 31 | 11-Apr |
| Presentation Rehearsal to MME Faculty | 25-Mar | 25 | 18-Apr |
| Senior Design Org Project Feasibility | 29-Mar | 12 | 10-Apr |
| Final Presentation to IAB and MME Faculty | 18-Apr | 4 | 18-Apr |

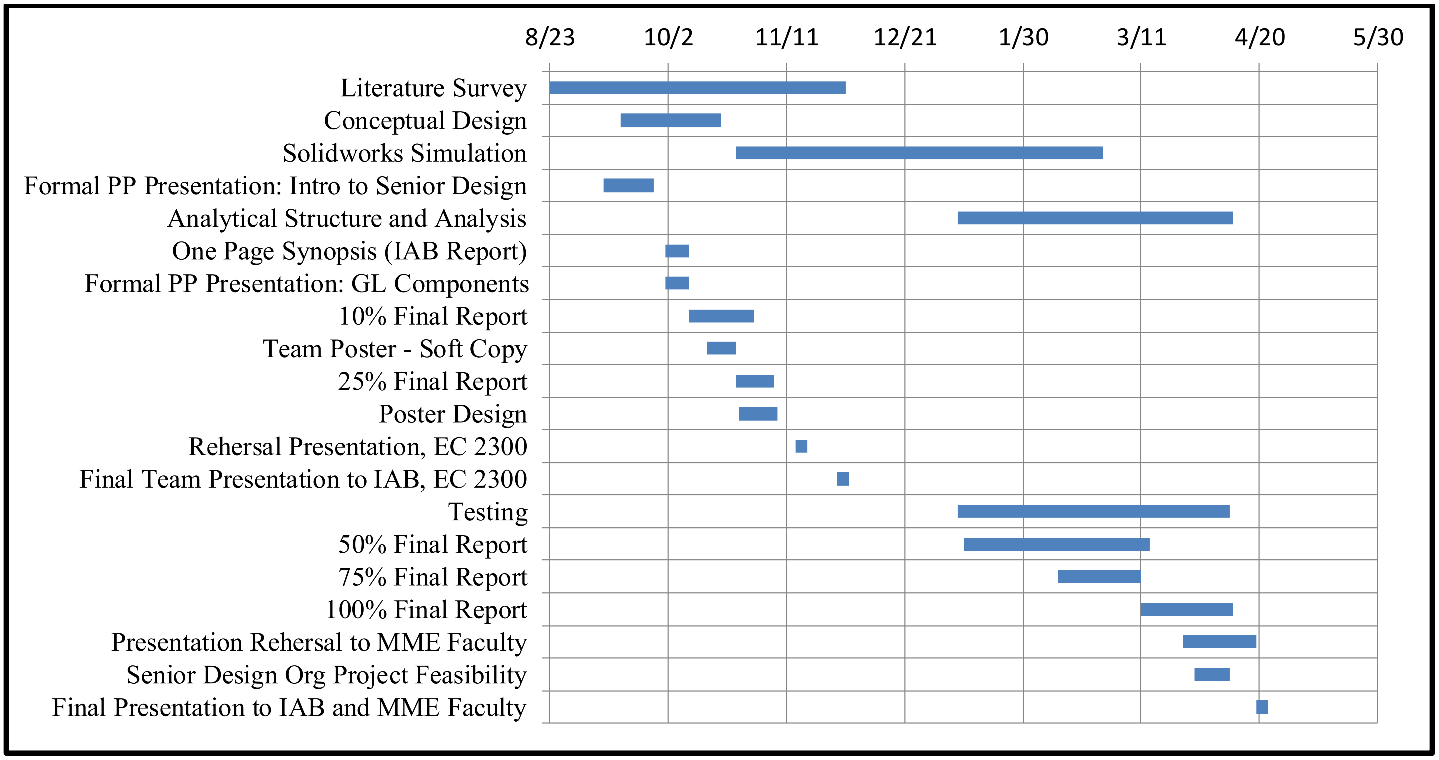


**Figure 23: Timeline**

## 5.4 Breakdown of Responsibilities among Team Members

Responsibility was broken down into five different experiments for the five different team members. The first design was designated to Devon Barroso, which was finished at the beginning of December 2012. Once the results come back from testing, the next design will be conducted depending on what the client is looking for. The next team member scheduled to create the design will be Ernesto Vallejo; this design is estimated to be finished by the end of January 2013. After this design is sent in, Guillermo Fernandez, Javier Seoane, and Jorge Barrera will conduct the remaining designs. The work was also distributed for the senior report as can be seen from the report distribution outlined above. The way that the report was split up was each of the team members had an equal share in writing. Editing of the report was assigned to Ernesto Vallejo in order to ensure consistency and flow of the final report.

**Responsibilities Division**

- Devon Barroso: Projectile Design, Time and Budget Analyst, Solidworks Modeling.
- Jorge Barrera: Target Design, Material Analyst
- Guillermo Fernandez: Target Design, Solidworks Modeling
- Javier Seoane: Target Design, Conceptual Developer
- Ernesto Vallejo: Projectile Design, Structural Analyst, Simulation Analyst

## 5.5 Cost Analysis

To calculate the cost of the shock loading experiments, the project is broken down into three categories:

### 5.5.1 Labor

Labor costs are a substantial part of the project's total cost. AFRL heavily emphasized the need for research when selecting the correct materials for the specific experiments. Figure 24 examines the break down for hourly labor through the whole experiment from research, design, fabrication, to implementation. In the research section of labor, it was estimated that three hours a week for an estimated sixteen weeks would be sufficient enough time to grasp the knowledge needed to design the experiment. The next subcategory of labor is design, which entails the calculations needed to select the correct material for both the projectile and target. This part of the labor takes the most time due to the lengthy calculations and computer design. It is estimated that eighteen hours a week for a length of three months would be a safe estimate to assume for design time. The fabrication process will be out of the hands of the designers and is being subcontracted to a local machine shop in AFRL. The estimate given by the machine shop was a total of forty hours to complete all five projects. As for the implementation of the experiment, AFRL performs each shot on a twenty-four hour spacing bases. This is due to the fact that for each shot, it takes about half a day to setup and another half day to retrieve the specimen from the tank after its been shot. It takes such long hours to recover the material because the recovery tank is under vacuum and thus takes a lengthy period of time to adjust to atmospheric conditions. More importantly, quoted directly from AFRL, the price for a testing day is $10,000.

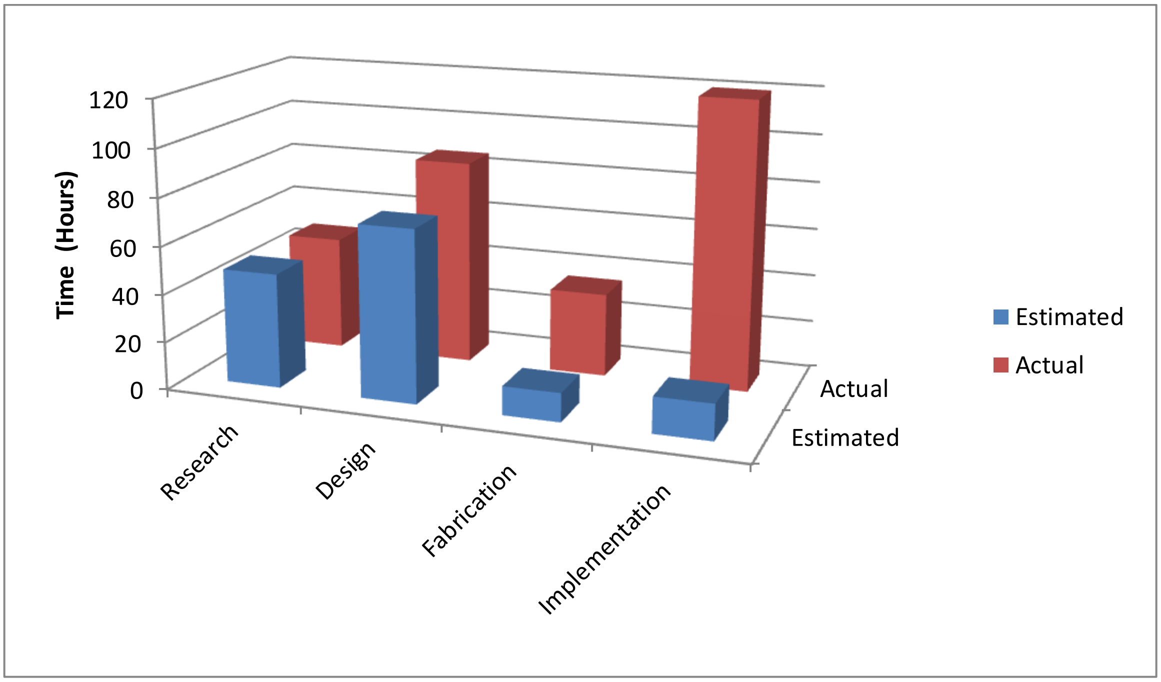


**Figure 24: Cost Analysis**

### 5.5.2 Travel

The HP3 labs are located in Pensacola, Florida, 680 miles away from Miami, Florida. Since this is the case, travel costs have also been analyzed. The cheapest airfare found was on cheaptickets.com with a total cost of $1,684.45 for all five team members round trip. This trip is necessary to grasp concepts and the scale of the experiment.

### 5.5.3 Prototype

Copper selections with the properties needed varied in price from hundreds to thousands depending on the source. The most economical price found for copper was from William Metals and Welding Alloys for a cost for both purchase and shipping of $520.60. This price quote was for copper alloy 110 rod with a diameter of five inches that weighs about forty-five pounds.

The next price quote was for a copper alloy 101 (oxygen free copper) with the same diameter of five inches. An online source was found to have the most inexpensive prices for this material and size. The quote was $132.62 also including shipping. The next material selected was for the target holder, which was aluminum alloy 6061. This cylinder will be machined to fit the target material. Supplier onlinemetals.com quoted this raw material at $82.06 also including shipping.

The other material that will be looked at for the experiment will be PMMA, which was found for a price of $85.65 on Interstate Plastics website. The PMMA rod is two feet long with a diameter of two and a half inches which should more than enough for the 15 target plates.

**Table 13: Estimated Project Cost Breakdown**

| Estimated Project Cost Breakdown | | | |
|---|---|---|---|
| **Category** | **Quantity** | **Unit Price** | **Cost** |
| | | | |
| **Labor** | | | |
| Student Hours | 289 hours | $65/hour | $18,785.00 |
| Implementation | 120 hours | $10,000/24 hours | $50,000.00 |
| Subtotal | | | **$687985.00** |
| | | | |
| **Travel** | | | |
| Hotel, Airfare, Meals | 5 members | $329.69/member | $1,684.45 |
| Subtotal | | | **$1,684.45** |
| | | | |
| **Materials** | | | |
| Copper 110 | 1 rod | $520.60/rod | $520.65 |
| Copper 101 (OF) | 1 rod | $132.63/rod | $132.62 |
| Aluminum 6061 | 1 rod | 82.06/rod | $82.06 |
| PMMA | 2ft rod | $85.65/rod | $85.65 |
| Miscellaneous | N/A | N/A | $1500 |
| Subtotal | | | **$2320.98** |
| | | | |
| **Total** | | | **$72,790.43** |

## 5.6 Patent/Copyright Application

Being that the design is of the actual thicknesses and materials of the projectile, patent possibilities are not promising. If the design involved some sort of apparatus and or new material, a testing patent could be researched and established. Another factor that added into not researching a patent was that the project is being conducted for the Department of Defense, which in this case is the United States Air Force.

