University of Southern Queensland

Faculty of Health, Engineering and Sciences

Projectile Impacts on Hardened Alloy Steel Plate

A dissertation submitted by

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Table of Contents

Abstract

The use of steel armour plate targets for competitive sports shooting has been increasing in popularity over the last forty years. Steel armour used in battle may only be used for short periods and receive impacts only in the hundreds, from specific threats that occur in battle and the majority of past research is based around this. In contrast steel targets used in competition are subject to thousands of impacts over their life span, f a variety of commercially available projectiles. Hence the approach to their designs is more interested in the limit that causes no damage, rather than the limit which prevents total penetration.

This study deals with the impacts of commercially available target and hunting style projectiles impacting against 12mm Bisalloy 500, which is a common choice for targets in Australia. Five different projectiles were selected with the following matching characteristics; different diameter and similar mass, different diameter and similar length, same diameter and different length and same diameter with different nose shapes. The projectiles were fired into test plates at 25 m using matching and stepped velocities and their penetration depths recorded. Data was compiled in MATLAB and compared with the Allen Rogers penetration model and the Alekseevskii Tate penetration model.

Trends were identified with the long ogive hollow point projectiles when normalized, showing that there is a distinct pattern which cannot be predicated using the AR or AT model using the standard inputs. The AT model was able to be matched up with the penetration for the short and solid construction projectiles, giving a reasonable estimate for the penetration depth up to impacts around 950 m/s, where plates are very close to failure. It has been shown that there is a substantial difference in the penetration based on the construction of the projectile and short blunt projectiles have a far lower velocity threshold to prevent damage.

From this research the following maximum impact velocities have been recommended that will cause minimal (>0.5 mm) damage to 12mm Bisalloy 500. For long ogive hollow point projectiles a maximum impact velocity of 900 m/s and for solid short and blunt projectiles a maximum impact velocity of 750 m/s.

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Sign:____________________________ Date:____________________________

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List of Figures

List of Tables

List of Appendices

Abbreviations

COAL	Cartridge overall length
OGAL	Ogival overall length (from ogive of projectile to back of cartridge)
FPS	feet per second
B.C	Ballistic coefficient
M.V	Muzzle velocity
S.D	Sectional density
cal	Caliber
AP	Armour piercing
BTHP	Boat tail hollow point
HP	Hollow point
FP	Flat point
JHP	Jacketed Hollow Point
SP	Soft point
FB	Flat base
VLD	Very low drag
AMAX	Hornady low drag projectile
SG	gyroscopic stability factor
V_{50}	Standard term for velocity required for 50% of projectiles to penetrate during testing
V_c	Critical velocity for penetration to commence
R_t	Targets resistance to penetration
Y_p	Dynamic strength of penetrator
ρ_p	Density of penetrator (projectile)
ρ_t	Density of target (test plates)
gr	weight in grains (1 grain equals 6.4798×10^{-2}grams)

Chapter 1. Introduction

1.1 Background

For nearly as long as steel has been invented it has been used as a form of armour and in the present day this is still the case for the majority of heavy armour applications, which can be seen by simply looking at construction of most modern military equipment. Its properties of strength and ductility make it very suitable for the protection from high speed impacts.

Steel targets are used in sports shooting for a number of reasons as follows:

- Audible report; steel makes a distinct sound upon impact which can be heard from as far as 1500m away, this makes it ideal for long range sports shooting where the impact holes in a paper target would be impossible to see without moving closer. It is also interactive and gives the shooter instant response to whether they have made a hit or miss.
- Visual response; the target will react to an impact and may move or fall over giving response to the shooter of a hit. An impact will also produce a large mark from the lead splatter that can be seen from a long distance to indicate the point of impact on the target.
- Lifespan, Efficiency and maintenance; steel targets can be setup and used repeatedly without having to need any special care or maintenance, many ranges leave their targets out permanently and often the only repairs that need to be made are when the item supporting the target is damaged. Steel targets are easy to score during competition and are quicker to reset than replacing conventional paper targets.

Records show the first steel silhouettes were used for competition in 1948 (Michigan Rifle & Pistol Association, 2004). There are now over nine different shooting disciplines which shoot at metallic targets around the world, some of these are:

- Metallic Silhouette: Animal silhouettes are shot at from distances of 200-500m with high power centre-fire rifles.
- Steel challenge: targets are shot at close range <20m with pistols ranging from small to large caliber such as .38 super and .357 sig.

- IPSC, IDPA: targets are shot at ranges from 7m with pistol and greater than 250m with centre-fire rifle
- 1920 Action match: targets shot at close range <10m using centre-fire pistol.
- Single action match: targets are shot as close as 7m with pistol and rifle using only pure lead ammo.
- ICORE: targets are shot at ranges from 7m with pistol.
- 3-Gun: targets are shot at ranges from 7m with pistol and greater than 250m with centre-fire rifle.
- Big Game Rifle: targets are shot from 200 to 1000yard using large caliber rifles suited for hunting large game and using heavy projectiles.

Some of these disciplines are estimated to have over forty five thousand members and even if they only compete once a year, this would equate to over thirteen million projectile impacts on steel targets for one discipline only.

With all this use of steel for targets, there is very little information available in relation to the threshold levels that cause damage to steel plates, when impacted using target and hunting style projectiles. From discussions with fellow shooters and through perusal of online shooting forums, it is evident that there is also a common myth between the general shooting communities. This Myth is that the most damage to targets occurs from the most powerful cartridges. With sporting projectiles this is normally not the case at all and is one of the main motivations for the author undertaking this project.

Terminal ballistics is the study of impacts of objects against other mediums. For armour steels the majority of research is focused on military applications and predominantly focuses on the threats that are common in battle and determining the ballistic limit for particular armours. The ballistic limit is defined as the limit for penetration of an armour plate in 50% of impacts for a given projectile and impact angle (U.S Army research labratory, 2008). In military applications the primary purpose of armor is to stop full penetration whereas with civilian target shooting applications the purpose is to impart minimal or no damage at all and maximize the lifespan of the target.

The steel that is used for target materials can range from normal mild steel to HHA plate but for the majority of targets a grade of HHA plate is used and this project will focus around the HHA grades of plate and impact velocities within the small arms ordnance range of 0-1500 m/s.

Projectiles used for normal target shooting are vast and range from cast pure lead construction to lathe turned solid brass. In all cases of target and general hunting projectiles they are always substantially lower in their yield strength and hardness than the targets that they are being used on. This adds an extra challenge to predicting penetration as the projectile will suffer large deformation and in many cases will result in total consumption of the projectile during the impact, with the projectile being turned into debris, molten and vaporized metal as can be seen in Figure 1.1-1.

Figure 1.1-1 Debris and vapor cloud from impact

1.2 Project aim

The aim of this project is to build data of target and hunting projectile impacts on steel armour plate. Compare this data with already documented models looking for trends and the ability to predict the damage caused by different projectiles. Make recommendations to the threshold velocity levels for the selected plate that will cause minimal or no damage and also any models that can predict penetration accurately.

This data can then be relayed to the sports shooting community and clubs to allow them to make informed decisions when purchasing targets and deciding upon safe distances for shooting. This would help to prevent damage to targets and also help to predict the lifespan of targets.

1.3 Objectives

A number of objectives have been set for this project. These have been set with the limitations that were present and in some cases are limited by the budget of this project, as it is self-funded. This limitation meant that not as many tests projectiles could be selected for testing. There is sufficient enough selection to provide accurate data for the selected projectiles but more test projectiles would allow the recommendations to be expanded to cover a broader range of projectiles. The objectives should provide enough information to satisfy the project aim, provide reliable information for making assumptions and recommendations based on the results and research collected. The primary objectives are:

1. Test penetration of two similar mass projectiles in different calibers with equal velocities.
2. Test penetration of similar design projectiles (scaled versions) of different calibers at equal velocities.
3. Test penetration for similar length projectiles of different calibers at equal velocity.
4. Test penetration of the same weight projectile in same caliber at different velocities.
5. Compare the test results with theoretical calculations and look for trends and patterns and make recommendations on these results.

Chapter 2. Literature Review

2.1 Past research

Terminal ballistics has been an area of interest for many scientists and engineers, which can be seen by the vast number of publications and books available on the subject. It can be related to many different fields of engineering such as Civil, Mechanical and Aeronautical. Studies range from impacts of projectiles on armour plate, impacts of objects on buildings such as falling debris or a car impacting a structure, the impact of a meteorite on a space station to the impact of birds on an airplane windscreen. These impacts can range from low velocity under the speed of sound to hypersonic velocities over Mach 15. It is an area that is under constant research and development. For instance in the military field as weapon technology advances with time, so does the need for better armour for protection from these advancements. There are a number of facilities around the world that specialize in the ballistic testing of armor and related materials. One of the most commonly known facilities is the Army Research Laboratory located on the Aberdeen proving ground in Maryland. There are also a number of small facilities in Australia such as Craig International Ballistics, BMT, and Advanced Armaments International. Most of these facilities are able to carry out testing using projectiles up to .50 cal. The Journal of Impact Engineering has been a major source for up to date articles on armor testing with a number of different penetrators and target materials.

Research around the penetration of armor plate is predominantly conducted using specific military projectiles that are designed to be used against armored targets. There are three major mechanisms that are commonly used by the military these are:

1. AP (armor piercing) small arms ammunition with tungsten or hardened steel core and usually fired from conventional small arms.
2. Long rod penetrators, usually made from a high density material such as tungsten and have a ratio of L/D greater than 20, these are usually fired from artillery style weapons.
3. Shaped charged jets, formed by the detonation of a shaped charged at a specified distance from the armour to create a high velocity jet penetrates via erosion of the target material.

2.2 Research benefits, target audience

This project is focused on the penetration and effects that occur due to impacts of normal target and hunting projectiles on armour plate. The use of steel armor plate for civilian shooting applications and range design is an area which is increasing in popularity (Winkler, 2010). Armour plate is used for civilian applications in two main areas those being:

- The use of steel armour plate as an actual target cut out into a desired shape.
- The use of steel armour plate as a safety mechanism on ranges to deflect ricochets, catch projectiles or direct them in specific directions.

This shows the need for information on the properties of armor plate impacts with conventional projectiles to allow engineers and designers to be able to make safe decisions on plate selection based on the use of conventional soft projectiles. At the present time there are over 9 different shooting disciplines in Australia alone that utilize steel plates as part of their course of fire. Some of the main disciplines engage steel targets as close as 7m and others to extreme ranges of 1500m. The calibers used are vast and range from low velocity rim-fire calibers to high velocity centre-fire and custom designed cartridges.

Range design is can also benefit from further research of conventional projectile impacts on steel armour plate. Traditionally ranges were always located far from any local infrastructure and required large parchments of land to allow for stray bullet fallout zones and hence needed very little protection to ensure that projectiles stayed within the fallout zone. With cities increasing in population indoor ranges are becoming more popular, also housing and infrastructure often encroach on existing ranges forcing extra measures to be added to contain stray projectiles. These indoor ranges and new protection measures often involve the use of steel armour plate and proper selection of this is important to ensure long life and projectile containment. With the additional research around soft projectile impact engineers can make more informed decisions when it comes to selecting correct materials in range design.

2.3 Available research documentation

Books:

- Applied Ballistics for Long Range Shooting: This book addresses all major facets of ballistics in simple and easy language. It is a major source for ballistics data, stability predictions and projectile data.

- Hornady handbook of cartridge reloading. This book lists all projectile styles manufactured by Hornady and also load data for all popular sporting cartridges. Used as a source for selection of projectiles and for load development with Hornady projectiles.
- ADI Powders hand loaders guide: Handbook with specific information for powder charges in various different cartridges using ADI manufactured smokeless powders. Major source for calculation of starting and maximum loads for each cartridge.
- Terminal Ballistics: Book based on research on the penetration of armour using a number of different mechanisms. Contains a number of different models and discussions on the validity and application of these models. Was used as the major source for selection of appropriate models and modes of failure expectations.
- Berger Bullets reloading manual: This book lists all projectile styles manufactured by Berger and also load data for all popular sporting cartridges. Used as a source for selection of projectiles and for load development with Berger projectiles.

Online sources:

- Berger projectiles website: Used for projectile selection and load workup
- Thales website: Lists online data For ADI handbook for powder charge selection and contains any updated information that is not yet in the printed handbook.
- Standards Online: Source for AS standards for ballistic panels and US MIL standards.

Journal Articles

- Perforation resistance of five different high-strength steel plates subjected to small-arms projectiles: Data from density and strength for copper jacketed projectile used and information on computer modeling from copper-lead projectile impact cited.
- The effect of target strength on the perforation of steel plates using three different projectile nose shapes: Comparison of different nose shapes used to backup theory for plate failure from adiabatic shear.

