EML 4551 Design Organization

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REQUIREMENT FOR THE DEGREE OF
BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

Impact Loading and Recovery of Copper
25% Report

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This B.S. thesis is written in partial fulfillment of the requirements in EML 4905. The contents represent the opinion of the authors and not the Department of Mechanical and Materials Engineering.

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.

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Abstract

This work will focus on the research and development of five separate projectile designs 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 in order to accurately study the point of spallation of copper and the shock loading developed throughout the projectile after impact.

For reasons of exact precision that is needed and material access to do the experiments, the projectiles and targets will be designed using Solidworks here at Florida International University which will then be sent to the Eglin Air Force Base. After full analysis is done by Air Force Research Laboratory (AFRL) project mentor, the data will is sent to Florida International University. Here is where the students will analyze the data themselves and make modifications to the next projectile and target for the next experiment. The pressures that the projectile and target will undergo 1, 1.1, 2, 2.5, 3 GPa after impact. This work abides by the Air Force Research Laboratory standards and regulations.

Introduction

Problem Statement

The United States Air Force Research Laboratory at Eglin Air Force Base, Florida is home to the Advanced Warhead Experimentation Facility. This facility conducts research on a wide variety of materials, including metals such as copper and steel, for use in the development of weapons and armor for military applications. The experimentation facility is home to the High Pressure Particulate Physics Facility where very high strain rate testing devices are located. This facility houses a 60 millimeter gun which is used to conduct shock loading experiments. This facility conducts research on a wide variety, but the primary focus of this work will be the study of void nucleation in copper specimens. The concepts from the design of these experiments may be applied to any material however.

The 60 millimeter gun fires into a catch chamber inside of which the target assembly is located. The target assembly holds the metal specimen so that it can be impacted by the projectile fired by the gun. This impact represents the shock loading imparted on the material. After the impact occurs, the specimen is soft recovered to prevent deformation so that postmortem metallurgical analysis can be conducted.

The objective of this project is to design 5 different target specimens with 5 corresponding impactors so that the spallation effects of the impacts can be studied. The experiments will focus on the effects of shock loading on copper metal specifically. Each target/impactor combination must be designed to meet specific impact pressure and pressure wave propagation conditions specified by the party by which the project has been commissioned. This is to be accomplished by manipulating the projectile speed as well as the target and impactor geometries and materials to achieve the desired results. The ultimate goal is to find a correlation between the predicted effects of impact and the experimental results.

Motivation

The Air Force Research Laboratory is interested in the study of incipient spall in copper through shock recovery experiments. The project will be fully funded and monitored by the AFRL Acting Branch Chief of the Damage Mechanisms Branch Dr. Joel House.

Literature Survey

Shock loading experiments are classified as "very high strain rate" conditions where the specimen experiences strain rates of 10^4 s^{-1} or more [1]. Such experiments are conducted in order to further understand the effects of dynamic stress on a material. Shock loading experiments can be performed using high exposure explosives, gun-launched impactors, exploding foils or direct radiation impingement such as lasers, electron beams, etc. [2]

Shock loading experiments at the High Pressure Particulate Physics Facility are carried out using the gun-launched impactor method using a 60mm powder-fired gun. The projectile is launched through a 45ft long, smooth-bore barrel, whose muzzle sits approximately 30in inside the catch chamber. Mounted immediately in front of the muzzle is the target assembly, which holds the test specimen in place to be impacted, or shock loaded, by the projectile, after which it is soft recovered.

Shock loading experiments are a vital aspect in the design of new weaponry and armor because of the intrinsic dynamic nature of their operation. Typically, these experiments are done for one of two reasons: to determine the equation of state of a material or to study the microstructure changes in the specimen induced by the shock loading process [2]. This work will deal with the latter.

Spallation, or "spall," is an effect that occurs when fragments of a body are broken off a larger body due to transient wave motion in the body. Research in this field dates back to the research of John Hopkinson and his son Bertram Hopkinson first documented damage to materials due to wave propagation [2]. Hopkinson showed that if a specimen experiences a compressive stress pulse, the reflected tensile wave can induce damage and that the degree of the damage is related to the strength of the initial stress pulse [2]. When a compressive stress wave reflects and the magnitude of the tensile stress wave results in local stresses which exceed the materials spall strength, internal damage will occur. This damage process is referred to as "incipient spall" when internal damage and cracking begins but no fragmentation occurs, and is referred to as "spallation" (formerly known as "Hopkinson fracture") when fragmentation does occur [2].

In typical shock loading experiments, up to three types of shock waves are possible – elastic, plastic I and plastic II [2]. The difference between a plastic I and II wave is that the later involves pressure-induced phase transformation. As noted by Hopkinson, the magnitude of the imposed stress pulse dictates the nature of the wave propagation. For very low impulse magnitudes, only elastic waves will occur. If the impulse magnitude is increased to some critical value, a plastic wave will occur as well.