# 6. Prototype Construction

## 6.1 Description of Prototype

While many of the components of the system are not in the control of the design team, they are just as important to the success of this project. These components include the shock loading system, which consists of the pieces needed to hold all the data acquisition systems used for experimentation and analysis of the impact plate. The other side of the prototype consists of the gun itself along with its components that include the gun breech, gun barrel (launch tube), and the projectile itself. Below is an image of the whole system together which is already set in place at Eglin Air Force Base.

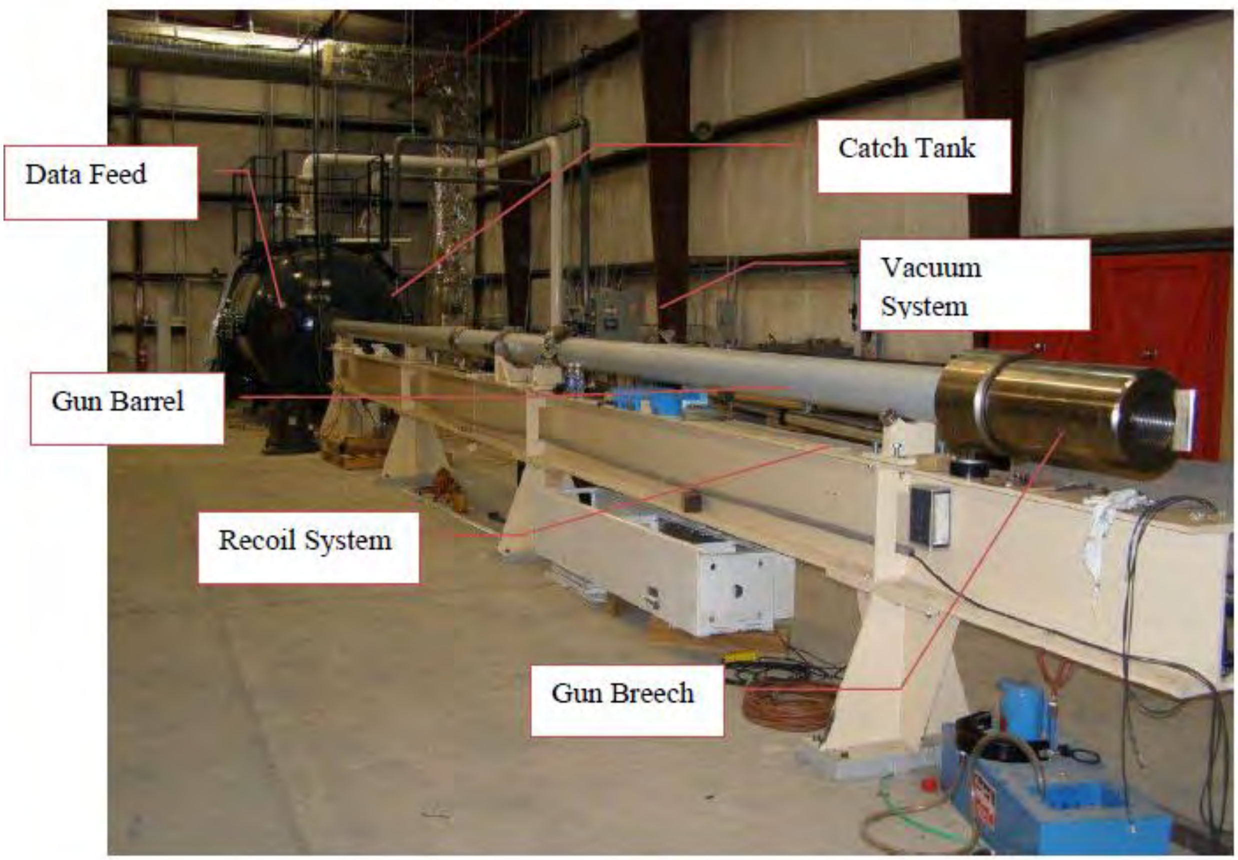


**Figure 25: Prototype System Courtesy of AFRL, Munitions Directorate [1]**

For the shock loading system, the components include the target itself, along with tilt pins, guard rings, velocity pins, driver plate, and a spall plate. Each of these components has their own unique job in order to achieve the final goal for each experiment. The final goal is to achieve results where the target for each of the five experiments is to experience only uniaxial shock loading. Moreover, it is critical to hold all the components in place in order to minimize the error. Initially, it was requested that the material be a copper target and a copper projectile, but through various calculations, this is deemed to be a faulty premise and thus other materials have surfaced to be used as the target and the projectile. The spall plate inside the experimental chamber is intended to try to minimize the material fracture that will likely occur in the material of the target if not for the spall plate's intent to divert the shockwaves created by the collision.

The side of the apparatus where the gun is set and the projectile is to be placed includes other components that are essential for the success of these experiments. The gas gun itself, which will be used for this experiment, is capable of shooting the projectile upwards in the range of 500 to 2000 meters per second with an accuracy of ± 50 meters per second. The projectile is explained in detail in sections 1 through 4. The projectile is to be placed at the gun breech (which is rated at 90 ksi max pressure) detailed in the prototype system picture (Figure 25). Once fired, the projectile will travel the length of the barrel which has a pseudo vacuum system to achieve higher velocities and more accurate measurements in speed and application. The main propulsion system in the gun is the M30 propellant powder which will be stimulated with a standard percussion initiation system.

## 6.2 Prototype Design

Since the target assembly and projectile are components that will be destroyed when the experiment is performed, there will be no real tests performed on the prototypes. Moreover, due to the type of equipment used to perform the experiment, the availability of such machines is concentrated only to certain national laboratories, air force bases, and private research facilities. Thus, the only testing on the prototypes will be done by theoretical calculations and possible computational analysis with special software. This being said, the special software requires expert knowledge which cannot be attained in the timeline of this project.

## 6.3 Construction

The construction of the projectile and target will be left up to the client. Since the projectile will be shot out of a gun powder setup, if the tolerances are not correct, the projectile may jam within the barrel and the gun may become a bomb. The projectile weights around two pounds and is shot at velocities around the speed of sound, thus, to become lodged in the barrel, the projectile can cause destroy the gun. This being the case, the construction and manufacturing will be left up to the client and the AFRL machine shop. The research and construction consist of the manufacturing of the projectile body, which is standard for all five shots. The projectile body is made separately from the projectile impactor. Manufacturing the impactor comes with great attention to thickness and width which affect the results. After the machining of both the projectile body and impactor, the next step in the construction is to join the two pieces. This is achieved with a light adhesive on the front of the projectile body.

The target assembly also requires small tolerances which have to be met for the success of the experiments. The methods used for the construction of the target are standard in HP3 facility. Proper communication with the machinists at HP3 is essential in the accuracy of the design parameters set through this project for all the designed shots.

# 7. Testing and Evaluation

## 7.1 Overview

The goal of having five projectile/target packages is to cover the range of possible results from no spall to complete spallation of the target material. The goal is to maintain all of the shots around the pressure where the spall would begin to form in order to get a more accurate picture of the process from the experimental data recovered. This means that not any single experiment should either greatly exceed or achieve a pressure that is much less than that required for spallation.

## 7.2 Description of Experiments

For each of the five experiments, the gun will be loaded at the breach with the preassembled projectile/impactor combination. The speed of each shot will be controlled by varying the amount of gunpowder used to propel the projectile. After traversing the barrel of the gun, the impactor will travel a length of open space which is less than the length of the projectile it is affixed to. This will help ensure that the impactor makes planar contact with the target assembly and that its flight is not altered in any way.

Because the actual target plate will be a separate piece from the momentum trap/target assembly combination, it will be propelled backwards before the edge effects of the target assembly reach its geometry. The target plate will then be soft-recovered in order to evaluate the results of the experiment. It is the first time the High Pressure Particulate Physics Facility at Eglin Air Force Bases utilizes a momentum trap and conducts soft recovery of shock loading experiments.

## 7.3 Evaluation of Experimental Results

Data will be collected as each experiment is conducted using different telemetry probes on the target assembly. Photon Doppler Velocimetry probes will be used to measure the front surface, or projectile impact velocity, and the rear surface, or local particle velocity, during the experiments. Such information will help measure the actual velocity and update the mathematical predictions of the equipment. Data from other probes includes the orientation of the impactor so that a planar impact can be verified. Conducting the experiments over the specified range of pressures should provide a progression of “snapshots” of the spall formation process in the copper target material. The targets used have undergone cold forging during their manufacturing.

**Figure 26: Soft Catch System**

### 7.3.1 First Shot

The first shot will be conducted at 350 meters per second using PMMA for the projectile and Copper for the target. A shot simulator, set up and results shown below, was used to verify the calculations done earlier.