- Ballistic Resistance of Steel Plate Hardox upon Impact of Non-Penetrating Projectiles: Used to compare the energy of the impact of projectiles and its effect on penetration depth.

2.4 Projectile design

The range of projectiles that are available on today's market are vast. Hornady manufacture over three hundred different projectiles and is one of several projectile manufacturing companies that produce projectiles for target shooting and hunting. Other manufacturers include Lapua, Sierra, Berger, Speer, Nosler and Barnes. Target and hunting projectiles have an array of different types of designs depending on their application, although most of these are still based on a copper jacket and lead core construction. A number of these manufacturers are now producing a range of lead free projectiles, which are based on a solid copper design or the incorporation of a sintered metal to replace the lead core (Barnes Bullets, LLC, 2013).

A number of sources were reviewed comparing the weights and designs available for each caliber and looking for the largest difference in calibers that have the same weight projectile. This resulted in the following two calibers and their projectile weight ranges (Berger Bullets, 2013) (Johnson (ed), 2010):

- .22 caliber with weights from 35 to 90 grains
- .30 caliber with weights from 90 to 230 grains

With this combination it will be possible to fire to different caliber projectiles of similar weight at the same velocity.

Projectile shape is a factor that requires consideration in the selection of correct test projectiles. From researching different styles the following shapes from Berger and Hornady have been identified for use. Berger list four main designs as listed below:

- BTHP (boat tail hollow point): This is a long slender bullet designed to be used for long range shooting and is optimized to minimize drag and the effects of wind during flight. It utilizes a tangent style radius for the nose radius see Figure 2.4-1.

Figure 2.4-1 BTHP projectile

- FBHP (flat base hollow point): Flat base projectile which usually has a tangent style nose radius but some also available with a secant nose radius (Figure 2.4-2).

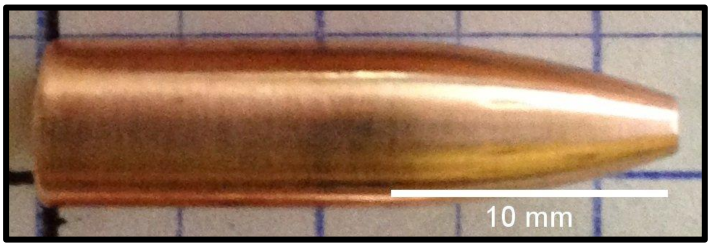

Figure 2.4-2 FBHP projectile

- VLD (very low drag): Similar to the design of a BTHP except with the use of an secant profile for the nose radius (Figure 2.4-3).

Figure 2.4-3 VLD projectile

- Hybrid: A combination of a BTHP and a VLD which utilizes a nose radius that is a combination of a tangent and secant nose radius (Figure 2.4-4).

Figure 2.4-4 Hybrid projectile

Hornady have similar shapes but also have the following extra designs:

- JHP (jacketed hollow point): Flat base style of bullet with a semi flat hollow point tip (Figure 2.4-5).

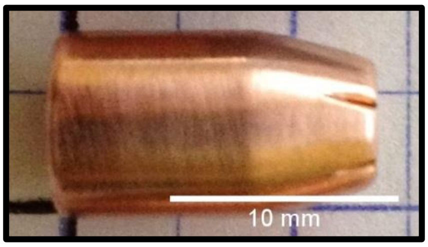

Figure 2.4-5 XTP projectile

- SP (soft point): Flat base style of projectile with a soft lead point (Figure 2.4-6).

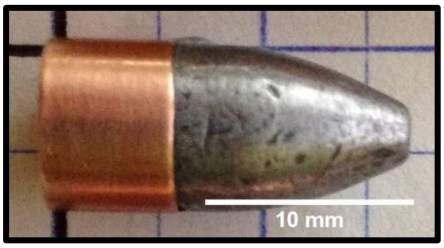

Figure 2.4-6 SP projectile

Nose shape can have a pronounced effect on plate penetration and it is highly dependent on the material properties of the target material and also the projectile itself. In 2004 a study was performed on the differences between blunt, conical and ogival projectiles impacting a range of different steels (Børvik, et al., 2004). The projectiles used all made from hardened steel and the following conclusions were found from the testing:

- As tensile strength of the target material is increased the ballistic limit for blunt nosed projectiles decreases and the ballistic limit for conical and ogival nose projectiles increases.
- Blunt projectiles cause a plugging failure due to adiabatic shear.
- Conical and ogival projectiles caused failure via ductile hole enlargement.

For soft projectiles there is a lack of data in response to the properties nose shape have on penetration but it is assumed at this stage that it is similar to that of a rigid projectile.

Jacket stabilization is a factor that requires consideration for the testing process. Light projectiles at high velocity can cause the jacket to fail and the projectile to disintegrate in flight. This will be an issue with the lighter projectiles in the larger caliber as they will likely be designed to operate at lower velocity. The limit for jacket failure also has variance depending on the manufacturer and the projectile design. Manufacturers recommended values for max velocity can be as low as 310 m/s for copper jacketed projectiles (Johnson (ed), 2010). This value may include a large margin of safety to prevent injury or misuse as personal experience and discussion's with competition shooter's show success with projectiles at speeds above their rating, although this is not recommended without strict controls.

Twist rate will significantly impact the projectiles ability to hold together during flight. For instance a projectile fired from a 1 turn in 12" (1 turn in 305 mm) barrel at 975 m/s will have an *rpm* of 192,434 whereas the same speed and projectile in a 1 turn in 10" barrel gives an *rpm* of 230,314. This formula can be used to determine the rpm.

$$rpm = velocity\left(\frac{m}{s}\right) \times \frac{60}{dist\ per\ turn\ (m)}$$

This factor will be considered as part of the selection process for determining the correct twist rate for a given caliber/projectile during the selection of a test barrel ensuring slowest twist possible is used to reduce the chance of jacket failure.

Projectile strength and density also play a large part in the penetration process and a number of models for predicting penetration use the projectiles density and yield strength. Projectile manufacturers don't publish any detailed information about the properties of the lead or copper used in their projectiles, which makes it hard to gather any data for projectile strength. This is further complicated by the different designs of projectiles and would require extensive testing. Rather than determine these values for strength and density, they were taken from previous research (Børvik, et al., 2009). Projectiles were modeled as if they were of a lead only construction, as it is the primary material in commercial projectiles. The values selected from this research and used were:

$Y_p = 24\ MPa$ $\qquad$ $\rho_p = 10660\ kg/m^2$

2.5 Projectile propulsion

Methods of projectile propulsion vary depending on the desired projectile velocity and the weight size and shape of the projectile. Common to most ballistic laboratories is the gas powered gun, which utilizes a propellant or energy source to drive a ram down a cylinder of compressed gas, which then has a burst plate located at the far end just before the projectile to be fired (Dekel & Rosenberg, 2012). Once the ram compresses the gas to a certain pressure the burst disk ruptures and the pressure generated then propels the projectile down range. Using this method velocities of up to 10km/s are able to be achieved. The speeds required for this research are that of which is obtainable using conventional small arms, thus the need for high powered gas guns is not required. The test can be carried out using rifles chambered to suit the selected calibers for testing.

Maximum velocity from a rifle is dependent on a number of factors such as projectiles weight, case capacity, barrel length and projectile diameter. The calibers that have been selected for testing are .22 and .30 caliber. These were selected as they have projectiles available in the same weight, are a common and popular size for sports shooting and have an array of different cartridges developed for them. To be able to satisfy the objectives of the research, projectiles of the same weight need to be propelled at the same velocity. The factor that controls the velocity is the smaller caliber as it requires more force to drive the same weight projectile. This is due to the decreased cross-section of the projectile and also due to extra friction that is generated by the longer bearing surface against the barrel rifling.

From section 2.4 the closest weight that both projectiles are available in is 90 gr. The velocity for the Berger .22 90gr projectiles fired out of a 22-250 Remington cartridge is approximately 936 m/s (Berger Bullets, 2013). To achieve slightly higher velocity the 22-250 chamber could be modified to 22-250AI which would give a maximum velocity of approximately 975m/s. To stabilize the 90gr projectile would require a different rifling twist rate then what is normally supplied with a standard 22-250 Remington rifle. A 1 in 8" twist gives a stabilization factor at an altitude of 305 m of approximately 1.22 which is marginally stable (Litz, 2011) . The same velocity for a 90gr projectile in the .30 caliber is easily achieved with standard calibers and a .308 Winchester with a standard 1 in 12" twist will stabilize up to 185gr projectile weights pending on their design. This stability is calculated from the Miller stability formula Equation 2.5-1 below with an applied correction for velocity and a correction for atmospheric conditions. This yields the gyroscopic stability factor SG which indicates that factors over 1 are gyroscopically stable. In practice higher factors of around 1.4 are usually desired for ideal stability allowing a factor of safety for error. This is to allow for errors in calculations, imperfectly balanced projectiles and changing atmospheric conditions (Litz, 2011).

Equation 2.5-1 Miller stability formula and correction factors (Litz, 2011)

$$SG = \frac{30m}{t^2 d^3 l(1+l^2)} \times \left(\frac{v}{2800}\right)^{1/3} \times \frac{29.92(FT+460)}{519PT}$$

Where:

$m = projectile\ mass\ in\ grains$

$t = rifling\ twist\ rate\ in\ calibres\ per\ turn$

$d = diameter\ (calibre) in\ inches$

$l = length\ of\ projectile\ in\ calibres$

$v = velocity\ in\ feet\ per\ second$

$FT = air\ temp\ in\ fahrenheit$

$PT = air\ pressure\ in\ inHg$

2.6 Failure modes

There are six common modes of failure that can occur during impact of projectiles on an intermediate thickness target and they vary greatly depending on the target properties, impact velocity and projectile properties and design (Dekel & Rosenberg, 2012). Some of these modes are shown in Figure 2.6-1.

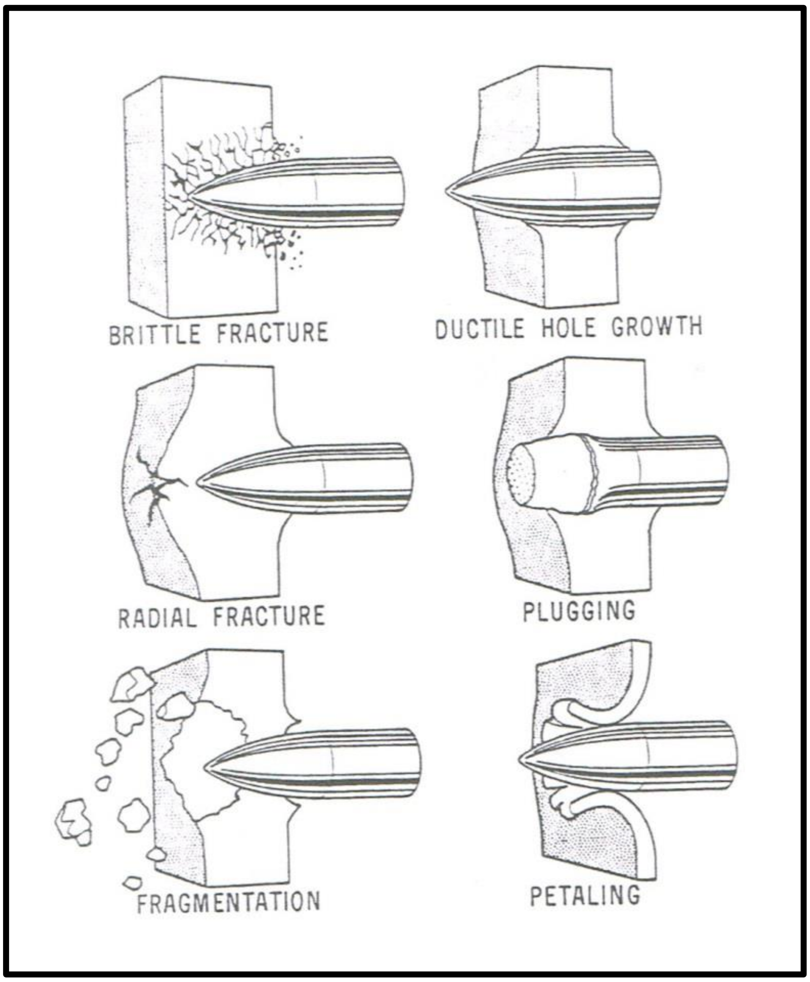

Figure 2.6-1 Failure modes Roesneberg, Dekel (2012)

There are two modes of failure that are expected to occur using the high strength steel that the author is testing. The first is plugging, this is due to high localized strain and adiabatic shear generated during the impact (Dekel & Rosenberg, 2012). This is most common when using blunt projectiles and often occurs at lower velocities than other modes (Dekel & Rosenberg, 2012). The second mode of failure expected is ductile hole growth except the material is expected to be eroded and not pushed aside by the projectile (Dekel & Rosenberg, 2012).