Since this work aims to focus on incipient spall studies, it is desirable to have only one shock wave pass through the specimen at a strength great enough to cause spallation. The magnitude of the initial compressive wave should be high enough that the reflected tensile wave causes local tensile stresses which are greater than the material's dynamic tensile strength, but not so much greater that fragmentation or complete separation occurs.

Components

TARGET

Phenolic Ring

The phenolic ring for every experiment will be have the same dimensions. The purpose of this ring is to be placed in the chamber to hold the target in place and will be destroyed upon impact.

Target Ring

The target ring for every experiment will be made of the same dimensions, and it will be made of Aluminum. The purpose for this ring is to hold the momentum trap in place, and it will also be destroyed upon impact.

Momentum Trap

The momentum trap is made of two components that will be analyzed by the project manager. The outer ring is made of Copper with a diameter of 40 mm. The inner disk material and design will be dependent on the members of the senior design team. The momentum trap will stay in contact for every experiment and will be the only component analyzed by the AFRL project manager.

PROJECTILE

The portion of the projectile that will be designed by the members of the senior design group will be the tip. The tip of the projectile is a disk which will be made by material chosen by the senior design team. The dimensions and material will be dependent on the calculations and physical properties of the material.

Conceptual Design

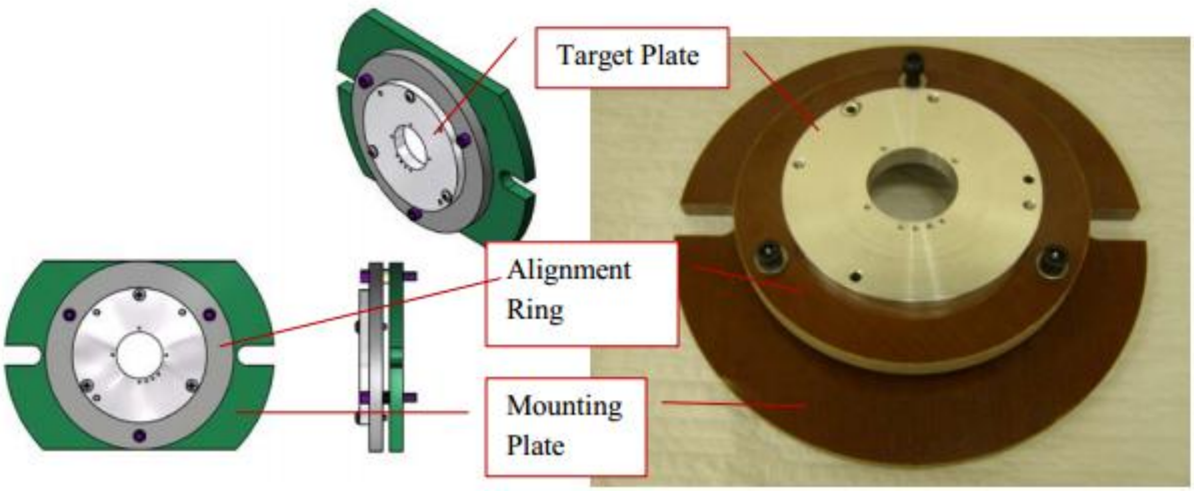


Figure 1: Target Plate Courtesy of AFRL, Munitions Directorate

The design above is the current mounting setup to be used for the target in the testing of the five different configurations to be used. Some values for this will stay constant throughout the different shots fired, such as the outer diameter of the ring which is set at D_o = 120mm, also the diameter and of the momentum trap will remain the same, set at D_c = 40mm and copper, respectively.

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. The material of the target is open to change although it will most likely stay copper throughout, but further testing may dictate a possible change in future shots. Variables that are likely to change include the thickness of the target, as well as the size of the target.

On the other side of the spectrum, the current conceptual design of the projectile to be shot and modified is displayed below in figure 2.