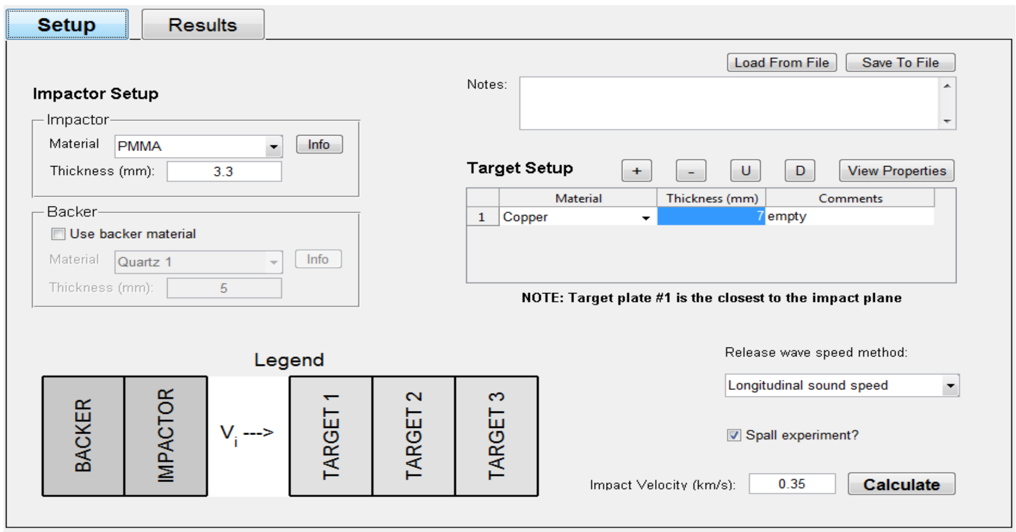


**Figure 27: First Shot Simulation Set Up**

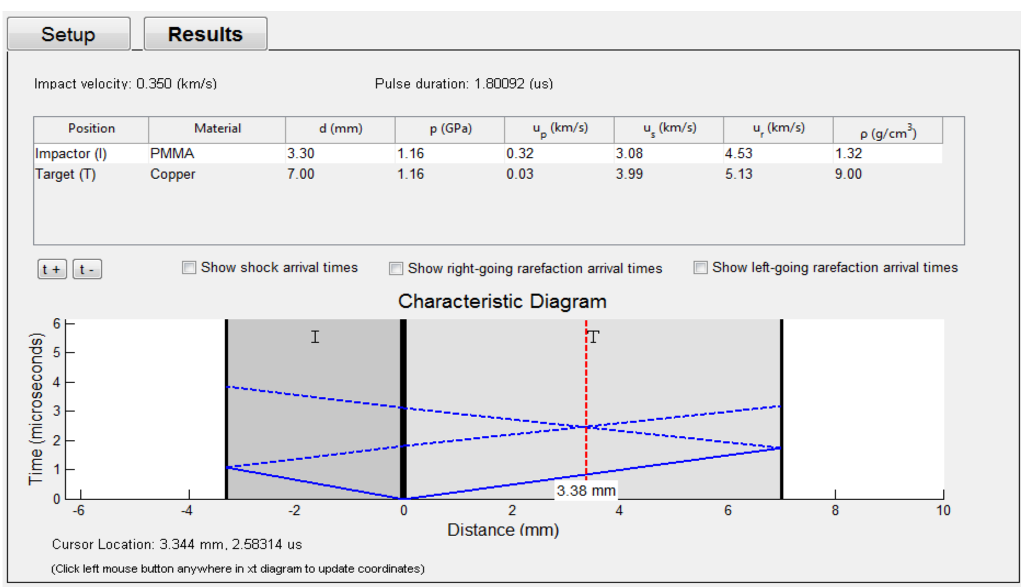


**Figure 28: First Shot Simulation Results**

From what is show in the results, the area of were spall should take place will be at 3.38 millimeters. The impact pressure is approximately 1.16 GPa which is what is expected from the calculated data. This pressure at 1.16 GPa will not show spall since the spall strength of copper is 2.6 GPa, which is what is intended for this first shot.

### 7.3.2 Results and Analysis of First Shot

The first shot was conducted Friday, March 22nd, 2013 at 9:00 A.M., Eglin Air Force Base local time. Photos from the recovery are shown below. The projectile was found approximately 30 inches inside the soft catch system. No projectile impact velocity was recorded.

**Figure 29: Soft Catch Recovery System**

**Figure 30: Recovered Momentum Trap**

**Figure 31: Recovered Target**

The data collected at AFRL from the first shot is presented in Figure 32.

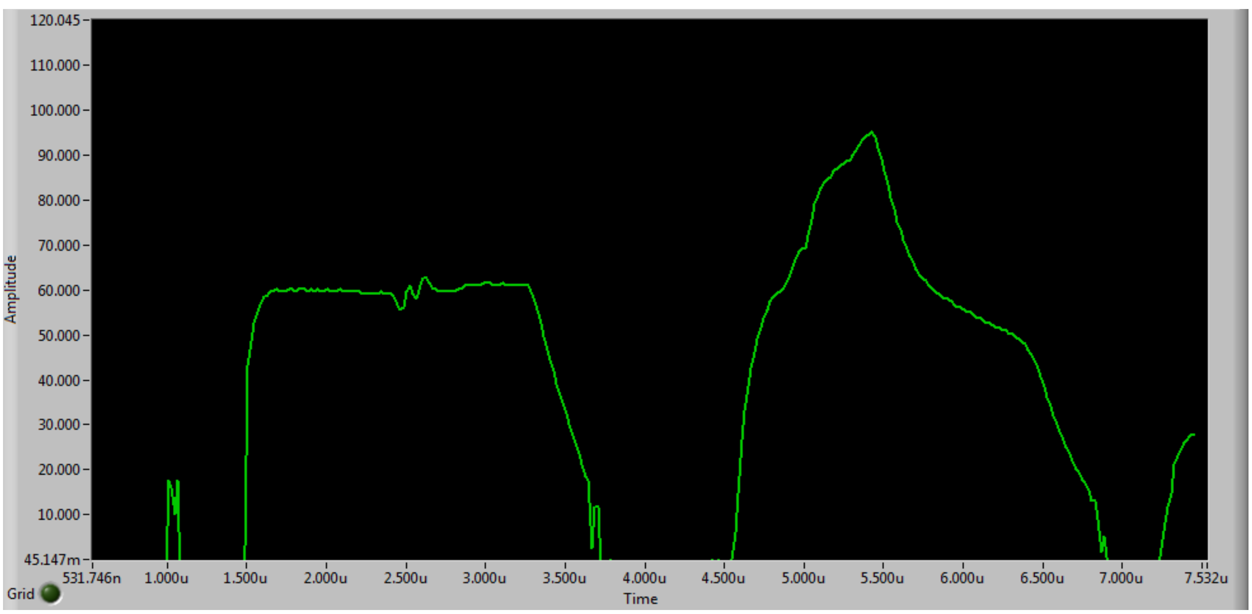


**Figure 32: First Shot Data**

The shockwave that is shown outlined in Figure 33 is the shock impact data that was expected from the analysis. Using the material properties of the copper target we can verify that the pressure was achieved at 1.07 GPa (Table 14). The pulse duration recorded for the shockwave was approximately 2.25 microseconds.

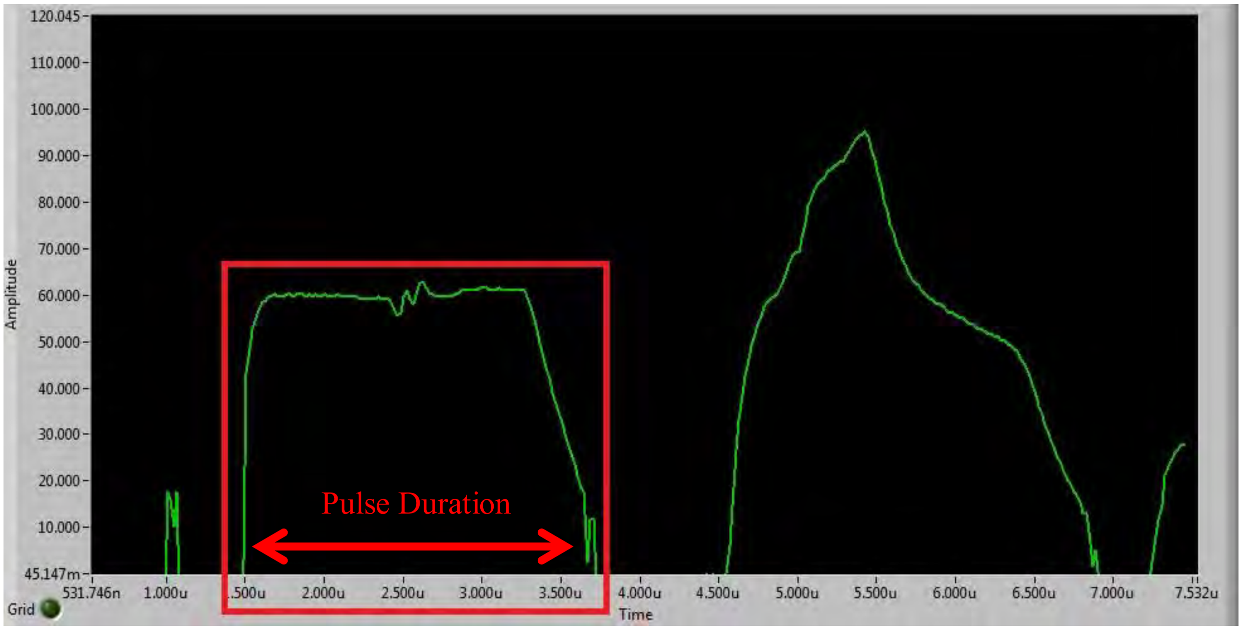


**Figure 33: Second Shot Shockwave Signal**

**Table 14: Experimental Pressure Calculation First Shot**

| Experimental Pressure Calculation | |
|---|---|
| $\rho = 8.952$ | $P = \rho_o c_o u_p + \rho_o s u_p^2$ |
| $c_o = 3.94$ | |
| $u_p = 0.06/2 = 0.03$ | **P = 1.07 GPa** |
| $s = 1.489$ | |

**NOTE:** Table 14 presents the use of Equation 3 derived for the target at impact. (Sample calculation page 16 Step 1).

For Figure 34, the highlighted spike is unknown data. AFRL will conduct the necessary analysis to understand the significance of the spike recorded. The peak might represent microstructure changes inside the target plate or can be a focusing effect from the geometry of the target plate's draft angle.

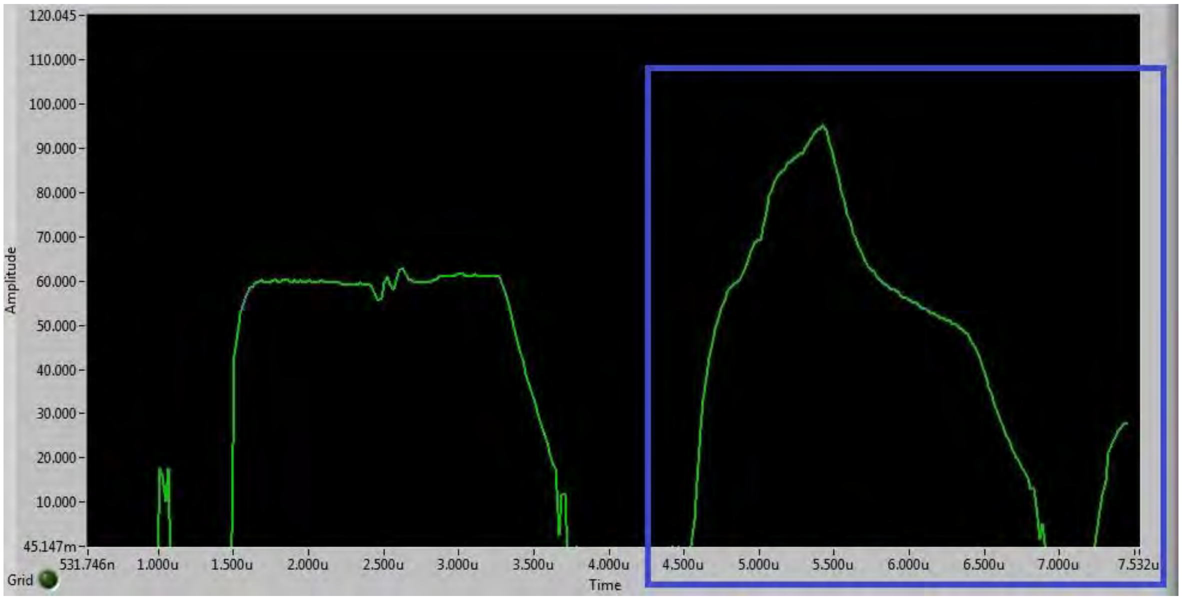


**Figure 34: First Shot Unknown Data**

The areas highlighted in yellow in Figure 35 can be considered as noise waves and can be neglected until further investigation is performed by AFRL.