Adiabatic shear is the forming of localized shear bands, due to the high rate of temperature change during an impact a band of material softens from thermal change, quicker than it work hardens from the deformation (Farrand, 1991). Unlike the normal process where the deformation will strain harden and distribute stress to another area, in an adiabatic shear the material does not strain harden and remains soft causing the stress to concentrate on this softer area (Farrand, 1991).

Projectiles are often characterized and modeled by the behavior in which they exhibit when impact a target, for rigid penetrators they are often modeled as if they maintain their shape and mass (Dekel & Rosenberg, 2012). Dekel (2012) lists two typical examples of rigid penetrators, AP (armor piercing small arms ammunition) and high hardness long rod penetrators. These penetrators are readily modeled using a number of different software programs such as AUTODYN and LS DYNA which, with the correct parameters, can predict impact behavior and penetration accurately (Børvik, et al., 2004). Børvik (2009) conducted a number of tests using AP and soft core projectiles on a number of different strength steel plates, from their findings they were able to predict the behavior of the AP projectile using computer modeling to an accuracy of approx. 12%. At the same time a model was developed to try and mimic the behavior of the soft core projectiles but the results were inconsistent and not able to be applied reliably, it did however still give a reasonable estimate of exit velocity for a full penetration (Børvik, et al., 2009).

Eroding penetrators are characterized by their erosion as they penetrate a target. The two most common forms are explosive shaped charge jets and long rod penetrators that are constructed from high density materials such as depleted uranium or tungsten (Dekel & Rosenberg, 2012). A number of different formulas and models have been developed to try and mimic the behavior of eroding penetrators, this analysis can become quite complex, especially when trying to account for entrance and termination phases of an impact (Dekel & Rosenberg, 2012). The Allen Rogers Model is a simple model that was developed by Allen and Rogers in 1961 during the testing of a number of different material rods impacted by an aluminum cylinder. This method was often termed reverse ballistics and was excellent for analyzing the impact of soft rods as they would tend to deform upon firing from the test gun (Dekel & Rosenberg, 2012). The final formula was a modified version of the Bernoulli equation that was developed from integrating the equation over time (see Equations 2.6-1).

$$\frac{P}{L} = \frac{V-\mu\sqrt{V^2+Q}}{\mu\sqrt{V^2+Q}-\mu^2 V} \quad \text{where:} \quad Q = 2\sigma \times \frac{1-\mu^2}{\rho_t}$$

$$\text{and} \qquad \mu = \sqrt{\frac{\rho_t}{\rho_p}}$$

Equations 2.6-1 Allen Rogers Penetration Formula (Dekel & Rosenberg, 2012)

The Alekseevskii Tate Penetration model (Dekel & Rosenberg, 2012) provides a reasonable guide for predicting the penetration depths of an eroding penetrator for velocity's within the small arms ordnance capabilities. The following nomenclature is used:

Vc= critical velocity for penetration

Rt= targets resistance to penetration

Yp= Dynamic strength of penetrator

Using determined values from testing or previous data the following formulas (Equations 2.6-2) can be utilized:

$$\frac{1}{2}\rho_p(V-U)^2 + Y_p = \frac{1}{2}\rho_t U^2 + R_t \quad \textbf{eq. 1}$$

$$\rho_p \ell \frac{dV}{Dt} = -Y_p \quad \textbf{eq.2} \qquad \frac{d\ell}{Dt} = -(V-U) \quad \textbf{eq. 3}$$

$$V_C = \sqrt{\frac{2(R_t - Y_p)}{\rho_p}} \quad \textbf{eq. 4} \qquad U = \frac{V-\sqrt{\mu^2 V^2 + (1-\mu^2)V_c^2}}{1-\mu^2} \quad \textbf{eq. 5}$$

$$\mu = \sqrt{\frac{\rho_t}{\rho_p}} \quad \textbf{eq. 6}$$

Equations 2.6-2 Alekseevskii Tate penetration formula (Dekel & Rosenberg, 2012)

By solving equations 1, 2 and 3 (Equations 2.6-2) the relationship of penetration and velocity can be plotted to simulate the expected depths of penetration for a given projectile.

To be able to use the formulas further data is required to develop the values for Rt and Yp by either determining values from testing or assuming values from previous research. It is noted by Dekel & Rosenberg that this model is not as reliable for prediction as it does not take into account the length to diameter ratio of the projectile. This ratio causes effects during the initial penetration phase or the final phase that are not accounted for by the Alekseevskii Tate formulas.

Hub & Komenda (2009) carried out some testing on 10mm Hardox 450 (a HHA grade of steel plate) using soft projectiles in .338 and .308 caliber. Penetrations were able to be achieved with the .338 at a velocity of 900m/s and energy of 6500 J but the .308 would not penetrate at all with a velocity of approximately 760 m/s and energy of 3000 J (Hub & Komenda, 2009). Looking at this case would suggest that the failure that has been observed is from an adiabatic shear where the energy is enough to cause a direct shear failure in the plate or the velocity is now above the threshold limit for that plate. There is also another failure mechanism that should be considered that is by erosion which occurs at much higher velocities. Previous testing by the author has seen perforation of 12mm armour plate with energy below 3000 J using soft projectiles so it is important to also consider this mechanism when testing plate materials.

2.7 Steel Armour Plate

There are a number of different types of High hardness plates that are used for various testing in the literature that has been reviewed The strength of the plate material is the most important property in determining the penetration depth of both rigid and eroding penetrators (Dekel & Rosenberg, 2012). The hardness of the steel also affects it’s performance and typically the ballistic efficiency increases as hardness increases (Dekel & Rosenberg, 2012), (Børvik, et al., 2009). As per Figure 2.7-1 it can be seen that as the steel hardness approaches 450BHN and higher the ballistic efficiency of the HHA plate will increase. The two Armour steels that are listed in Figure 2.7-1 are RHA and HHA. RHA (Rolled Homogenous Armour) is made by a process of continuous rolling high tensile steel to achieve a homogenous structure and HHA (High Hardness Armour) undergoes a quench and temper process to achieve a high hardness and still retain some ductility.

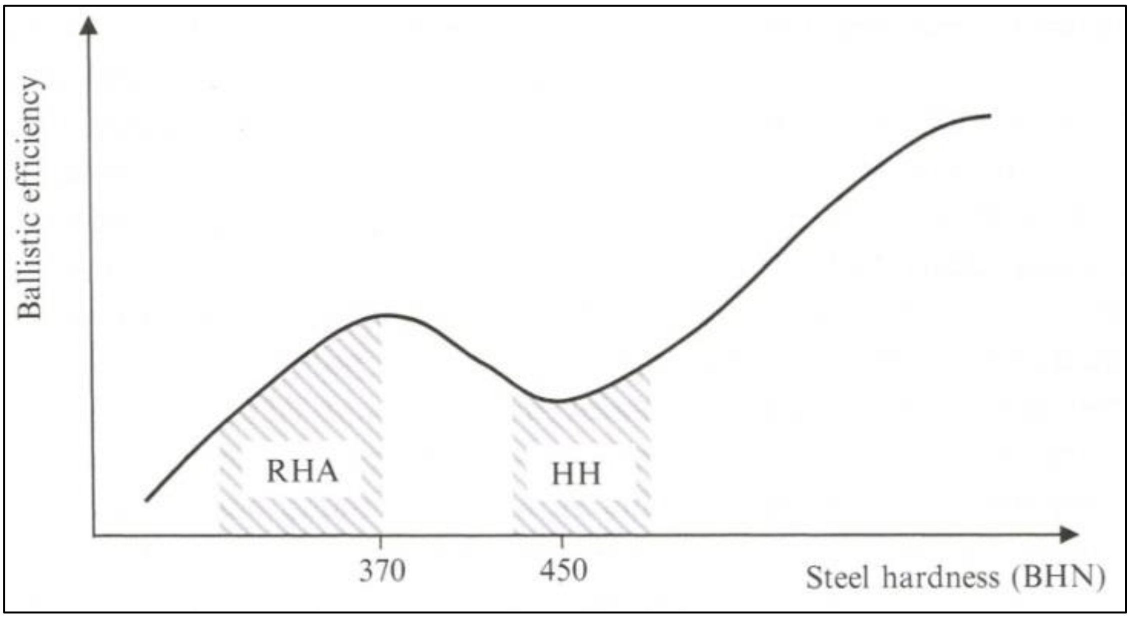

Figure 2.7-1 Ballistic efficiency vs. hardness (Dekel & Rosenberg, 2012)

The most common armour plate that is manufactured in Australia is Bisplate HHA and this is made by Bisalloy in Wollongong NSW. Availability of HHA is usually only by special order but Bisplate 500 is one of their wear grades which has very similar strength and hardness properties and is readily available and stocked by many steel suppliers. It is also the choice for the majority of steel targets that are used on ranges throughout Australia. The most common sizes that are used on ranges for targets are 10 mm and 12 mm. Cutting of Bisalloy 500 is best performed with either laser or water- jet to minimize the heat affected zone around the edge of the target. Laser cutting results in a heat affected zone of approximately 0.2 mm around the edge of the cut and water jet cutting does not induce any heat affected zone at all (Bisalloy Steels, 2006).

From the Bisalloy technical manual the properties of Bisplate 500 and Bisplate HHA are specified in Table 2.7-1 &

Table 2.7-2. In comparison to mild steel of approximately 300 MPa yield strength and 160BHN hardness it is approximately four and a half times stronger and three times harder.

Table 2.7-1 Bisalloy Chemical composition (Bisalloy Steels, 2006)

Material	C	P	Mn	Si	S	Cr	Mo	B	CE
Bisplate 500	0.29	0.015	0.3	0.3	0.003	1.0	0.25	0.001	0.61
Bisplate HHA	0.32	0.025	0.4	0.35	0.005	1.2	0.30	0.002	0.61

Table 2.7-2 Bisalloy mechanical properties (Bisalloy Steels, 2006)

Bisplate 500		Bisplate HHA	
Yield strength	1400 MPa	Yield strength	1400 MPa
Tensile strength	1640 MPa	Tensile strength	1640 MPa
Elongation in 50mm	10 %	Elongation in 50mm	14 %
Hardness (BHN)	477-534	Hardness (BHN)	477-534

Testing has been performed on Bisalloy HHA against AP and FSP rounds and the V_{50} ballistic limit for 12mm plate was determined to be 826 m/s for a /30 cal APM2 projectile and 835 m/s for a .50 cal FSP (Dwight D. Showalter, 2007). Comment is also made that during testing of a number of different grades of hardness plate the ballistic limit reduced for an FSP projectile as the plate hardness increased (Dwight D. Showalter, 2007).

2.8 Review findings

From the literature review the following conclusions have been drawn:

- The largest possible diameter difference with the same weight projectile is .22 cal and .30 cal.
- To use heavy projectiles in a small caliber barrel requires a different twist rate to stabilize the heavier projectile.
- Ogive style projectiles require more velocity to penetrate as plate hardness increase, whereas blunt projectiles will require less velocity to penetrate.
- Deformable projectiles penetrate similar to that of eroding penetrators on impact causing erosion rather than ductile hole growth.
- The L/D ratio of a projectile can have significant effects on the depth of penetration and lower ratios are more efficient in their penetration rate.
- There is a critical velocity that should result in no damage to armor plate which is related to the strength of the plate the strength of the projectile and its density.
- There are many models for predicating penetration but the Alekseevskii Tate model is a simple model which has been used by a number of different researchers. It does not have the ability to predict the L/D effect though (Dekel & Rosenberg, 2012).

Chapter 3. Safety & Risk

3.1 General

Multiple risks were associated with my thesis which were present during the practical component. To manage these risks and identify any high risk activities a general risk assessment based on consequence and likelihood was developed see **Error! Reference source not found.**.

There are 3 main high risk factors that are identified by the risk assessment after control measures have been implemented and they are listed below:

- Distractions and other vehicles whilst driving: As the author lives approximately two hours away from the university and the range chosen for testing the risk from travel is greatly increased due to the duration on the road. It is not possible to account for the actions of other drivers and control their fatigue or possible distractions and due to this the risk has been listed as high, by implanting the stated controls the risk can be minimized as much as possible.
- Over charging a cartridge during reloading: This usually occurs due to lack of attention during the charging process and an accidental double charge is placed inside the cartridge. This would not normally be possible with the cartridges being used as they would be close to case capacity under normal loading but due to using reduced load the volume of powder is smaller. Given that the chance of this occurring is possible it is highly unlikely as long as the control measures are followed. The main reason for the high rating is that it could cause severe injury in an incident.
- Pressure overload during firing: Shooting sports when compared to many other team sports is by far one of the safest sports in term of injuries but the nature of releasing pressures of upwards of 40,000psi only inches from ones face does present the need for some care to be taken. Safety mechanisms are built into modern rifles to divert pressure in case of an overload situation but injury has still occurred in major overloads. The high risk rating indicating that this is an area where care must be taken.