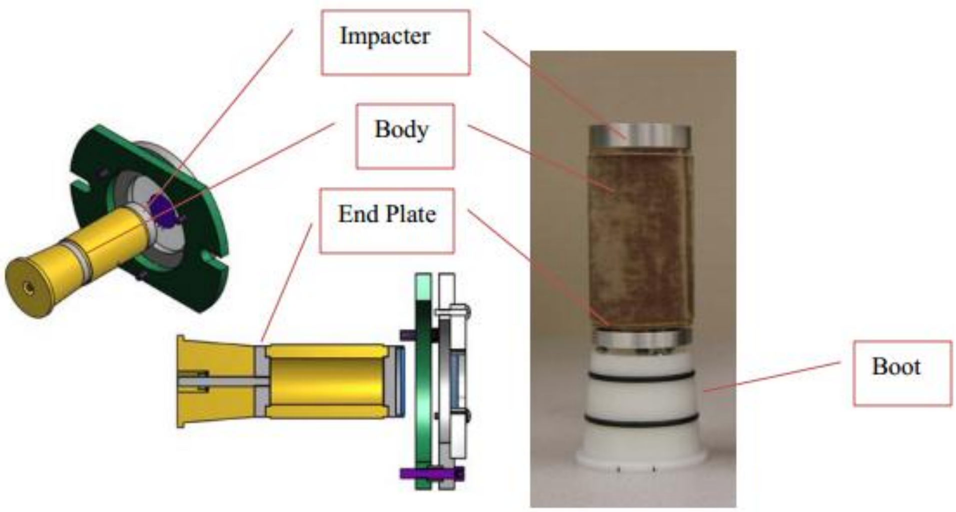


Figure 2: Projectile Courtesy of AFRL, Munitions Directorate

Similarly to the target, there are several variables that will remain constant throughout each of the five shots, while there are others that are up to the team to calculate and design. The main variables that will be expected to change throughout each experiment will be the thickness and the material of the projectile tip.

Proposed Design

Currently, there are only a few factors that the senior design team has control of, research will need to be done to modify what will need to change as each of the experiments take place. Below is a drawing of the target along with a drawing of the projectile and what can be changed and what cannot.

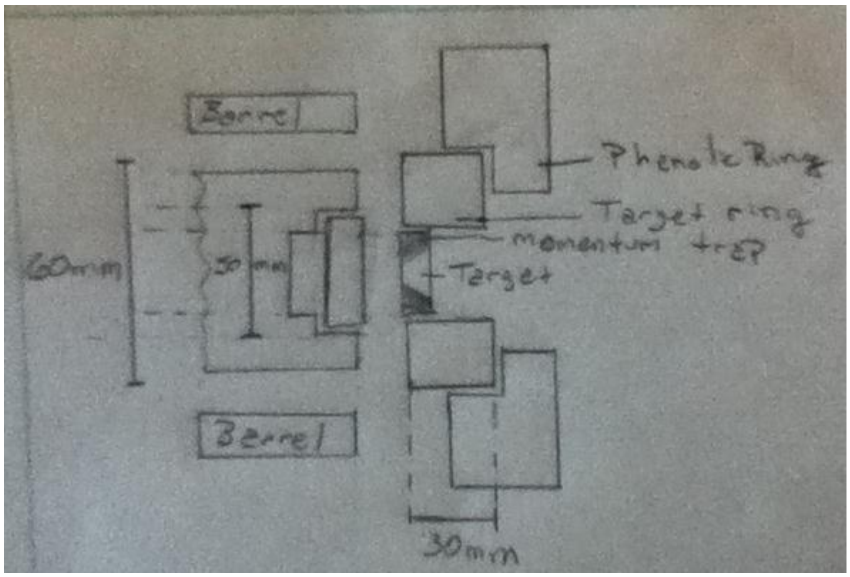


Figure 3: Experiment Overview

Above, the shaded area is the momentum trap where the target will be placed for testing just ahead, the surrounding elements are, while pieces will be destroyed during every shot, they will stay the same dimensions. The shot will be coming from the left side of the drawing and come out to the right and into a soft catch recovery system.

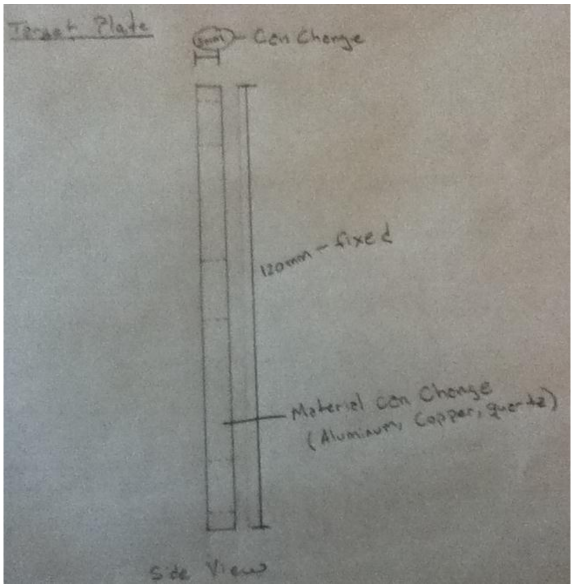


Figure 4: Impactor Plate

Above is a drawing to scale about the target plate with what can be changed and what cannot change, current possibilities for the material that may take place is aluminum, copper, and quartz, among others depending on results from the first and second shots. Copper is likely to be the first material used, and again, depending on the results that material may stay constant with only slight differences in the thickness of the target.