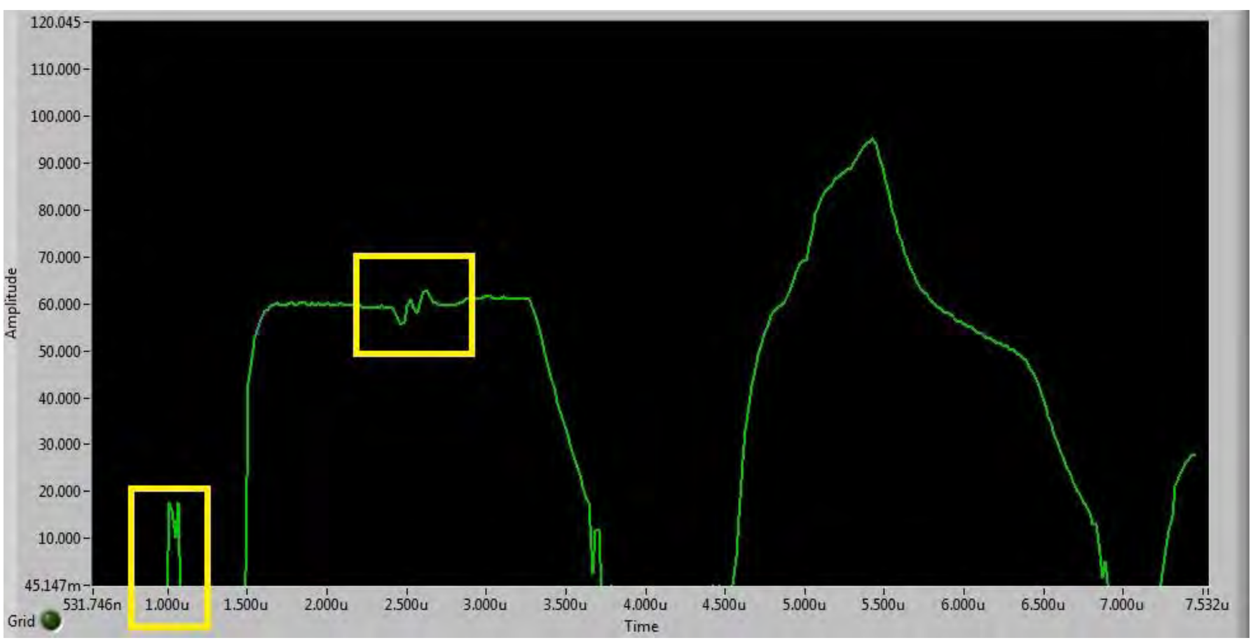


**Figure 35: First Shot Noise Waves**

Further investigation will be performed on the shockwave results and data at a later time. For the purposes of this project the copper target did not show any visual spall as expected.

### 7.3.3 Second Shot

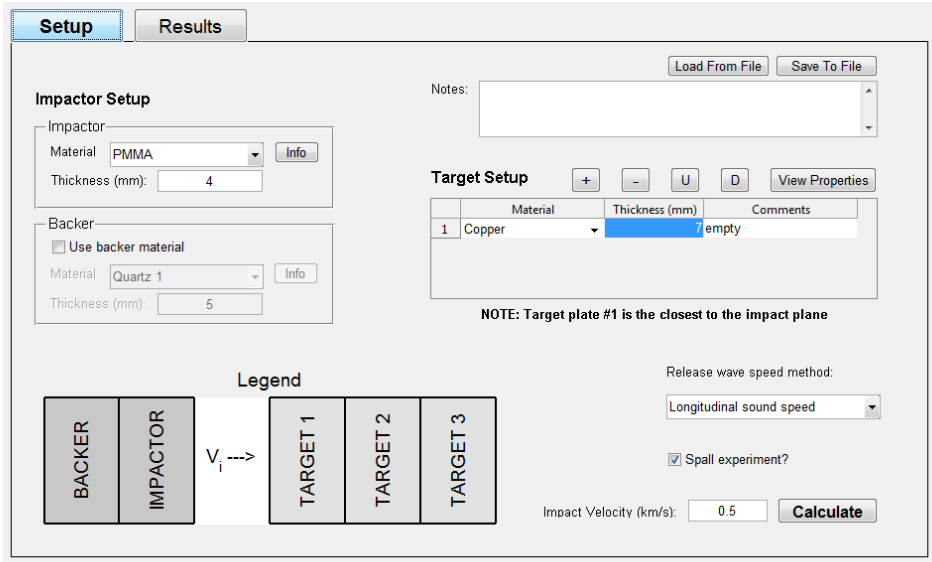


**Figure 36: Second Shot Simulation Set Up**

For the second shot of this experiment AFRL used the same dimensions for all the assembly components at a higher velocity of 500 meters per second. The predicted impact pressure is 1.76 GPa. A shot simulator, shown in Figure 36-37, is used to predict the location of the spall along with the pulse duration and impact pressures.

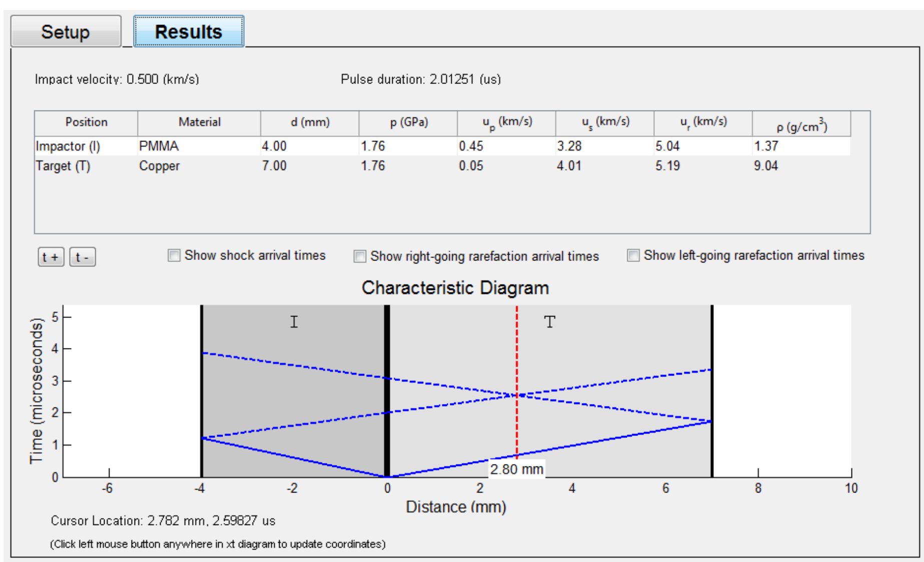


**Figure 37: Second Shot Simulation Results**

### 7.3.4 Results and Analysis of Second Shot

The second shot took place on Monday, March 25th, 2013 at 9 A.M., Eglin Air Force Base local time. Unfortunately, the rear surface velocity from the acquisition system could not be collected due to a malfunction in the velocity pins that record the data. Nevertheless, the projectile impact velocity was measured at 518 meters per second. Only the physical target and momentum trap were recovered, shown in Figure 38, 39 and 40.

**Figure 38: Front view of second shot recovered**

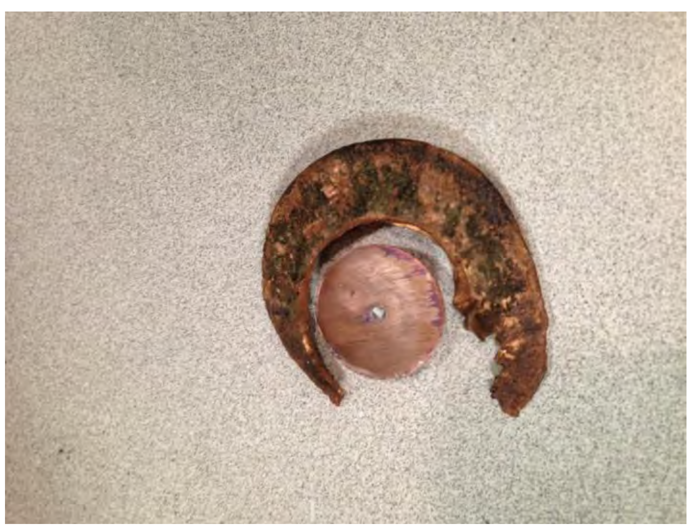

**Figure 39: Back view of second shot recovered**

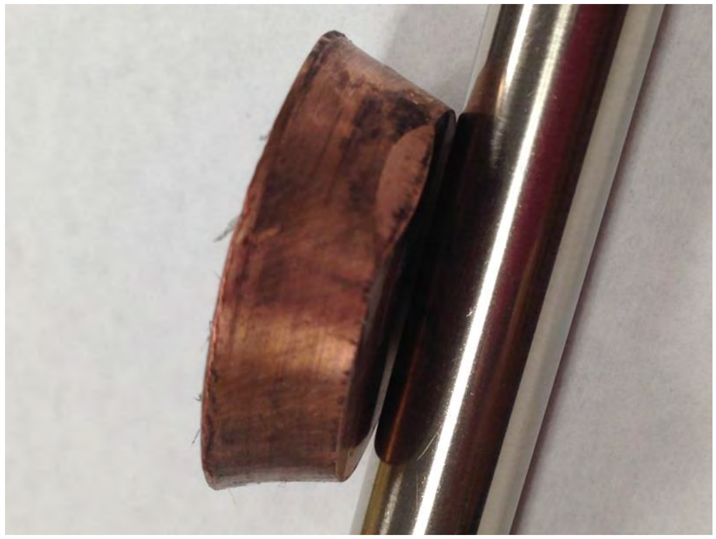

**Figure 40: Lateral View of Second Shot Recovered**

Even though data was not collected, a physical analysis can be conducted with the results shown from the shot simulator. The spall strength of copper is 2.6 GPa, from the simulator it is shown that the impact pressure achieved is 1.7 GPa; this means that there would be no spallation within the target. These results are compared to the Figures 38, 39 and 40 where the target can be seen still intact with very little damage to outer surfaces.

### 7.3.5 Third Shot

The third shot will be conducted with a 2024 Aluminum impactor and a copper target plate. The thicknesses for the components are 6.5 mm and 7 mm respectively. The shot velocity expected is 300 meters per second. The use of aluminum for the impactor will produce a 3.2 GPa impact pressure. Since the predicted impact pressure is greater than 2.6 GPa, the probability that the target will undergo visual deformation is expected. The use of predictive software was also applied for his shot.

### 7.3.6 Results and Analysis of Third Shot

The third shot took place on Monday, April 1st, 2013 at 9 A.M., Eglin Air Force Base local time. The projectile impact velocity achieved was measured at 321 meters per second, which was 7% higher than the targeted velocity. Figures 41 through 44 present the acquired data, soft recovered target plate, deformed momentum trap and impactor. The recorded rear surface velocity was 182 meters per second.