3.2 Commercial risk

Damage to equipment can be costly and set back not only the project timeline but also possibly affect other research that is dependent on equipment used for this thesis. Three items that have been identified as needing special attention to ensure protection during the testing are listed below:

- Chronograph: Many a chronograph has been destroyed by the inexperienced shooter not compensating for scope height at short range or not looking down the barrel before shooting to make sure the muzzle is aiming through the middle of the chronograph pickup sensors. The cost to replace these screens is approximately $200 but more damaging is the lead time to replace if damage was to occur. Without the chronograph the testing cannot be carried out as the velocity is a critical measurement that must be taken. To reduce this risk the procedure before firing every shot through the sensors is to perform a check on the muzzle alignment and also to place the chronograph as close as possible to the muzzle without been affected by muzzle blast. The Lexan protection screen used for protection at the firing position also helps ensure alignment with the sensors as it only has a small ported area to fire out of refer to Figure 3.2-2
- Test rifles: Identified as one of the hazards that could cause injury is an over pressure during firing. This is at the extreme end but on a small overpressure there may be no injury to the operator but the rifle could still be rendered inoperable and cost could exceed $900 to repair any damage. The controls that cover the overpressure in the risk assessment are sufficient enough to reduce this risk as much as possible.
- High speed camera: The highest commercial risk that has been identified is that of damage to the high speed camera. Damage to this unit could exceed $30,000 and also affect other projects that are relying in the use of the camera. Replacement not only would be costly but could have long lead times as these cameras are a specialized supply item. The camera will also be within close proximity to the targets during testing and the most likely form of damage would be from shrapnel or ricochets off the target. To prevent this, the camera will be placed in an enclosed steel box, which is shielded with extra armoured plate on the side facing the targets and also the side that is facing the test bench. Viewing will be through the front of the box through a 12mm thick

Lexan cover plate which protected the camera from any shrapnel from the target and still allow viewing of the impacts (Figure 3.2-1).

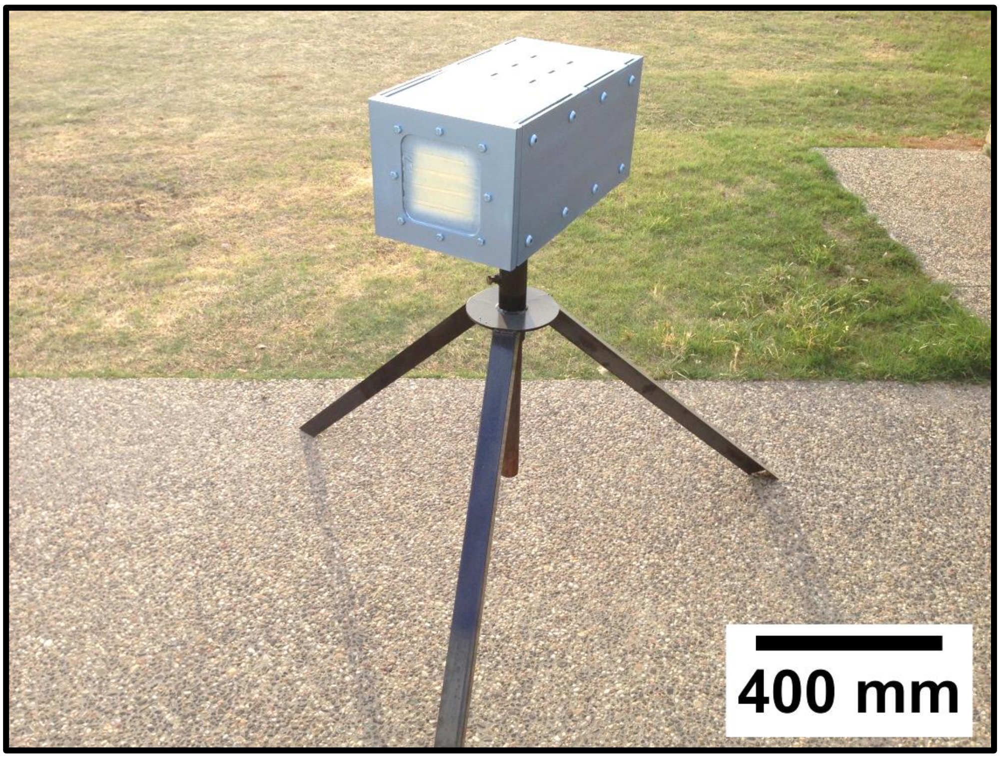

Figure 3.2-1 Camera protection

Figure 3.2-2 Firing position protection

Chapter 4. R&D and Methodology

4.1 Research, Design

4.1.1 Plate material selection and Retention

As identified Bisalloy 500 is a readily available armour style steel that is widely used for targets on ranges throughout Australia. For this project, testing was on 150mm squares of 12mm thick Bisplate 500 laser cut with two 13mm mounting holes. This will ensure that the HAZ is kept to a minimum and to prevent this from affecting results, the impact points will be approximately 18mm away from each cut edge and each subsequent projectile impact on the plate as shown in Figure 4.1-1.

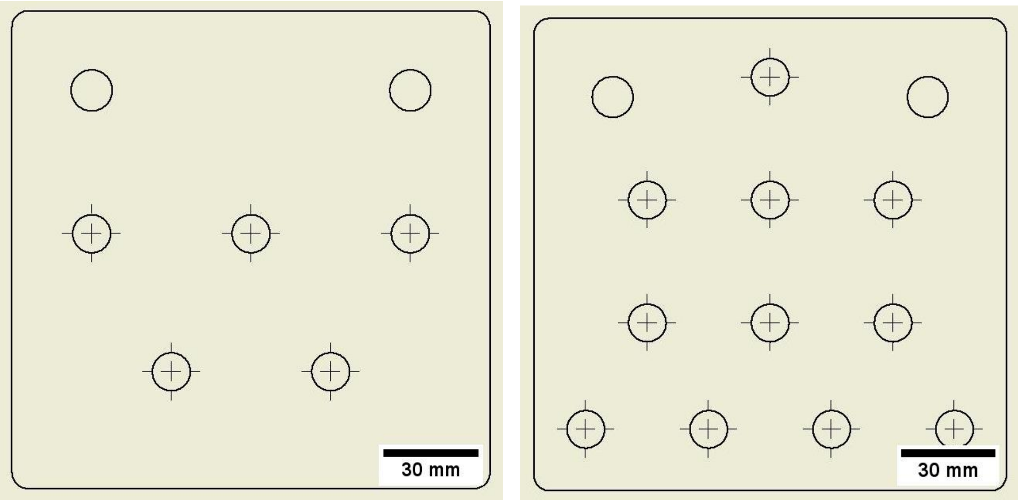

Figure 4.1-1 Impact locations

Mounting of the plates was via a rigid support frame constructed with 50x50x3 mm angle with a 300x400x6 mm mild steel plate with a cutout in the middle to mount the testing targets, see Figure 4.1-2 below. The frame stands the target plates at 1050 mm tall which fits in line with the benches that were used to fire the test projectiles from, this kept the impact angle perpendicular to the test plates. A rigid mounting was chosen to simulate worst case scenario of a fixed plate. The support frame will be fixed to the ground via heavy stakes and sand bags to increase its rigidity and prevent it from moving. It is expected that some deflection will occur during impact but remain at a constant amount throughout testing and be of minimal effect to the final results.

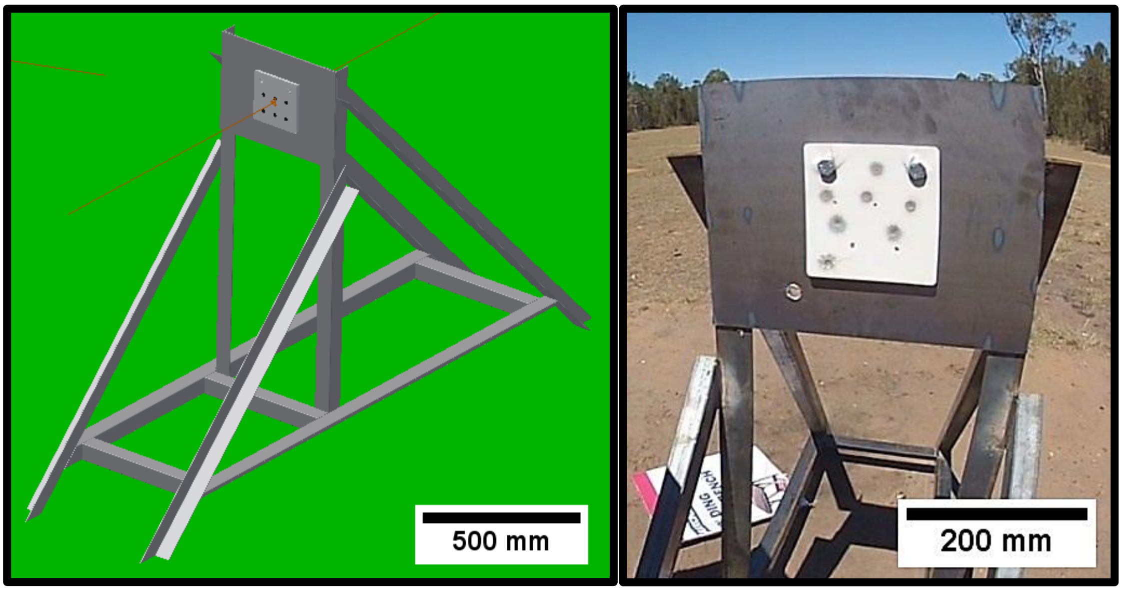

Figure 4.1-2 Testing frame

4.1.2 Cartridge and Caliber selection

From the Literature review it was identified that the 22-250 Ackley Improved cartridge was capable of achieving close to the upper limits for small arms velocity for civilian available firearms. This was chosen as the base and then the .308 Winchester as the second test cartridge as it could match the velocities for the diameter comparison. Both these calibers are easily reloadable with standard equipment. Using the 22-250AI a max velocity of approximately 1250m/s is achievable using a 50gr projectile. Barrel twist was selected to achieve minimum stability for the heaviest weight projectile for each calibre. This was based on the 90gr Berger BTHP projectile for the .22 cal and the 155gr Hybrid BT for the .30cal. Using the miller stability formula and atmospheric data for the testing facility (Appendix C) yielded the following stability factors at 975 m/s. 1.075 for the .22cal with a 1in 8 inch twist and 1.44 for a 1 in 12 inch twist in the .30 cal. This is the final barrel twist rates that were selected and all calculations are based on these rates (Appendix D).

4.1.3 Projectile selection

As stated previously .22 and .30 calibre projectiles are both available in 90gr weights. Berger makes a 90gr .22 caliber projectile and Hornady make a 90 gr .30 caliber pistol projectile. These were used for the diameter comparison. There is approximately 37.5% difference in the diameters and 89% difference in the cross sectional area. As a backup for the 90 gr Hornady projectile a 100 gr Hornady SP was also selected as the lighter 90 gr projectile may suffer from jacket failure at the testing velocity.

For the similar length comparison the .30 cal 155gr Berger and .22 cal 90gr Berger will be used as their length and sectional density is very close. There is 1.3% difference in the overall length and 9.9% difference in the sectional density. Comparing energy at 975 m/s the 155 gr has 4700 J and the 90 gr has only 2700 J which is a difference of 74%.

For the velocity step test, the following two projectiles were selected:

- .22 cal 50 gr Barnes varmint grenade.
- .22 cal 55gr Speer SP.

The 50 gr Barnes was selected as it is renowned for its ability to handle velocity over 1200m/s and also as it is an unusually long projectile for its given weight and size. It often referred to as a frangible round and instead of a conventional lead core it is filled with a sintered tin. The 55 gr Speer is a more conventional design with a solid lead core and of a more common length for that size (Johnson (ed), 2010) & (Berger Bullets, 2013). Comparing the two together they are similar in the nose style except the Barnes is a hollow point and the Speer a soft lead point. There is also approximately 28% difference between the lengths of the two. Each projectile style can be seen in Figure 4.1-3.