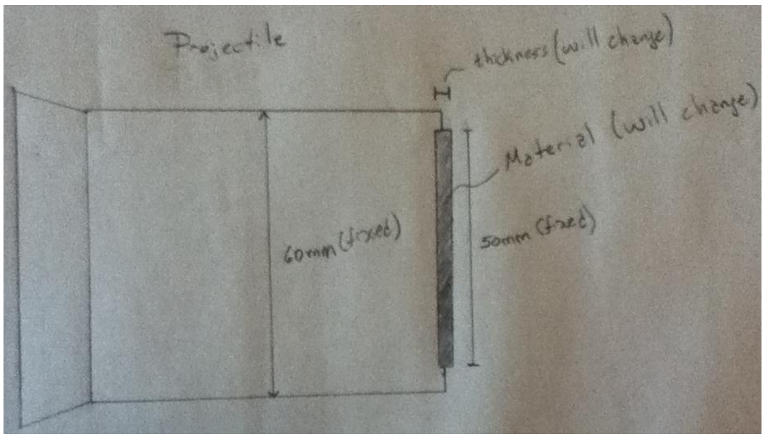


Figure 5: Projectile

Above is a rough drawing of the projectile to be used for testing. The body of the projectile will remain constant to fit into the gun, only the shaded part will be what the senior design team has control of. The possibilities for the material will be aluminum, copper, and tantalum.

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 Rehersal to MME Faculty	25-Mar	25	19-Apr
Senior Design Org Project Feasibility	29-Mar	12	10-Apr
Final Presentation to IAB and MME Faculty	19-Apr	4	19-Apr

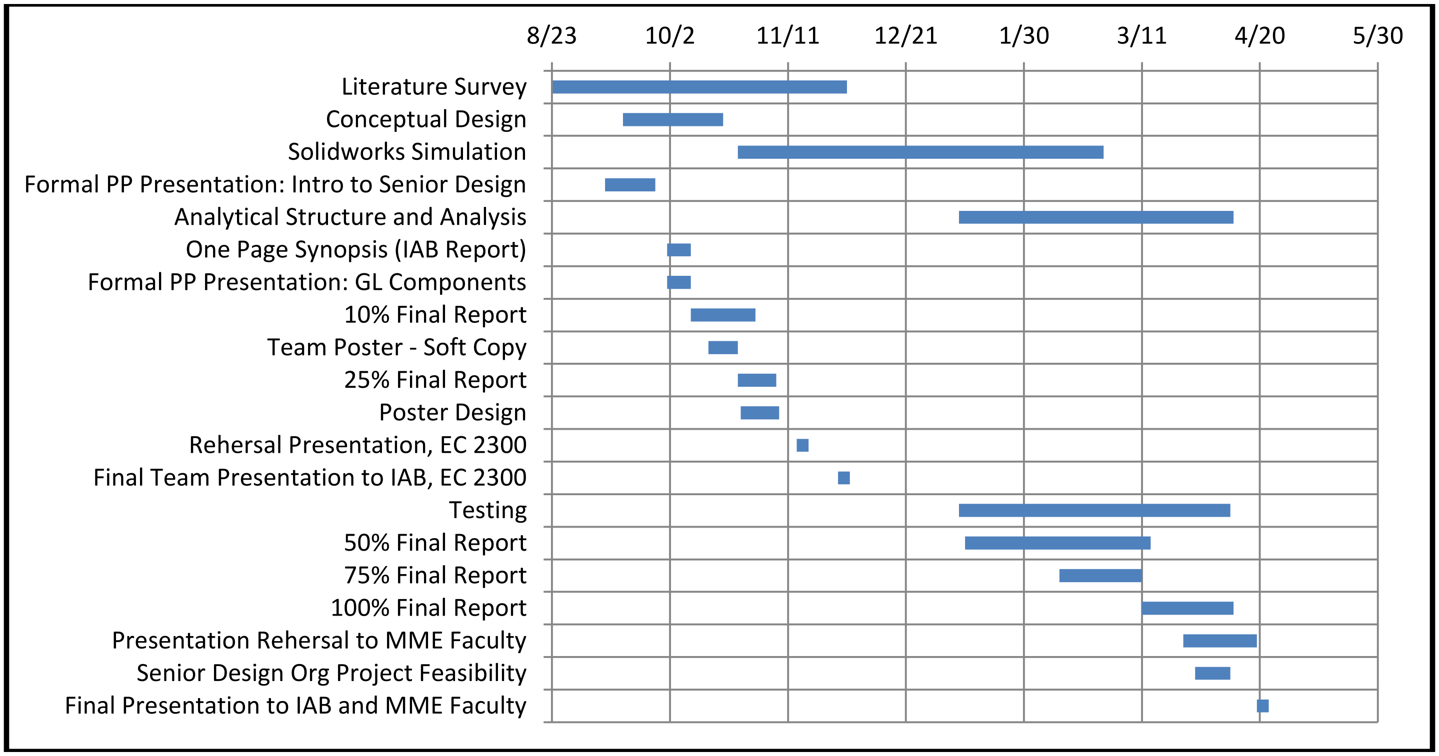


Figure 6: Timeline

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

Analytical Analysis

Through impact velocity 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 the AFRL is interested in copper the target for every experiment will be made from copper.