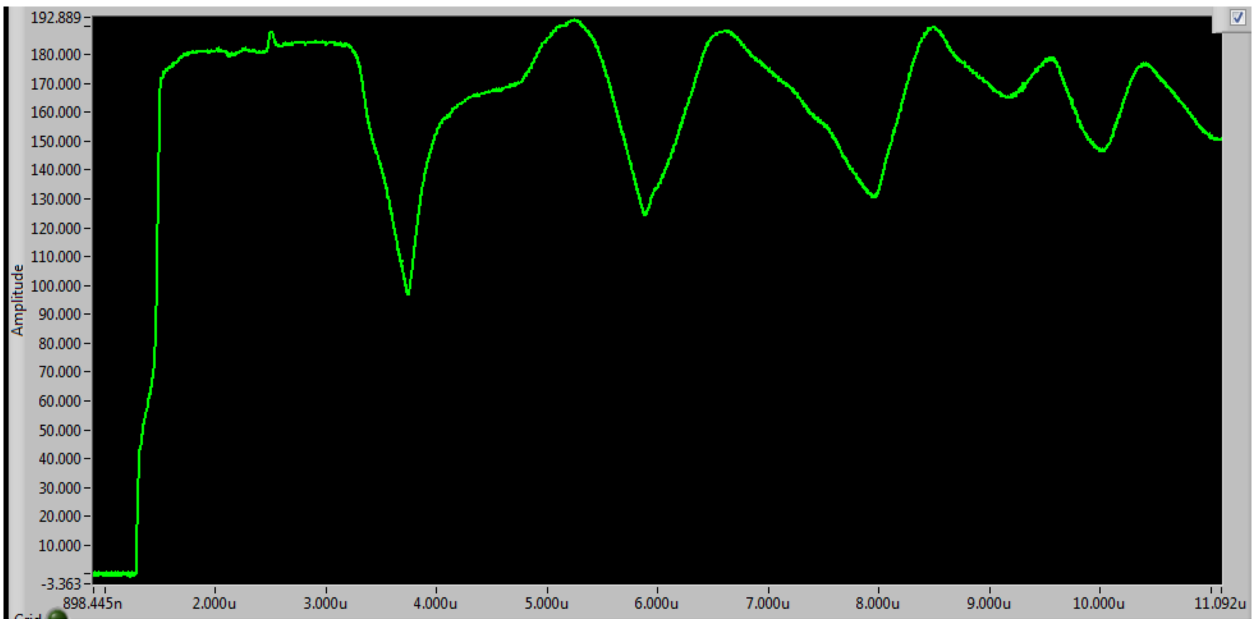


**Figure 41: Third Shot Data**

Figure 41 is the data recovered for the third shot. In Figure 42, the signal that characterizes spallation is highlighted in yellow. Such signal follows the expected behavior of copper during spallation. The "pull back" or change in velocity is used to approximate the actual value of spall strength of the specimen. Following Table 15, the recorded local particle velocity produces an impact pressure of 3.51 GPa, which is above the predicted impact pressure of 3.25 GPa. The pulse duration for the shockwave was approximately 2.65 microseconds.

**Table 15: Third Shot Experimental Pressure Calculations**

| Third Shot Experimental Pressure Calculation | |
|---|---|
| $\rho = 8.952$ | $P = \rho_o c_o u_p + \rho_o s u_p^2$ |
| $c_o = 4.22$ | |
| $u_p = 0.182/2 = 0.091$ | **P = 3.54 GPa** |
| $s = 1.489$ | |

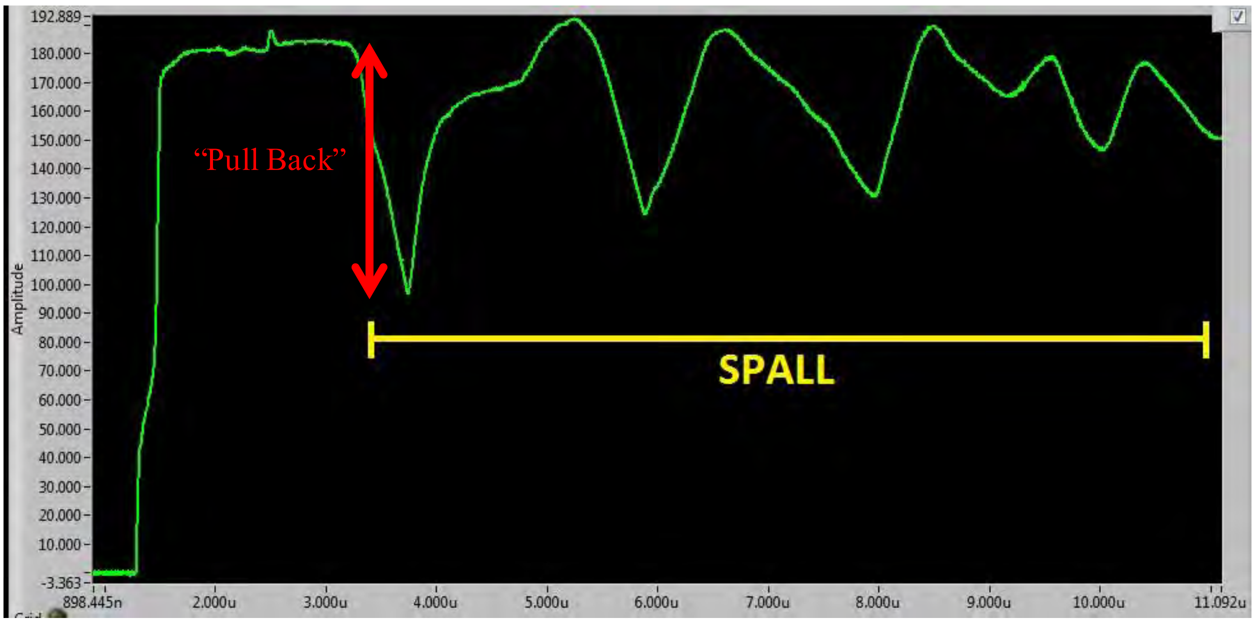


**Figure 42: Third Shot Data Spallation**

**Figure 43: Momentum trap and one dimensional spalled target**

Figure 43 presents the one dimensional spalled target plate which was soft recovered. The target was recovered at 32 inches inside the soft recovery apparatus. The completely spalled target supports the data signal in Figure 41. Moreover, the complete separation of the target was through a one dimensional plane which confirms the success of the momentum trap design. It is important to acknowledge that complete spall was not an expected occurrence for this shot. Nevertheless, the very high dislocation densities created in the target due to forging methods and cold work properties of the specimen, are believed to have aided in the complete spallation of the target.

**Figure 44: Deform 2024 Aluminum impactor**

### 7.3.7 Fourth Shot

The fourth shot will be a duplication of the failed second shot. It was decided to conduct a duplicate shot because the AFRL's advisor desired to acquire data that could be used for the analysis of the soft recovered specimens.

### 7.3.8 Results and Analysis of Fourth Shot

The fourth shot took place on Friday, April 5th, 2013 at 9 A.M., Eglin Air Force Base local time. In this case, the local particle velocity at the back of the target was successfully collected. The projectile impact velocity was measured at 534 meters per second. Figures 45 through 47 present the signal recovered and highlighted key components of such information.

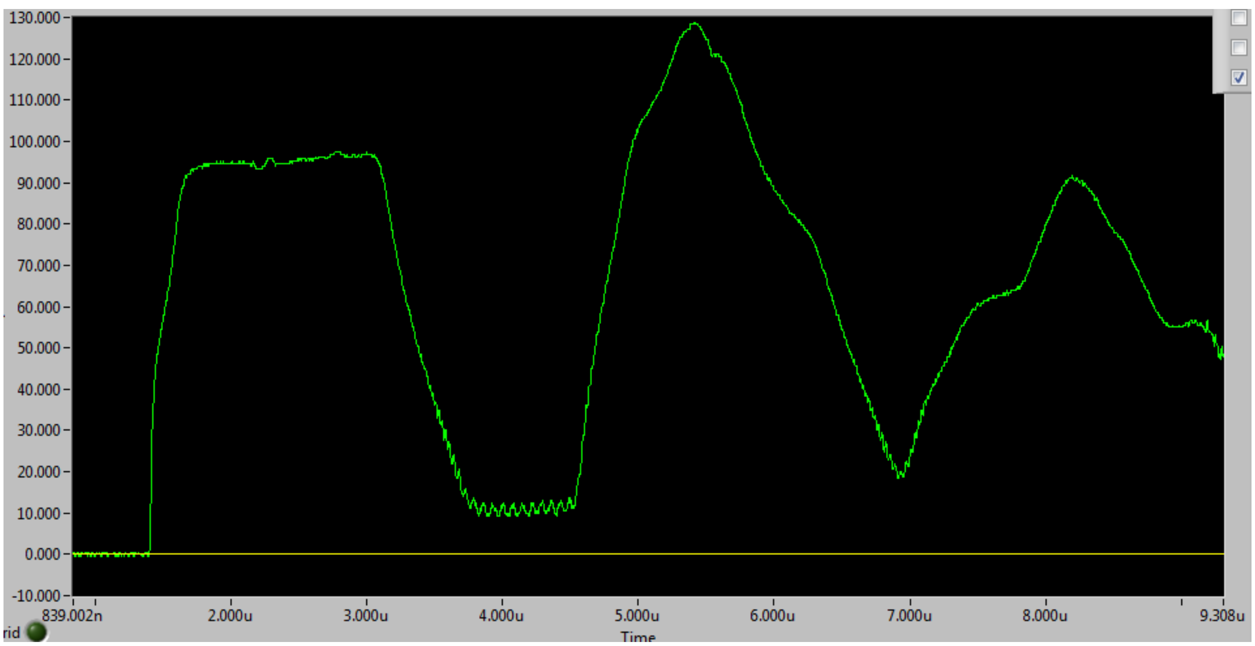


**Figure 45: Fourth Shot Data**

Figure 46 highlights the shockwave created on the target plate. The recorded local particle velocity at the rear surface was 95.5 meters per second. Then, the impact pressure is calculated to be 1.77 GPa. The updated prediction is 1.88 GPa, which is 5% more. The pulse duration measured in the shot is approximately 2.70 microseconds.