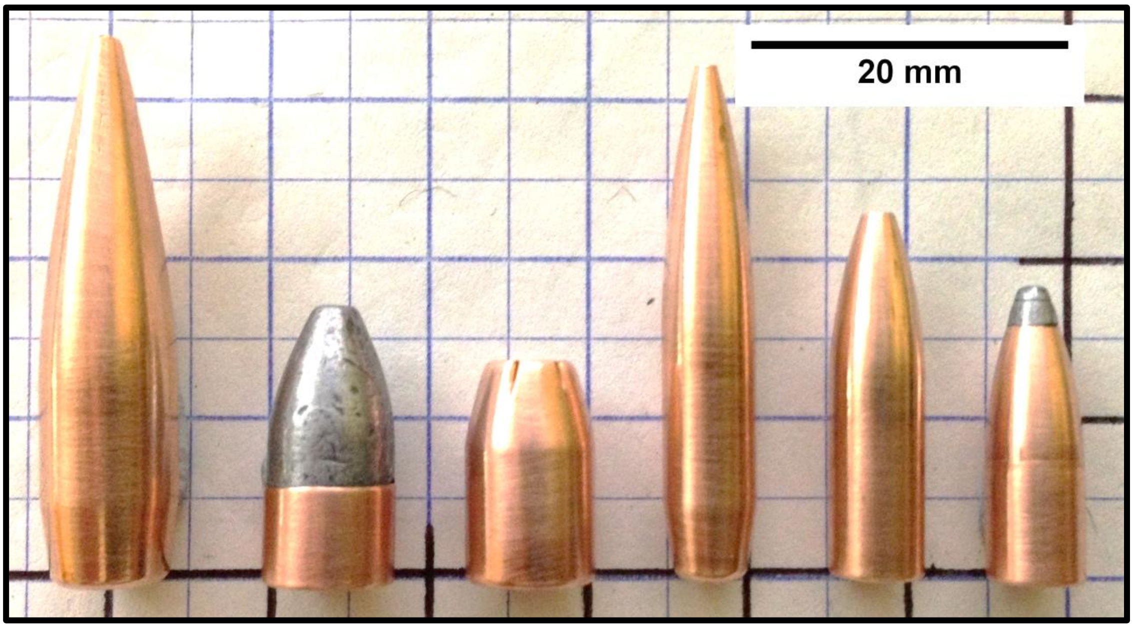

Figure 4.1-3 Projectiles, from left .30 cal (155gr, 100gr, 90gr) & .22 cal (90gr, 50gr, 55gr)

Stability of each projectile was checked using the miller stability formula Equation 2.5-1 (full description in Equation 2.5-1) and adding the correct velocity and atmospheric corrections. All projectiles have an SG of greater than 1, ensuring stability during the testing process. Table 4.1-1 shows the properties of each projectile selected for testing including their stability factors.

Equation 4.1-1Miller stability formula and correction factors (Litz, 2011)

$$SG = \frac{30\,m}{t^2 d^3 l(1+l^2)} \times \left(\frac{v}{2800}\right)^{1/3} \times \frac{29.92(FT+460)}{519PT}$$

Table 4.1-1Projectile properties

Projectile properties										
Calibre (inch)	Make	Weight (grains)	Length (mm)	Style	S.D	B.C	Target impact V (m/s)	Energy (J)	Twist (in/rev)	SG
0.22	Berger	90	32.1	BTHP	0.256	0.512	930	2522	8.0	1.0
0.22	Barnes	50	21.8	FBHP	0.142	0.183	1200	2333	8.0	1.9
0.30	Berger	155	32.5	BTHP	0.233	0.483	930	4343	12.0	1.4
0.30	Hornady	100	16.37	SP	0.151	0.152	930	2802	12.0	6.1
0.30	Hornady	90	13.23	JHP	0.115	0.136	930	2522	12.0	9.5
0.22	Speer	55	17	FBSP	0.157	0.212	1200	2566	8.0	4.3

4.1.4 Velocity selection

To select the velocities for testing, the major limiting factor was the maximum velocity that could be achieved using the .30cal 90 gr projectiles due to case capacity. From load development this was approximately 983 m/s. Loads higher than this were not possible with the current powder that was used. Working this velocity forward to the impact point using Ballistic AE gives an impact velocity of 930m/s. The other projectiles were then based from this, although they may not reach this value. This maximum will be used as it will ensure that the two exact weights are going the same velocity at the highest possible speed that can be achieved with the chosen testing equipment.

For the velocity step test the minimum velocity for testing was chosen at 750m/s (muzzle velocity) as values below this have shown no appreciable damage to plates through previous testing that was performed by the author. The maximum velocity was selected at 1250 m/s as this is the maximum available from the 50 gr projectile before pressure signs began to show, it is also the maximum velocity allowed at the testing facility. Testing will be stepped in 50 m/s intervals resulting in eleven shots total per projectile for the velocity step test.

To work out the impact velocities and desired muzzle velocity the program Ballistic AE was used, an app designed to run off an iPhone. It is an advanced ballistic calculation simulator and based on the proven JBM ballistics engine developed by James B. Millard (Zdziarski, 2013). This program uses the following data for basic calculation:

- Loads and measures local weather data.
- B.C.
- Chronograph velocity.
- Distance from chronograph to muzzle.

With this data entered it will output the velocity at any distance and the muzzle velocity input was altered a number of times until the velocity at 25 m reached the target impact velocity. The corresponding muzzle velocity was then used as the target chronograph velocity. Table 4.1-2 lists the desired chronograph speed measured 2m from the muzzle and also the target impact velocity calculated from this program. Note that the .30 cal 90 and 100 gr projectiles are losing velocity significantly quicker than the .22 cal 90 gr projectiles, showing the difference in velocity that air drag can cause.

Table 4.1-2Velocity Target Chronograph and Impact Velocity

Calibre (inch)	Make	Weight (grains)	Distance from chrono (m)	Target chrono velocity (m/s)	Target impact V (m/s)
0.22	Berger	90	2.0	**944.0**	930
0.22	Barnes	50	2.0	**1248.0**	1200
0.30	Berger	155	2.0	**945.0**	930
0.30	Hornady	100	2.0	**976.0**	930
0.30	Hornady	90	2.0	**983.0**	930
0.22	Speer	55	2.0	**1248.0**	1200

4.1.5 Major Equipment

The items listed below were the major items used for the testing process, all these were essential to the testing process. Unfortunately due to last minute issues with insurance off campus the high speed camera was not able to be used. Although not critical to the final testing process, it does mean that it was not possible to view the projectile shape just before impact or the tip interaction during penetration of each different projectile.

- Test rifle 1 .22 caliber chambered in 22-250AI with 1 in 8 twist barrel.

- Test rifle 2 .30 caliber chambered in .308 Win with standard 1 in 12 twist barrel.
- CED M2 chronograph for primary velocity measurement.
- Reloading equipment for 22-250 AI and 308 Winchester is available and ready for use.
- Metrology equipment, digital calipers, tape measure and laser range finder.
- Photron Fastcam SA3 High speed video camera.
- Ballistic unit for holding steel plates and providing protection for the camera.
- Portable setup to fix reloading equipment to allow in field velocity changes.

Test rifle two is a standard off the shelf rifle and was loaned for the testing, while test rifle one had to be custom fitted with the faster twist barrel to allow the stabilization of the 90 gr projectile. The CED M2 is a mid-range chronograph designed for sporting shooters and in good light it is accurate to 99.95% (Competitive Edge Dynamics, 2013). It is important though to keep consistent lighting during the testing to give consistency between velocities (Competitive Edge Dynamics, 2013). Measurement of penetration depth and crater diameter will be with digital calipers and also some gauge blocks and a ground cylinder to straddle the plate and improve accuracy during measurement.

Standard reloading equipment was used for load development and the powder scales used for testing were calibrated before use to ensure correct readings were displayed. A portable bench was designed to allow loading at the testing facility, this provided a huge time saving and allowed quick load development and the ability to make on the spot changes as needed.

All other general equipment used and consumables is listed in Appendix E.

4.1.6 Facilities licensing, Environmental controls

Millmerran SSAA shooting complex (Captains Mountain, south of Millmerran) was used as the testing facility, it is licensed and contains a range that is approved for the use of hard targets. Velocity is limited to 1250 m/s and energy to 6000 J measured from the muzzle.

Testing at this facility alleviates any concerns with noise pollution or ground contamination that are associated with testing on private property. It also has marked safety boundary to ensure warn of danger inside the range template. Testing took place over two consecutive days.

4.2 Load development

4.2.7 General loading

The load development process was a far more involved task than first anticipated. Load development took place over approx. 6 different days and each load had to be worked up from starting loads (Thales Australia, 2013) to the maximum level to determine the limiting velocities for each projectile. This was further complicated by the fact that some of the projectiles were running at velocities that are close or above the jacket separation limit (Johnson (ed), 2010). To keep the process as simple as possible powders and primers were kept to only two types and each projectile was worked up to its limits and the velocities recorded. As loads were worked up to their limits powder was only increased in 0.5 gr increments until the target velocity was reached or pressure signs began to show. To assist with load development load charts were used (see Appendix C) to keep the recording standard and prevent mix-up of load data.

4.2.8 22-250 AI Loads

The loads for the 22-250 AI all approach the upper limits for pressure and hence care must be taken during the load development stage. The following combinations were used:

- 50 gr Barnes varmint grenade Rem:
  - 9.5M primers.
  - 37.5 to 45 gr AR2209 for 1100 m/s to 1250 m/s.
  - 19 to 31 gr of AR2206H for 750-1050 m/s.
- .224 dia 55 gr Speer soft point projectiles:
  - 9.5M primers.
  - 41 gr of AR2206H for 954 m/s.
  - This load was not able to achieve the final velocity due to jacket failure in the early stage velocities so it has been removed for the testing process.
- .224 dia 90 gr Berger BTHP projectiles:
  - 9.5M primers.
  - 38.0 gr of AR2209 for 944 m/s.

4.2.9 .308 Winchester Loads

The .308 Winchester had one load that approached maximum pressures the .30 cal 155 gr Berger and had to be limited to 840 m/s. Loading of the light projectiles for this cartridge also presents its own challenges. Although they are not approaching the higher end of the pressure scale, the light projectiles chosen are near their limit for jacket separation (Johnson (ed), 2010). Loads were worked up to the target velocity or the limit where the jacket failed. This failure is often witnessed as a grey puff of smoke at some point down range and consequently no holes in the target. Another factor that also needs to be considered is the powder charge and filled case volume. Too little case volume with slow powders can result in a case detonation which is a serious hazard. To prevent this, lighter loads are based on AR2206H powder. This powder has specifically been tested with low case volume loads and proven safe for any load as long as it is within 40% of the maximum charge (Hodgon Powder Company, 2013). The following combinations were used:

- .308 dia 90 gr Hornady XTP projectiles:
  - 9.5 primers.
  - 52 gr of AR2206H for 984 m/s max case capacity.
- .308 dia 100 gr Hornady SP projectiles:
  - 9.5 primers.
  - 52 gr of AR2206H for 948 m/s.
- .308 dia 155 gr Berger Hybrid projectiles:
  - 9.5 primers.
  - 46.5 gr of AR2206H for 840 m/s.
  - This load started to show pressure signs before the target velocity of 945 m/s could be reached.

Figure 4.2-1 .30 cal 90 gr at Max case capacity

4.2.10 Final load results

The final load workup was conducted on the range during the testing to allow loads to be tailored and altered as atmospheric conditions changed and or problems were encountered.

The overall impact velocity had to be reduced to 930 m/s to achieve the same velocity for the two 90 gr loads as the maximum case capacity was reached using the AR2206H powder for the .30 cal 90 gr XTP, Figure 4.2-1. This was the same case for the .30 cal 100 gr Hornady soft point which could only reach an impact velocity of 900 m/s.

The .30 cal 155 gr could only reach 826 m/s instead of 945 m/s but it was still used for testing. Ideally this load could have been moved up to a larger cartridge capable of a higher velocity but this was not available at the time.

The .22 cal 55 gr Speer was removed from the testing process as it experienced jacket failure at 945 m/s making it unsuitable for the velocity step test.

All loads showed accuracy within 25 mm at 25 m except for the .30 cal 100 gr Hornady SP which showed signs of instability and accuracy was approximately 100mm at 25m. Velocity stability for all loads was within $\pm$ 0.6% see table Table 4.2-1 for each projectile variance.

Table 4.2-1 Velocity variance

Name	Velocity variance +- (m/s)
.22 cal 50 gr Barnes varmint grenade 930 m/s	N/A
.22 cal 90 gr Berger BTHP 929 m/s	0.43%
.30 cal 90 gr Hornady XTP 932 m/s	0.21%
.30 cal 100 gr Hornady SP 898 m/s	0.50%
.30 cal 155 gr Berger Hybrid 826 m/s	0.54%

4.3 Testing procedure

The testing fixture was placed at 25 m and the chronograph at 2 m from the firing position, measured using a standard tape measure. Each projectile was loaded with eight rounds for the comparison test and fifteen rounds for the velocity step test. These allowed two shots to sight in and confirm the impact point and one spare in case a projectile was placed off target. A paper target was placed under the plate to be used as the sight in target which minimized the need for readjustment of the firing position and to keep alignment with the chronograph.