Once a material is selected the data that is needed to begin the analysis from both copper and the selected material is the density (ρ), bulk sound speed (C_o) and the Hugoniot Slope (s). The equations used for analysis to find the normal shock wave relations are as follows,

$$\rho_0(u_s - u_0) = \rho(u_s - u)$$
$$p - p_0 = \rho_0(u - u_0)(u_s - u_0)$$
$$e - e_0 = \frac{1}{2}(p + p_0)(\frac{1}{\rho_0} - \frac{1}{\rho})$$

Where u_0 is the initial velocity, p is pressure and the unknown is u which is the velocity at impact. From here once we are able to final the velocity at impact we are able to calculate the velocity of the target and the projectile using the following equation.

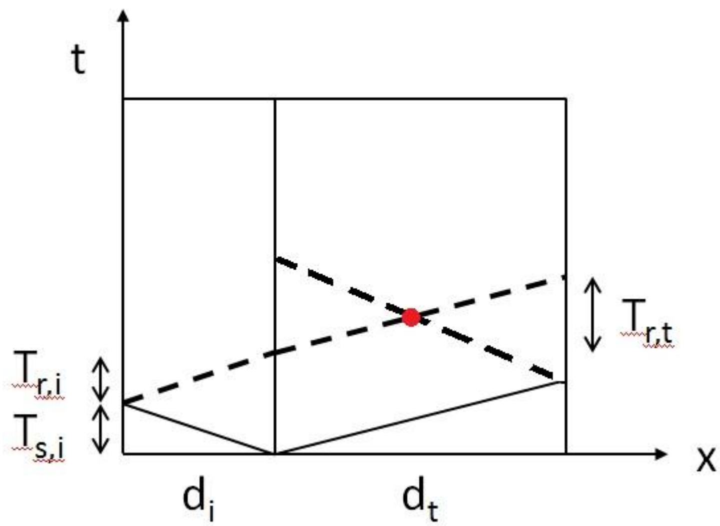
$$u_p^T = u$$
$$u_p^I = u_0 - u$$

Here because the targets initial speed is zero we are able to say that the final velocity of the target is the velocity at impact. As for the projectile there is a slight decrease in velocity thus we are able to subtract velocity at impact with the initial velocity of the projectile.

From here we are able to use the velocity at impact in the initial equation to find the pressure at impact. At this point we are able to see is there will be spallation in the material. To determine if there is spallation, the pressure calculated here 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 a new thickness, initial velocity or material must be changed. If the spall strength does exceed the pressure calculated then we are then able to proceed to find the shock was speed. Using the velocity at impact for both target and impactor we can then find the Shock Hugoniot EOS which was created by a series of experiments. The equations are as follows,

$$u_s^T = c_0^T + s^T u_p^T$$
$$u_s^I = c_0^I + s^I u_p^I$$

When the shock wave, solid black line, "bounces" off the wall of the material it is now a release wave, dashed line. This wave is created from both projectile and target and when intersected will create a spall in the material, which is shown in the figure below.



For the purpose of our experiments to calculate the release waves, first we must calculate the bulk sound speed at the pressure of impact, using the following equations,

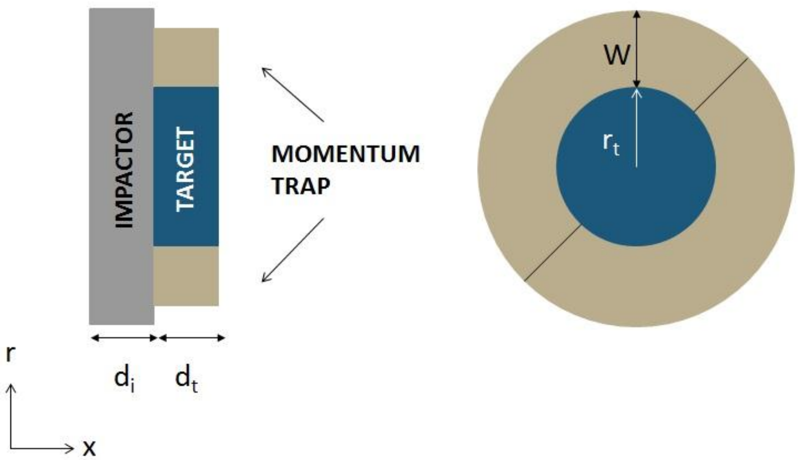
$$C_{0,p}^T = C_0^T + 2s^T u_p^T$$
$$C_{0,p}^I = C_0^I + 2s^I u_p^I$$

Once we have found the bulk sound speed of the materials at impact we can then find the release waves also known as the longitudinal waves with the following equation. This will be done for both target and projectile.

$$u_r = C_l = C_{0,p}\sqrt{\frac{3(1-\upsilon)}{1+\upsilon}}$$

From here we determine if the spallation that occurs will form in the target. If it is not then we are able to use basic physics to determine the thickness that is needed from both projectile and target to have the spallation in the target for study.