**Table 16: Fourth Shot Experimental Pressure Calculation**

| Fourth Shot Experimental Pressure Calculation | |
|---|---|
| $\rho = 8.952$ | $P = \rho_o c_o u_p + \rho_o s u_p^2$ |
| $c_o = 4.08$ | |
| $u_p = 0.0955/2 = 0.04775$ | **P = 1.77 GPa** |
| $s = 1.489$ | |

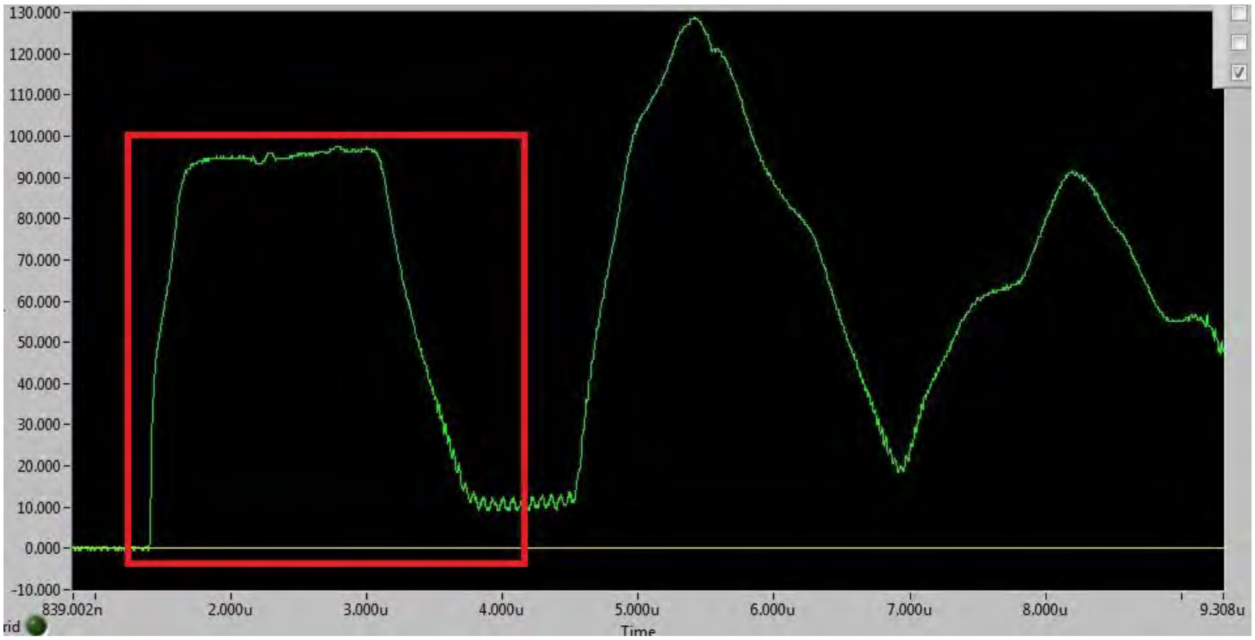


**Figure 46: Fourth Shot Shockwave Signal**

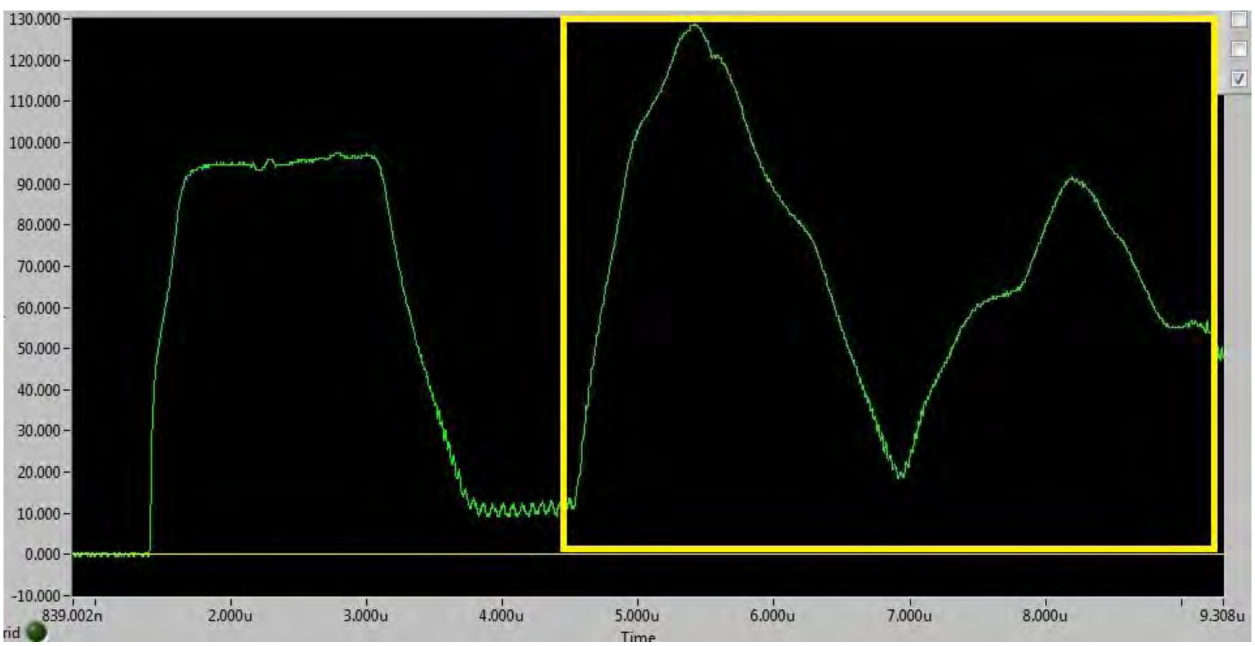


**Figure 47: Fourth Shot Unknown Data**

# 8. Design Considerations

## 8.1 Assembly and Disassembly

For the design of the projectile and target packages, the assembly of the components was not taken into account since the finishing of the parts will be done by one of the machinist who works within the same branch as Dr. House. The machinist will use the known specifications of the standard HP3 items as well as the specifications on the design package. It is noted that the assembly of the components for the target is done under very specific and precise conditions in order to ensure a planar impact with the projectile. The disassembly of the components is not a factor driving the design of the packages since most of the components are destroyed when the experiment takes place. The FIU team took into account the separation of the components after impact occurs since this has to allow for a clean recovery of the target. Thus, the FIU team does not take into full consideration the assembly or disassembly of the components since that is taken care of by ARFL.

## 8.2 Maintenance of the System

The maintenance of the projectile and target packages is not required since all of the components are destroyed during the experiment. What is taken into account is the preparation of the packages for the experiment and the aftermath of the shot. But such tasks are performed by AFRL personnel. Major maintenance of the system is not required since after each shot is performed, a new set is used.

## 8.3 Global Learning & Environmental Impact

The proposed design uses readily available materials (i.e. copper alloys, PMMA) which do not require the addition of environmentally dangerous methods of production. The design only requires very intricate and complex methods of machining in order to ensure the precision and accuracy of the impact between the projectile and target. Thus, the production of waste from the machining and finishing of the parts is the only environmental impact from the designs. The design itself will not cause any environmental impact since it is made of environmentally friendly materials such as copper and PMMA.

In another aspect, the development of improved protection may reduce the number of casualties occurring from the fragmentation of protective equipment. Improved morale of the customers from better protection and safer equipment could shift their attention to the task being performed in hazardous environment; therefore, efficiently increasing the performance of the personnel and the quality of the results expected from civil or military applications that utilize the research performed through this project.

A better understanding of shock loading can be applied to many circumstances where the outcome of an experiment including explosives cannot always be perfectly predicted. For example, every type of explosive must be tested when developed. Explosives are widely used in the construction industry, in both creation of new structures and in the safe demolition of existing structures. This means that there is a need for ranges that can isolate and contain these potentially hazardous experiments while maintaining the ability to observe meaningful results.

Principles learned from studying shock loading can be applied when designing the safety shelters that must be present at such ranges designed to keep the operators safe over the course of their work. Another consideration is the containment of such experiments in order to limit the potential risk area. An understanding of shock loading behavior can help in the design of barriers, boxes, and other types of containment apparatus used to contain the shrapnel that can be generated during these experiments.

As mentioned earlier, explosives are often used in the demolition of existing structures. A better understanding of shock loading can help with the proper safety precautions to avoid collateral damage from the resulting shock. In this situation, not only the effects of the explosives must be considered, but also the reactions caused by the collapsing structure. Safety equipment for the workers that oversee such operations must be designed with the possibility of shock impact in mind.

Another example where shock loading must be considered is in aviation and space industries. Aircraft and spacecraft must be designed to protect their occupants from the very real possibility of very high strain impacts. As airspace and close to earth orbit become more cluttered with man-made objects, as well as foreign space bodies in the case of orbit, high strain impacts will become more likely. The occupants of spacecraft and the delicate machinery that allows them to operate must be protected from potential spallation or other damage caused to the outside of the craft. If the sky and space truly are the new frontiers that human kind longs to explore, then shock loading protection is one of the most important applications this work can be applied to. In space, collisions must be considered at much greater speeds. Understanding the way the materials react in these situations will be paramount to our continued foray into the cosmos. Increased safety of the human explorers and reliable machinery will make it possible to explore ever farther from this globe which we call home.

## 8.4 Risk Assessments

Due to the requirements for the experiment, the risk can be measured by failure. Failure being the creation of a spallation plane outside the "sweet spot" in the target, no spallation plane created, or fragmentation of the target at premature impact pressures. The risk to human life is not accounted for since the required safety measurements have been established by AFRL procedures. The impact between the target and the projectile occurs inside a secure pressure vessel which ensures that pieces from either the projectile or target will not be a danger to human life. The only exposure that the projectile has to human endangerment takes place when the powder gun is fired. To overcome the risks of human fatalities, AFRL manufactures all the components of the packages utilizing established machining methods which ensure the extreme tolerances required for the experiment.

# 9. Conclusion

## 9.1 Conclusion

From the design development, a general formulation of shock-loading experiments has been established in a simple and straight forward matter under the aforementioned assumptions. The application of engineering ideas for the simplification of the project has allowed for a cost effective method of predicting and calculating the occurrence of spallation in a copper target. Moreover, the choice of utilizing PMMA as the main impactor further reduces the material and manufacturing costs of the experiments. When the proper analysis of the experimental results is conducted the method used through this design development can be validated and the experimentation of other materials can be undertaken. The application of this method would allow for rapidly available predictions which can then be used as a basis for comparison with experimental results.

Through the project development, a set of trade-in studies have been presented which allows the AFRL mentor to conduct multiple series of shots that enable a greater flexibility in the testing of copper. The set of trade-in studies covers the requested costumer's goals within acceptable ranges and will provide a thorough understanding of copper, thus ensuring AFRL's satisfaction of the project's results.

It can be observed that the stipulated requirements for the project at first did not allow for room to move, yet through extensive research and understanding of the advance physics controlling the situation at hand, multiple scenarios were considered and developed. Thus, the project's objective of designing a projectile/target package that can achieve incipient spall inside the target plate has been achieved through confident predictions. The momentum trap, key component of the system, allowed for satisfactory results since it attenuated the waves' propagation from the edges during impact. Consequently, it has been experimentally proven that the application of a momentum trap in shock-loading conditions simplifies the acquisition of significant results. Evidence of the success of the momentum trap can be seen in Figures 31, 38, 39 and 40. In those figures, it can be observed little to no distortion of the boundaries of the target plate in the radial direction, which strongly emphasizes the vitality of the momentum trap in this project. Moreover, Figure 46 presents a one dimensional spallation plane that resulted in the separation of a part from the target plate.

Finally, this project has effectively delivered two sets of five projectile/target packages that have been designed to the customer's specifications. The results obtained from all shots performed at AFRL are strong evidence of the success of this project.

## 9.2 Patent/Copyright Application

No patent or copyright application will be filed since AFRL is the only entity that utilizes the proposed designs. The publication of research papers open to the public also allows other private and public laboratories to use the proposed designs for their own experiments.

## 9.3 Commercialization Prospects of the Product

AFRL is the only customer for the proposed design. The commercialization of the components requires the acquisition of machining equipment that can guarantee the extreme tolerances required for the experiments. Moreover, the design of the projectile and target package is customized to fit the apparatus used at the HP3 center at Eglin AFB.