Each shot was fired then the velocity and point of impact on the plate was recorded on the test record sheet for that projectile (Appendix C). After all shots were completed on that plate it was removed and marked with the shot number for each impact, the details of the projectile and the velocity using a permanent marker.

Shots were aimed starting from the top left hand side and working to the right and down for each row. If accuracy was poor and this was not able to be achieved the shot number was marked between each shot to avoid confusion. This was the case for the .30 cal 100 gr Hornady soft point which resulted in an aim point in the center of the plate for all shots and marking after each shot.

Atmospheric conditions were taken at the commencement of testing and monitored during the testing process for any significant changes. Current conditions and the recorded chronograph velocity were used to calculate the projectile impact velocity using the selected program Ballistic AE. Final atmospheric conditions used for calculations are listed in Appendix C.

After testing was completed the penetration was measured and recorded in the corresponding column on the test data sheet. Penetration was measured using a digital depth gauge, ground flat cylinder and two pieces of ground square steel (Figure 4.3-1). A reference measurement was first taken beside the impact, outside of the affected area the depth measurement was then taken and the difference recorded as the penetration depth. This method minimized any error occurring from bending, warping or a raised area formed from projectile impact. The crater diameter was also measured as a reference using digital calipers. This was quite difficult for small penetration depths as the crater was often not clearly defined, so the best estimate of the start of the material deforming was used as the crater diameter measurement (Figure 4.3-2).

Once all the testing was completed the percent variation from the target velocity was calculated for each of the comparison projectiles and hand written records transferred to a soft copy to allow data to be compiled for comparison.

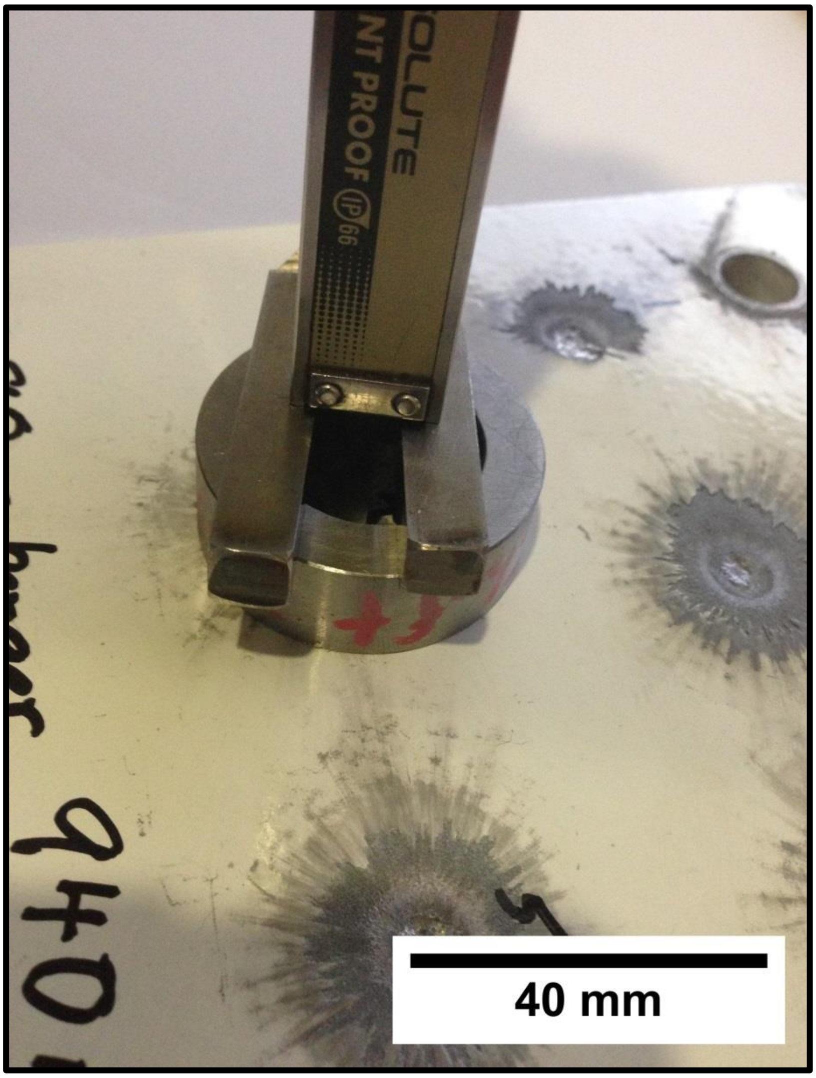

Figure 4.3-1 Measuring penetration depth

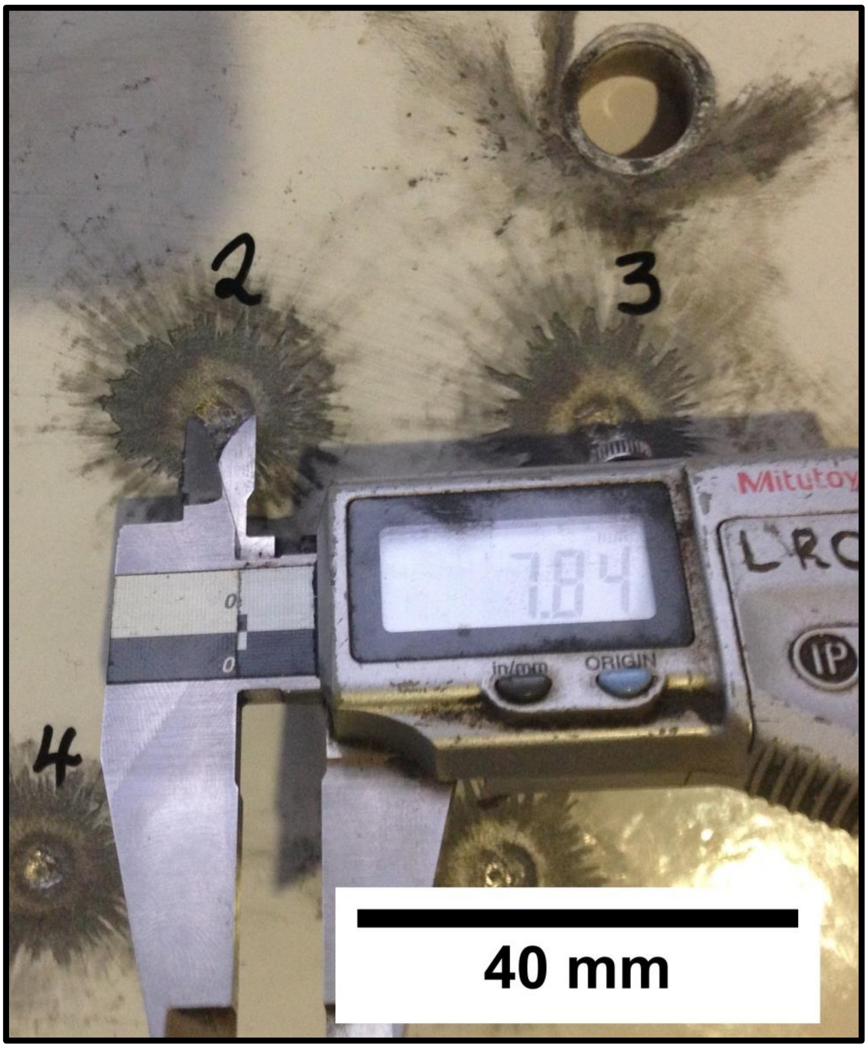

Figure 4.3-2 Measuring penetration and crater diameter

Chapter 5. Results

5.1 .22 cal 50 gr Barnes varmint grenade (velocity step)

The 50gr Barnes Varmint grenade was chosen for the velocity step test because of its capability to withstand high velocity and fast barrel twist rates. The first impact velocity was 711 m/s which only had a penetration of 0.05 mm and no appreciable mark in the plate. The velocity was increased until the maximum was reached with an impact velocity of 1199 m/s. This resulted in a penetration depth of approximately 2.19 mm and a crater of 14.5 mm. The change in penetration was gradual but after shot six at 888 m/s there was a definite change in the crater shape and material could easily be seen to be eroded. Shot eight at 1049 m/s also started to display an indentation on the back of the plate and this increased further for the higher velocities, to a point where the final shot looks to be close to a failure via plugging. Also note that the penetration at the comparison velocity is only 0.3 mm (Figure 5.1-1) & (Table 5.1-1).

Table 5.1-1 .22 cal 50 gr Barnes penetration

Shot no.	Impact velocity (m/s)	Impact energy (J)	Penetration (mm)
1	711	817	0.07
2	740	883	0.06
3	787	999	0.09
4	838	1134	0.14
5	888	1272	0.25
6	931	1401	0.3
7	993	1593	0.51
8	1049	1775	0.8
9	1098	1946	1.22
10	1138	2092	1.4
11	1199	2321	2.19

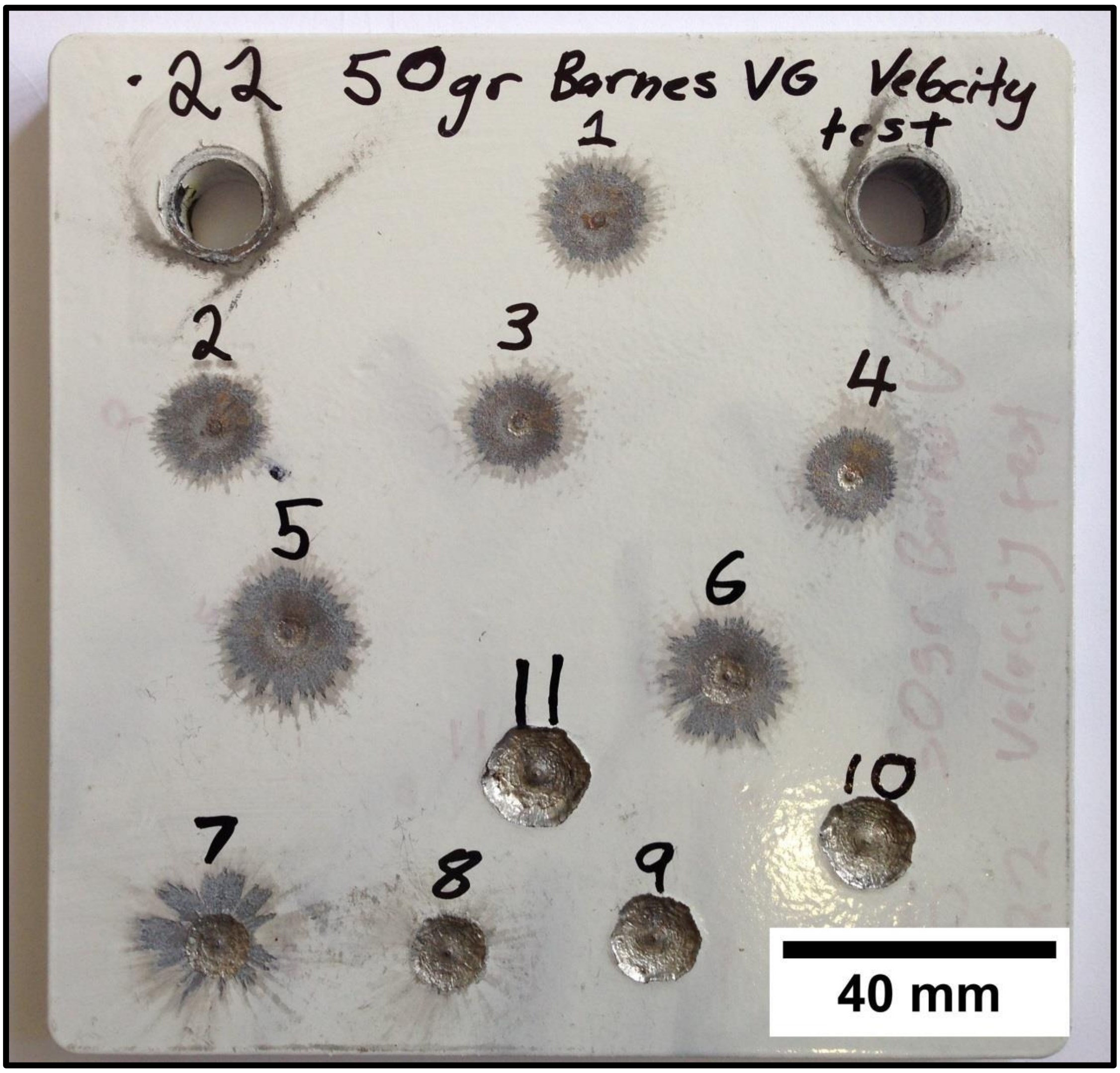

Figure 5.1-1 .22 cal 50 gr Barnes penetration

5.2 .22 cal 90 gr Berger BTHP

The .22cal 90 gr Berger had an average impact velocity of 929 m/s (Table 5.2-1) and penetration of 0.50 mm. The penetration craters are all very similar except for crater one which shows slightly more erosion but still a similar overall depth. There is no marking on the rear of the plate and damage is minimal to the front of the plate (Figure 5.2-1).