The final calculations to be made is the *w* which is the width of the copper ring that is needed to not have any "edge effect" that can ruin the experiment. The "edge" effect will change the shock and release wave in the material and will not allow for the right analysis. To find the minimum width of the copper ring in the target we use the following formula,



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

Once all calculations have been done and checked the Solidwork drawings are made for both target and projectile and sent for manufacturing to the Eglin Air Force Research Laboratory in north Florida. Each experiment will have different calculations because different material used and different testing pressures.

Major Components

Major components in these experiments are the target and projectile. Analysis will be done on the target to find the spallation in the material. This analysis will allow researches at AFRL to improve upon defense for components that is used by the air force. This analysis is also connected to the projectile to improve the artillery of the air force.

Structural Design

Since 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. The complex nature of wave propagation in solids restricts the use of computer-aided simulations; therefore this paper will only provide mathematical models derived for the different shock-loading conditions.

The use of CAD software will be applied since the dimensions of each of the projectile/target assemblies will require minute attention to detail because successful results will only be acquired at very small tolerances. In order to achieve the desired geometries, the following parameters of the components will be studied:

- 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 present this paper with the limiting parameters.

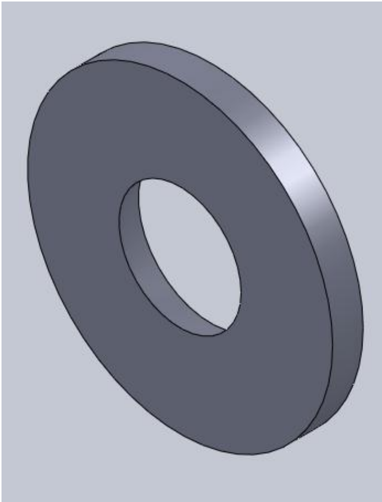


Figure 7: Momentum Trap

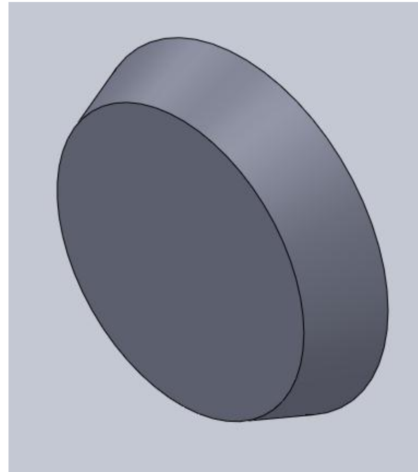


Figure 8: Target Plate

Figure 7 & 8 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 calculated theoretically. The draft angle of the target plate in Figure 8 will be defined from the conical projection due to fragmentation since the results need to be collected by a soft-catch system. The projectile's thickness is also an important factor for the experiment and will be obtained from the calculations of shockwave velocity. The diameters of the components are limited by the gun's barrel diameter.

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 three-dimensional edge effects will not cloud the shockwave path through the target. An optimal structural design of the target will have resulted in spallation voids being found inside the target plate without it fragmenting, and the continued growth of the voids with each new target and projectile delivered.

Cost Analysis

In calculating the cost of the shock loading project it is broken down into three categories

1. Labor
2. Travel
3. Prototype cost

Lobar costs are something that has to be taken in to consideration when valuing a projects cost. The client at HP3 facility heavily emphasized the need for research when selecting the correct materials for the specific experiments. The graph below 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 3 hours a week for 16 weeks would be sufficient enough time to grasp the knowledge needed to design the experiment. Next subcategory of labor is design which entails the calculations need 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 18 hours a week for a length of one month 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 the area surrounding the labs. The estimate given by the machine shop was a total of 12 hours to complete all five projects. Lastly implementation had to be taken into account in the labor cost due to the fact that the client might need assistance in use of the projectile and or target. A rough estimate of 3 hours per experiment was assumed giving us a total of 15 hours for implementation labor. All hourly labor will be distributed through the five members.