## 9.4 Future Work

The design of the projectile and target packages was performed through an iterative process. Therefore, after the series of proposed shots have been tested, there is ground to improve upon the knowledge of how incipient spall appears in copper. An increase in the number of shots tested will allow for a more thorough acquisition of data and can create a complete picture of how copper behaves. Annealed specimens will undergo the same series of shots performed to compare the effects of manufacturing process in the properties of copper. Thus, given the resources, AFRL can continue with this research and the design of more specific projectile and target packages to achieve more accurate and precise stress levels. The different scenarios covered through this project will allow for such eventuality. Nevertheless, the fact that the powder gun utilized in the shots does not consistently reach the desired projectile speeds weakens the possibility for future work at velocities close to 350 meters per second since it only allows for approximate impact stress levels. The development of a soft catch recovery system that can withstand speeds above eight hundred meters per second will allow for the testing of materials that are characterized by higher modulus of elasticity.

AFRL has shared the desire to conduct computer tomography of the soft recovered specimens; this would allow for a complete three dimensional view of the specimens. After the specimens are characterized, quasi-static compression and dynamic loading will be applied to the specimens that have experienced microstructural changes from the shock loading experiments. Such work will help understand the effects of shock loading on the tensile and compression properties of copper.

# 10. References

[1] Air Force Research Laboratory, High Pressure Particulate Physics Facility, Elgin AFB, FL: Munitions Directorate.

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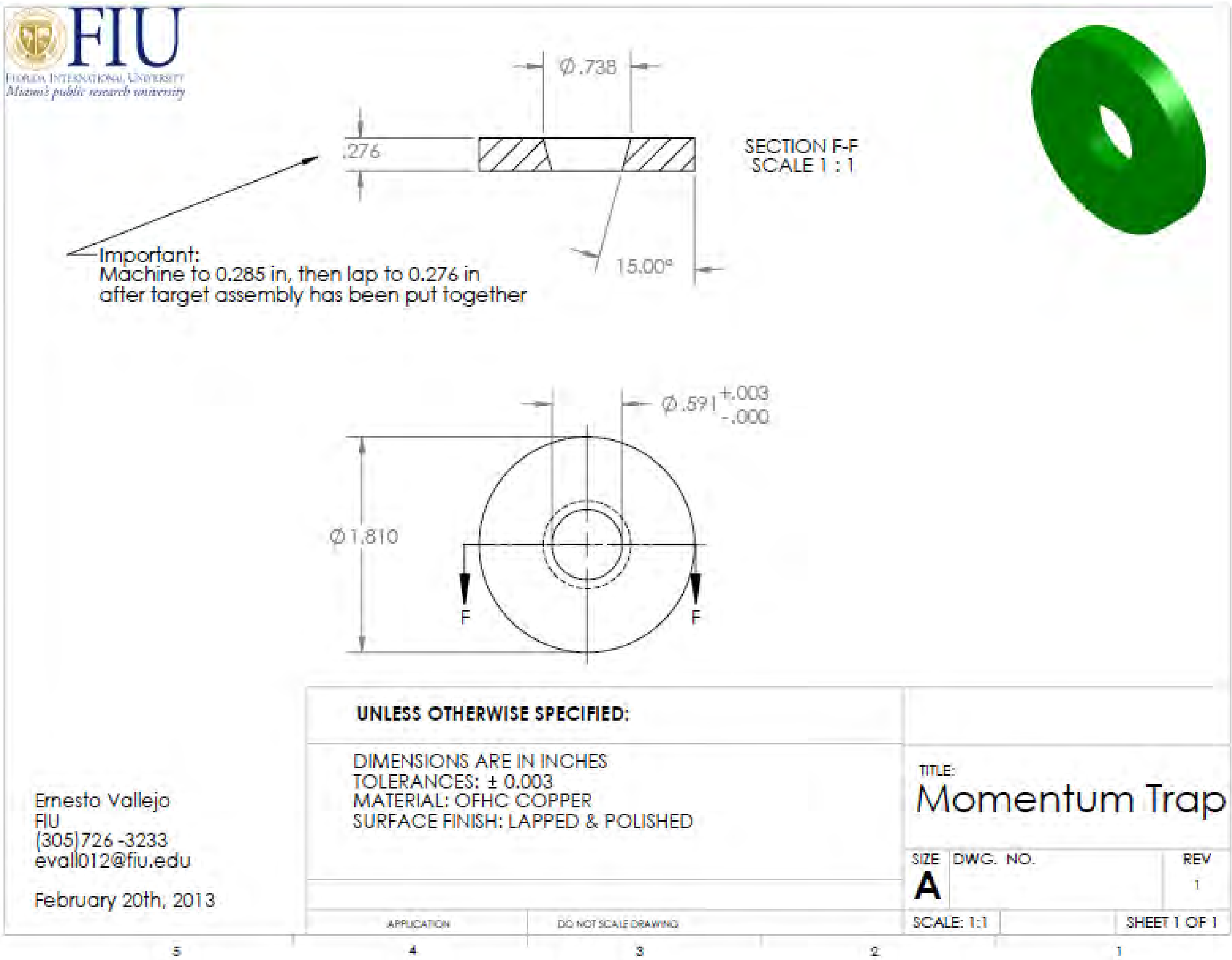
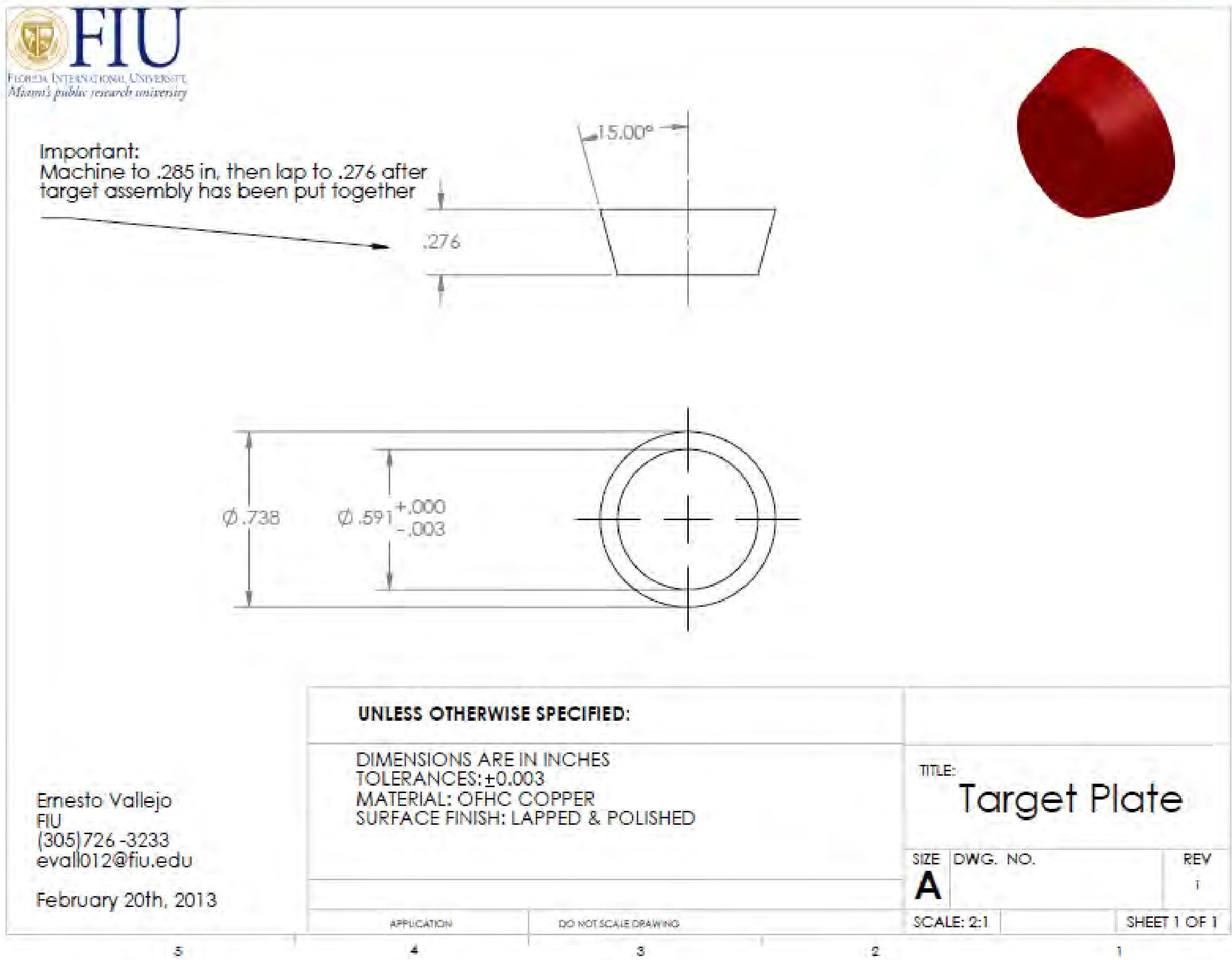
# 11. Appendix: Final Design Packages

## 11.1 Momentum Trap

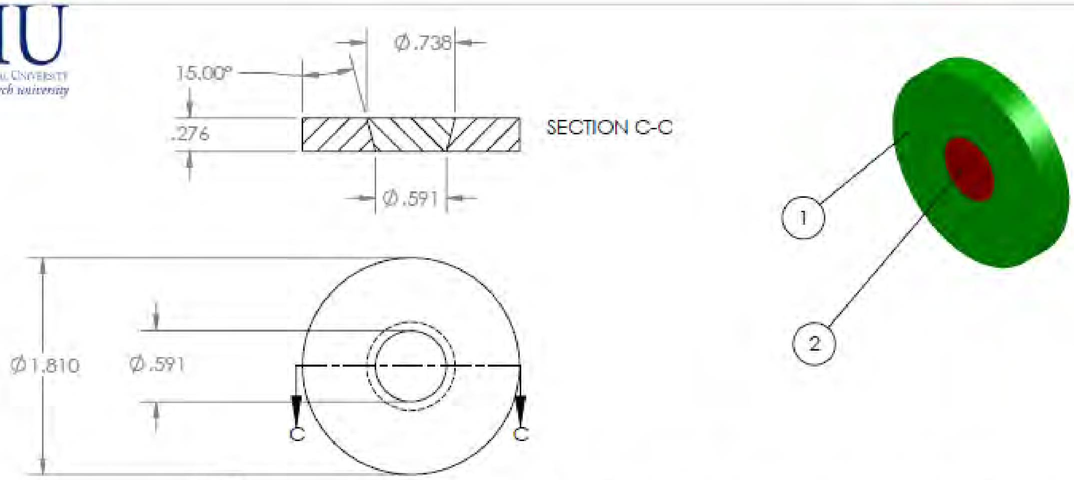


## 11.2 Target Plate



## 11.3 Target Assembly

FIU
Florida International University
Miami's public research university




**NOTE:**
**Surface finish needs to be performed after Target Plate and Momentum Trap have been assembled.**
**The use of epoxy to bond the two parts needs to be thorough in order to ensure proper coverage of all surfaces in all directions.**

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | Momentum Trap | Material: OFHC COPPER | 1 |
| 2 | Target Plate | Material: OFHC COPPER | 1 |