Table 5.2-1 .22 cal 90 gr Berger penetration

Shot no.	Impact velocity (m/s)	Impact energy (J)	Penetration (mm)
1	928	2508	0.55
2	927	2503	0.5
3	935	2546	0.46
4	928	2508	0.5
5	928	2508	0.5
Crater Diameter : 7 mm Average Velocity: 929 m/s Average Penetration: 0.50 mm			

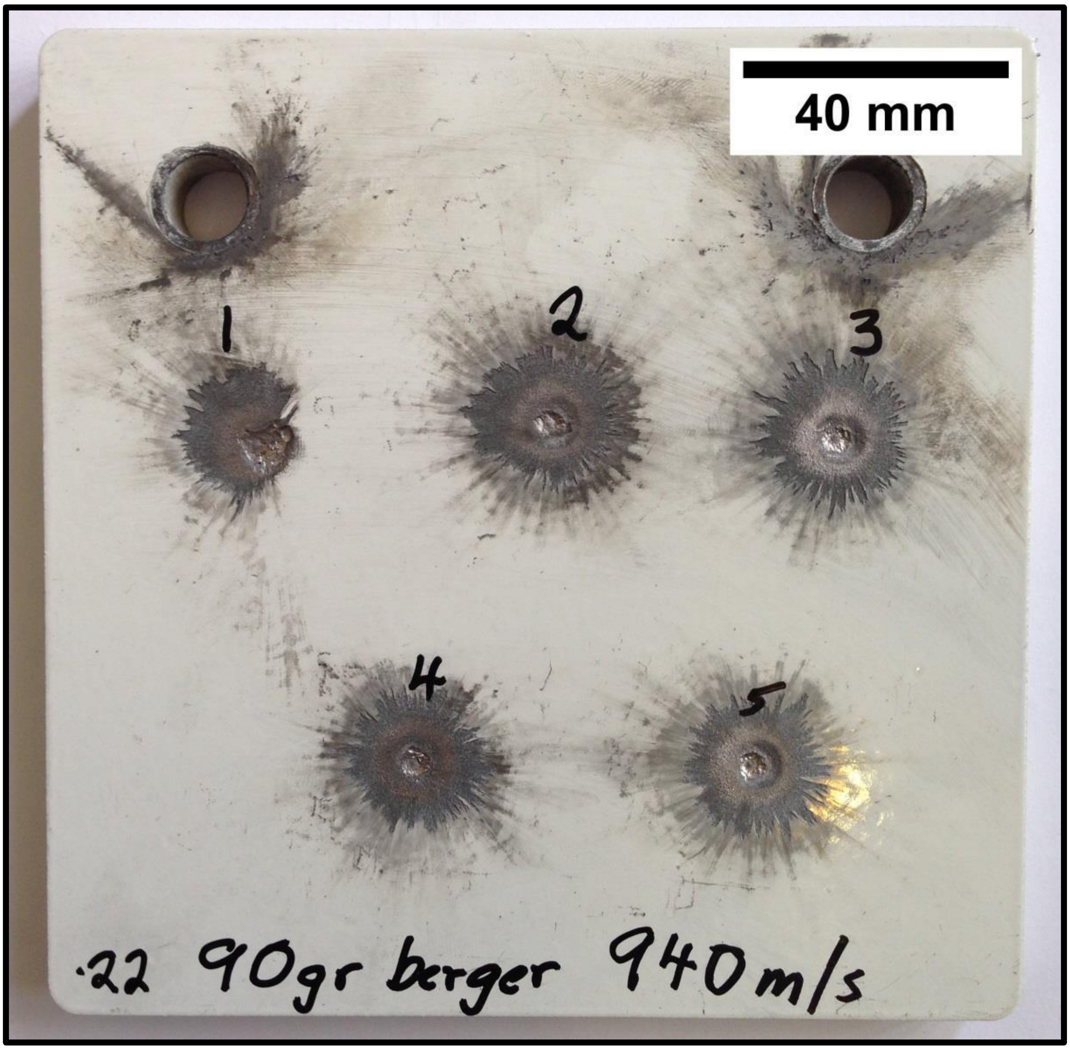

Figure 5.2-1 .22 cal 90 gr Berger Penetration

5.3 .30 cal 90 gr Hornady XTP

The .30 cal 90 gr Hornady had an average impact velocity of 932 m/s (Table 5.3-1) and penetration of 2.82 mm. There was 10% difference between some of the impact depths and the crater diameter (15mm at the largest part) was significantly larger than the original projectile. All impacts also showed initiation of plugging failure and protrusion of the plug could be seen on the back of the target plate (Figure 5.4-2). A star pattern which was a mirror image of the front of the projectile was also present in the centre of the impact crater and the centre of the impact also showed discoloration from heat (Figure 5.3-1).

Table 5.3-1 .30 cal 90 gr Hornady

Shot no.	Impact velocity (m/s)	Impact energy (J)	Penetration (mm)
1	931	2513	2.51
2	931	2519	3.10
3	934	2534	2.53
4	934	2534	3.17
5	930	2508	2.80
Crater Diameter : 15mm Average Velocity: 932 m/s Average Penetration: 2.82 mm			

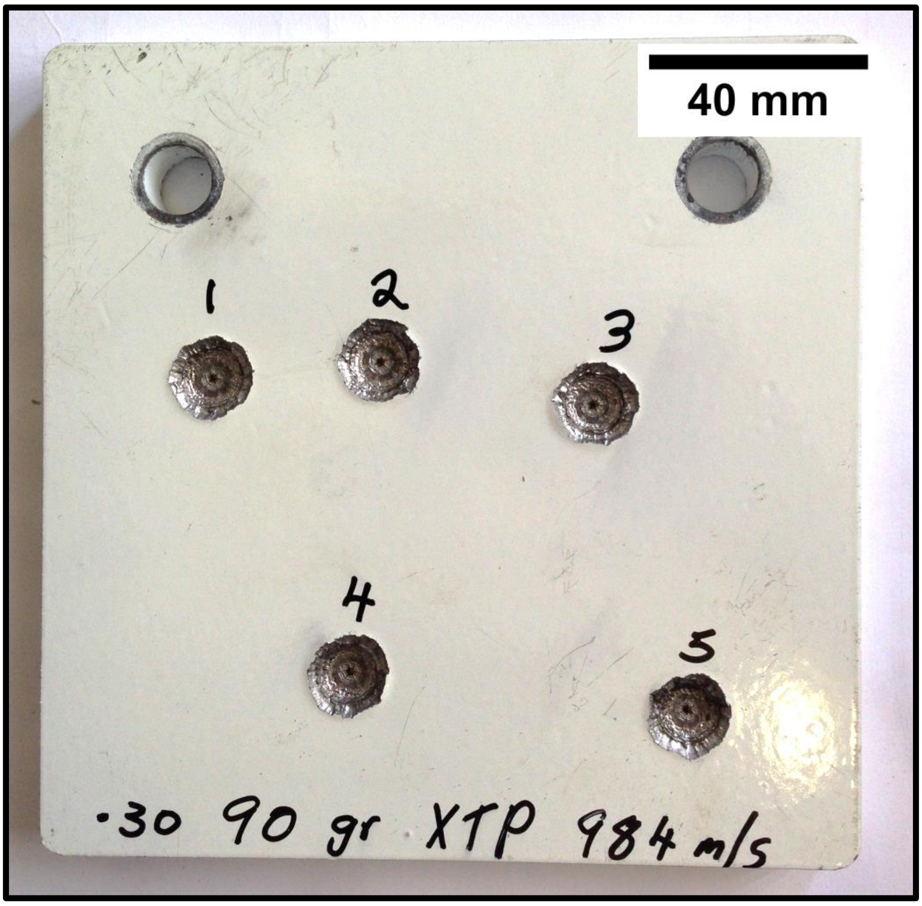

Figure 5.3-1 .30 cal 90 gr Hornady front

5.4 30 cal 100 gr Hornady SP

Only four shots were recorded for the .30 cal 100 gr Hornady projectile as it suffered problems with accuracy at the testing velocity. The first impact was on the edge of the plate so it was omitted due to been too close to the edge and HAZ. From the four impacts the average velocity was 899 m/s (Table 5.4-1) which is 3.3% lower than the other test projectiles. The average penetration was 3.4mm (Figure 5.4-1) and all impacts showed signs of plugging failure on the rear of the plate. Impact number three was very close to full penetration, the plug from impact was protruding approximately 3 mm and complete failure could be seen around the plug (Figure 5.4-3).

Table 5.4-1 .30 cal 100 gr Hornady

Shot no.	Impact velocity (m/s)	Impact energy (J)	Penetration (mm)
1	Not counted		
2	900	2613	3.08
3	903	2630	4.46
4	894	2580	2.87
5	897	2596	3.24
Crater Diameter : 15mm Average Velocity: 899 m/s Average Penetration: 3.4 mm			