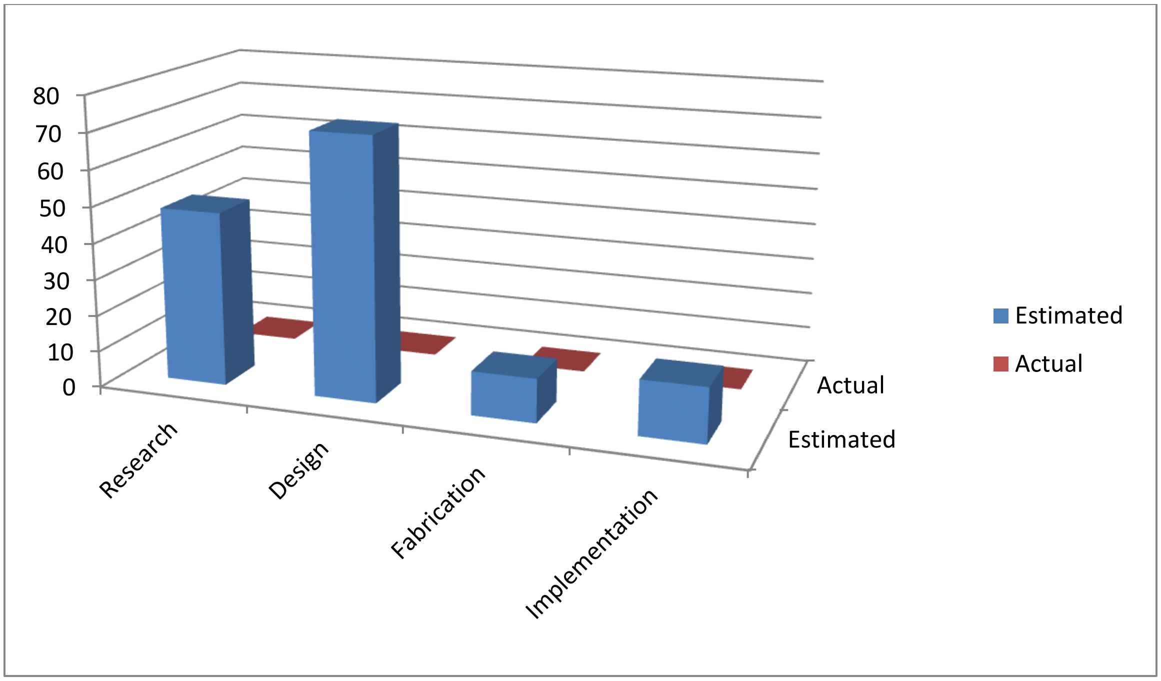


Figure 9: Cost Analysis

The HP3 labs are located in Pensacola Florida 680 miles away from Miami Florida this being the case travel cost have also been analyzed. The cheapest airfare found was on cheaptickets.com with a cost of $1,684.45 for All 5 team members round trip. This trip is a necessary to grasp concepts and scale of the experiment.

The client at HP3 specifically wants to test wave propagation through copper. Material selections were made for the parameters needed the prices of copper varied from thousands to hundreds. The most economical price found was from William Metals and Welding Alloys for a cost for both purchase and shipping of $520.60. this price quote was for a alloy 110 with a diameter 5 inches that weight about 45lbs. the next price quote was for a alloy 101 (oxygen free copper) with the same diameter of 5 inches. An online source was found to have the cheapest prices for this material and size which was quoted at $132.62 also including shipping. The next material selected was for the target holder which was aluminum alloy 6061 cylinder this aluminum will later be machined to fit the target material. Supplier onlinemetals.com quoted this raw material at $82.06 also including shipping.