**UNLESS OTHERWISE SPECIFIED:**

DIMENSIONS ARE IN INCHES
SURFACE FINISH: LAPPED & POLISHED

TITLE:
Target Assembly

SIZE A | DWG. NO. | REV 1

APPLICATION | DO NOT SCALE DRAWING | SCALE: 1:1 | SHEET 1 OF 1

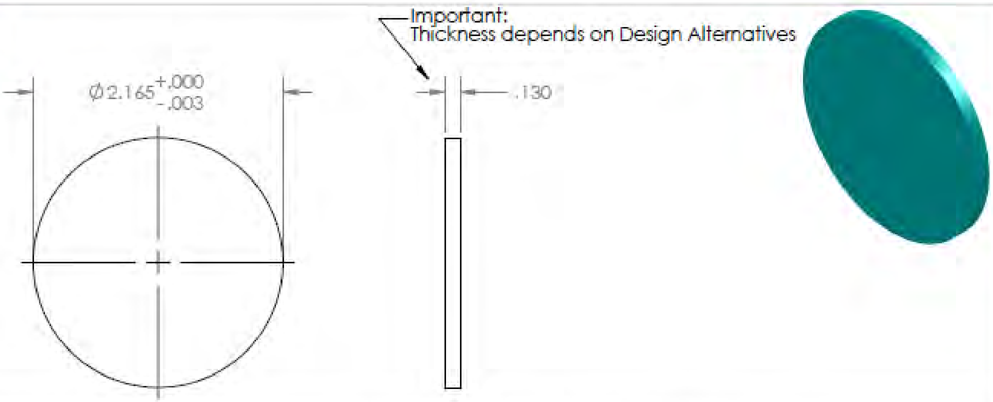
Ernesto Vallejo
FIU
(305)726 -3233
evall012@fiu.edu

February 20th, 2013

5 4 3 2 1

## 11.4 Projectile Impactor

FIU
Florida International University
Miami's public research university




| Design Alternative A | | Design Alternative B | | | |
|---|---|---|---|---|---|
| Constant Impactor Thickness 0.130 in | | Variable Impactor Thickness | | | |
| Shot # | Shot Velocity | Shot # | Shot Velocity | Impactor Thickness | Notes |
| 1 | 350 m/s | 1 | 350 m/s | 0.118 in | Machine to 0.130 in, then lap to 0.118 in |
| 2 | 500 m/s | 2 | 500 m/s | 0.128 in | Machine to 0.140 in, then lap to 0.128 in |
| 3 | 600 m/s | 3 | 600 m/s | 0.136 in | Machine to 0.145 in, then lap to 0.136 in |
| 4 | 700 m/s | 4 | 700 m/s | 0.141 in | Machine to 0.150 in, then lap to 0.141 in |
| 5 | 850 m/s | 5 | 850 m/s | 0.151 in | Machine to 0.160 in, then lap to 0.151 in |
| | | 6 (2024 Aluminum) | 300 m/s | 0.256 in | Machine to 0.265 in, then lap to 0.256 in |

Ernesto Vallejo
FIU
(305)726 -3233
evall012@fiu.edu

March 1st, 2013

**UNLESS OTHERWISE SPECIFIED:**

DIMENSIONS ARE IN INCHES
TOLERANCES: ± 0.003
MATERIAL Design Altenative A & B:
Poly(methyl methacrylate) - PMMA
SURFACE FINISH: LAPPED & POLISHED

APPLICATION | DO NOT SCALE DRAWING

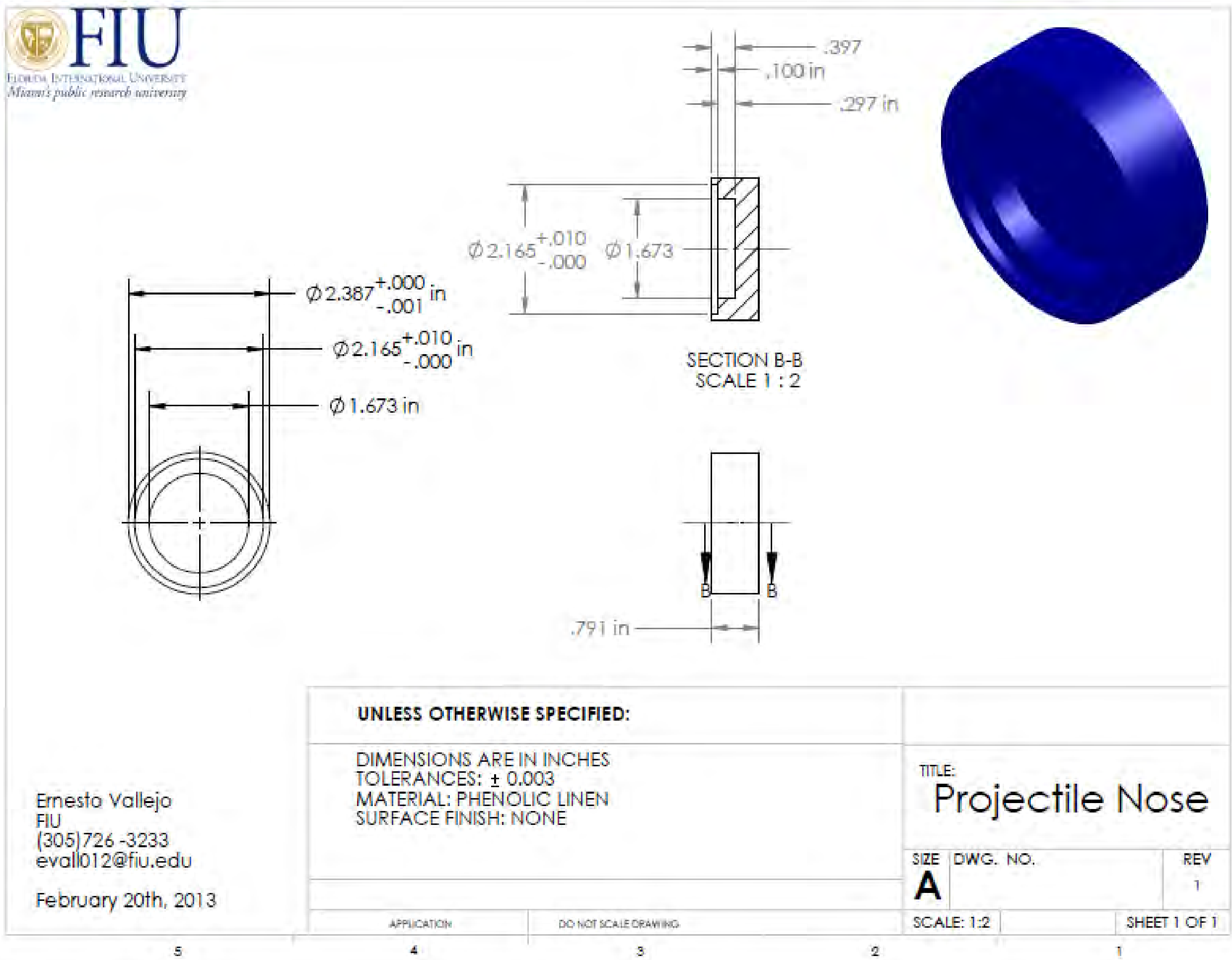
TITLE: Projectile Impactor

SIZE: A | DWG. NO. | REV 1

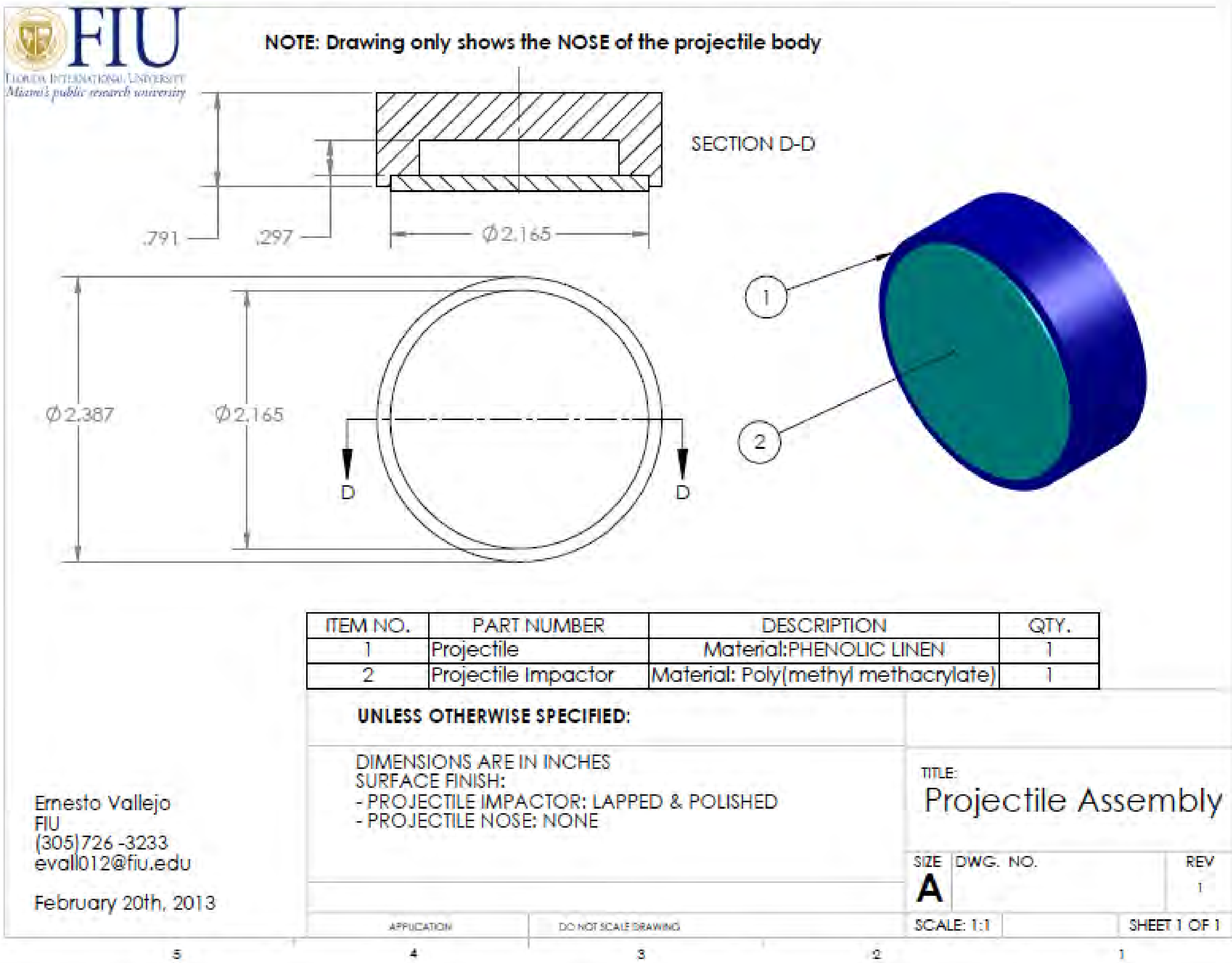
SCALE: 2:1 | SHEET 1 OF 1

5 4 3 2 1

## 11.5 Projectile Nose



## 11.6 Projectile Assembly




| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | Projectile | Material:PHENOLIC LINEN | 1 |
| 2 | Projectile Impactor | Material: Poly(methyl methacrylate) | 1 |