Total Project Cost

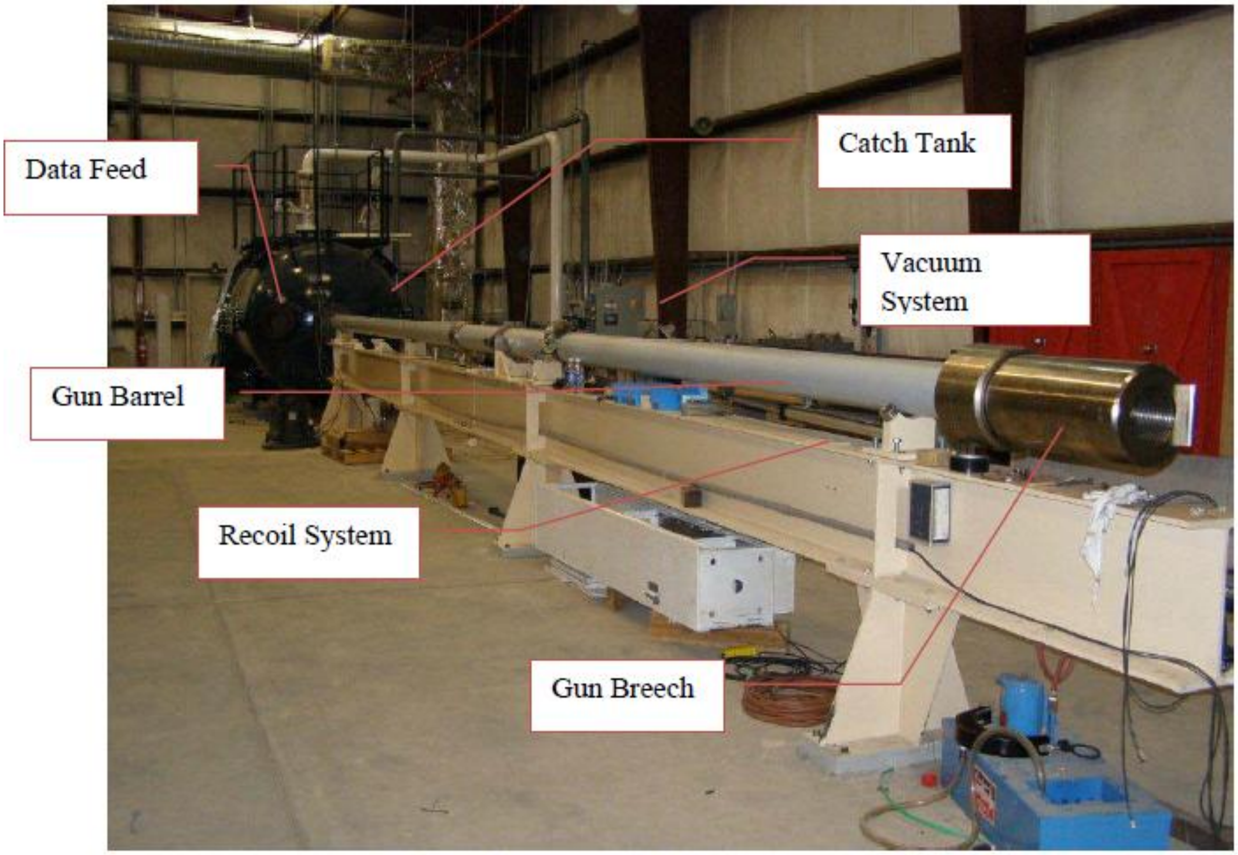
- 147 hours of labor at a 125 dollar per hour = **$1,8375.00**
- Travel cost for all five members = **$1,684.45**
- Cost of material for prototype ($520.60 + $132.62 + $82.06) = **$735.28**

Total = **20,794.73**

Prototype System Description

While many of the components of the whole 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 pieces used for experimentation and analysis of the impact plate. On 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 Elgin Air Force Base.

Figure 10: Prototype System



Prototype System
Courtesy of Air Force Research Laboratory, Munitions Directorate

For the shock loading system, the components include the target itself, along with tilt pins, guard rings, a moment trap, 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 that all of these components working together are to achieve a situation where the target itself for each of the 5 experiments is to experience only uniaxial shock loading, and to hold everything inside the experimental chamber in place in order to be analyzed with a minimum amount of error. The momentum trap is used to absorb the radial waves which are caused by the driver plate when shot onto the target, which will in turn fulfill the requirement of only uniaxial shock loading. As for the target itself, it is simply a circular sample of a material to be chosen by the senior design team, along with the thickness. 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.

For the other side of the apparatus where the gun is set and the projectile is to be placed, include many 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 and 2000 m/s with an accuracy of ± 50 m/s. The projectile itself is explained in detail in other sections, and it is to be placed at the gun breech (which is rated at 90 ksi max pressure) detailed in the prototype system picture above. 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.

Plan for Tests on Prototype

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.

Conclusions

Through the research presented in this paper, it has been found that the necessity for a better understanding of the behavior of copper at high velocity conditions is vital for the development of civilian and military applications. The main purpose of this project is the development of military applications nevertheless, it must be noted that the large deformation encountered throughout the design and analysis of each of the geometries for the projectiles presented will be applicable to crashworthiness studies. From the conceptual design, we have been able to target and record the various constraints and requirements that need to be considered for the success of this project. The design of the geometries will involve trial and error since the variables for each of the plates will depend on the theoretical concepts found in Meyers. By following the timeline provided, we will be able to fulfill each of the objectives of the project and thus provide the information requested by the Air Force Research Laboratory for the proper implementation of the experiment at each of the stated shock-loading conditions.

References

Meyers, M. A. (1994). *Dynamic Behavior of Materials.* San Diego: John Wiley & Sons Inc.

Cooper, P. W. (1996). *Explosives Engineering.* Wiley-VCH Verlag GmbH

Nemat-Nasser S. (1998). *Introduction to High Strain Rate Testing.* San Diego: University of California

Gray III, G. T. (1995). *Mechanical Testing and Evaluation: Shock Wave Testing of Ductile Materials Volume 8*. Ohio, Materials Park.