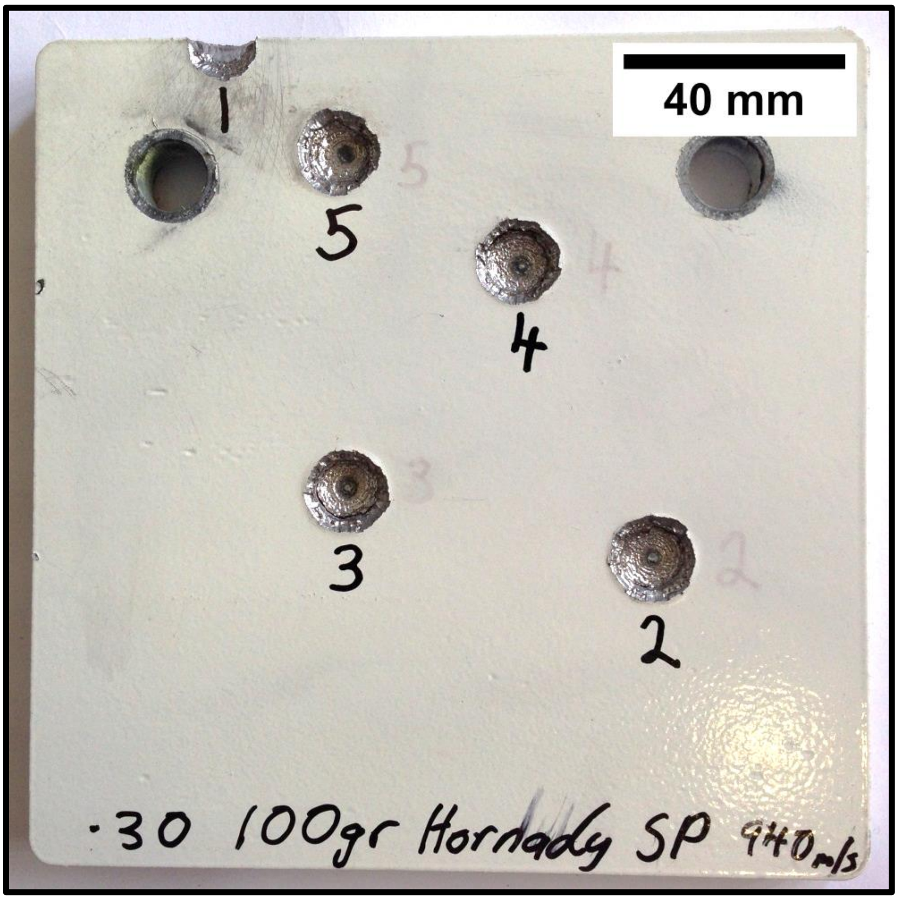

Figure 5.4-1.30 cal 100 gr Hornady

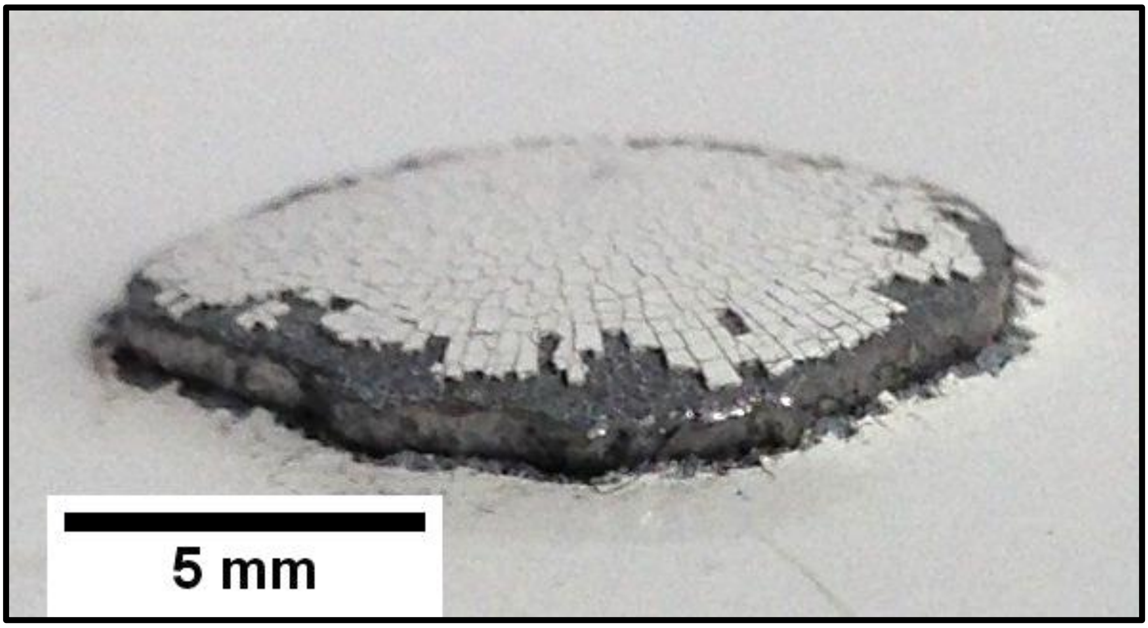

Figure 5.4-2 .30 cal 90 gr Hornady rear of plate

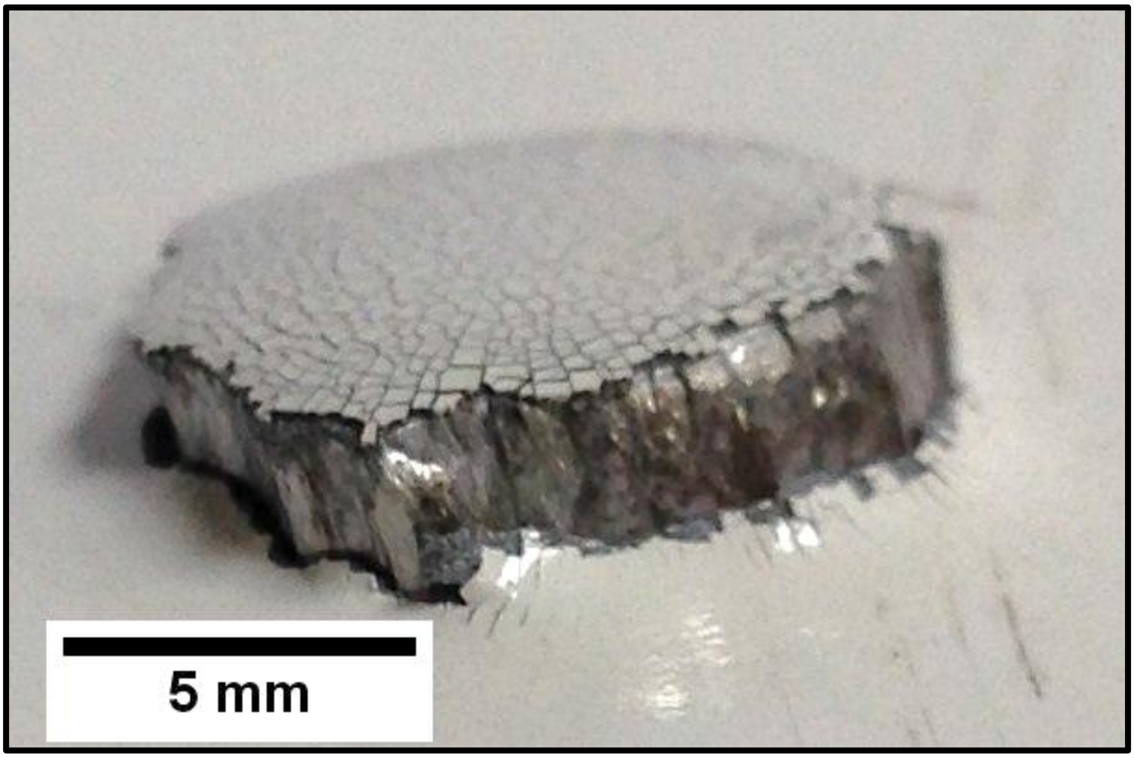

Figure 5.4-3 30 cal 100gr Hornady rear of plate

5.5 .30 cal 155 gr Berger Hybrid

The .30 cal 155 gr Berger only had an average velocity of 826 m/s (Table 5.5-1) which was 11.2% lower than the target velocity due to the maximum load been reached before the target velocity was able to be obtained. The average penetration was only 0.28 mm and this remained consistent for each impact. No deformation could be seen on the back of the target plate and only small marks could be seen on the front (Figure 5.5-1).

Table 5.5-1 .30 cal 155 gr Berger

Shot no.	Impact velocity (m/s)	Impact energy (J)	Penetration (mm)
1	824	3537	0.30
2	832	3474	0.30
3	826	3424	0.29
4	823	3400	0.24
5	826	3424	0.29
Crater Diameter : 9 mm Average Velocity: 826 m/s Average Penetration: 0.28 mm			

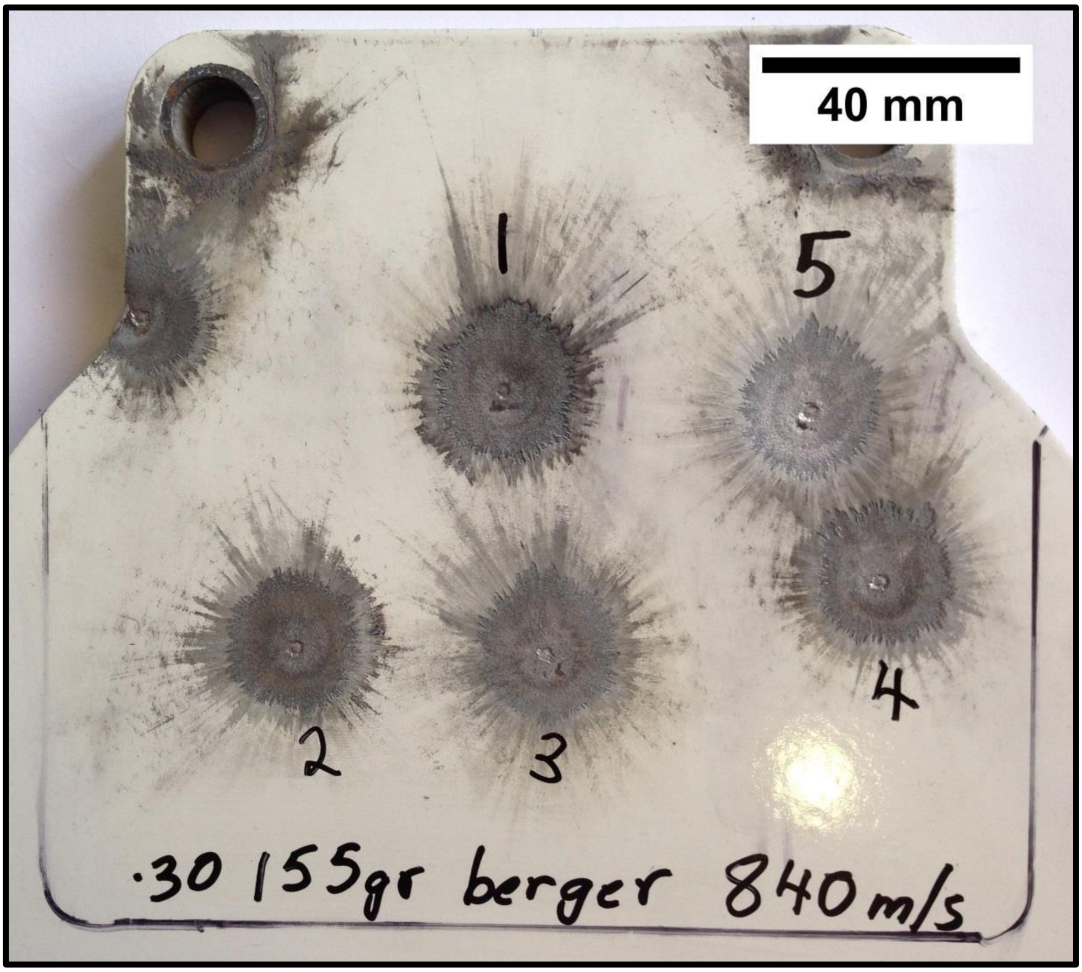

Figure 5.5-1 .30 cal 155 gr Berger

5.6 Accuracy of results

The results achieved were accurate suitable to use for analysis. The velocity variance for each test was within 0.6% of the average and all the 95th percentiles were less than $\pm 5.3\ m/s$ (Table 5.6-1). The penetration variance was around 10% for all the comparison projectiles except for the .30 cal 100 gr Hornady which had a penetration variance of 23%. It is possible that this larger variance is due to the plate been very close to complete penetration of the projectile.

Table 5.6-1 Projectile velocity statistics

.22 cal 90 gr Berger BTHP	
Max velocity (m/s)	949.4
Min velocity (m/s)	941.2
Extreme spread (m/s)	8.2
Average (m/s)	943.3
Standard Deviation	3.1
95th Percentile	4.9
.30 cal 90 gr Hornady XTP	
Max velocity (m/s)	988.4
Min velocity (m/s)	983.8
Extreme spread	4.6
Average	986
Standard Deviation	1.9
95th Percentile	3.1
.30 cal 100 gr Hornady SP	
Max velocity (m/s)	947.6
Min velocity (m/s)	939
Extreme spread	8.6
Average	943.6
Standard Deviation	2.8
95th Percentile	4.4
.30 cal 155 gr Berger Hybrid	
Max velocity (m/s)	846
Min velocity (m/s)	836.9
Extreme spread	9.1
Average	840
Standard Deviation	3.3
95th Percentile	5.1

Chapter 6. Discussion

6.1 Penetration Depth trends

A number of interesting behaviors were witnessed during the testing and the results have provided data for analysis of the behavior of each projectile and its impact on the test plates. Graphing the results from the comparisons at the same impact velocity shows that the largest penetration was clearly the .30cal 100 gr Hornady followed closely by the .30cal 90 gr Hornady XTP (Figure 6.1-1). These two projectiles penetrated approximately six times deeper than the others.

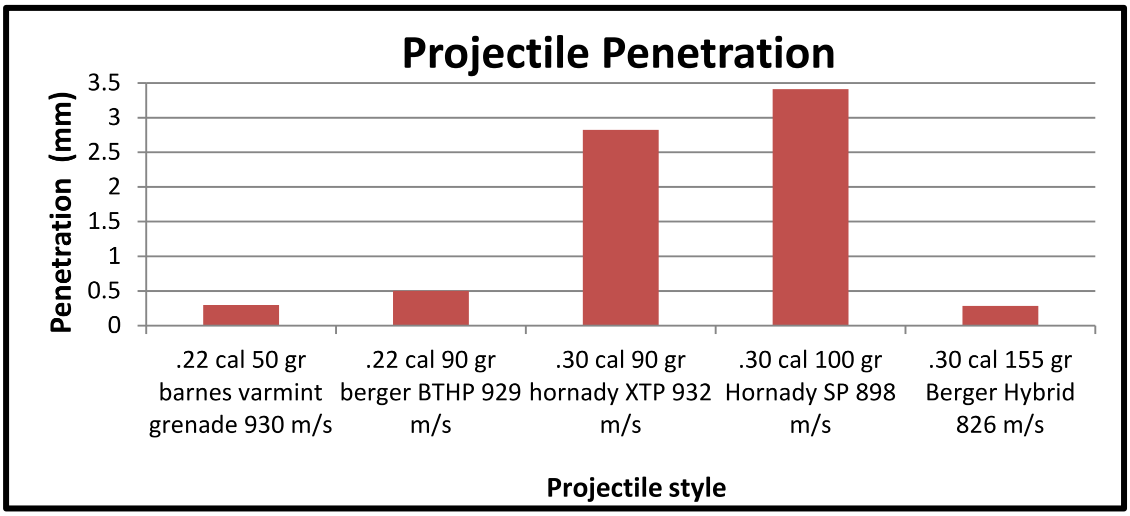

Figure 6.1-1 Penetration at comparison velocity

To help analyze the results the penetrations were normalized by dividing them by the projectile length and then mapping the points on a graph to look for trends in penetration. By normalizing the penetration depths it allows different lengths to be compared. From Figure 6.1-2 it can be seen that there are two distinct groupings of projectiles when graphed using the normalized penetration length.

The first is the .30 cal 90 gr Hornady XTP and the .30 cal 100 gr Hornady SP. These projectiles are very similar in their weight and also their design. They are both quite short in their length and are a solid construction. The 90 gr XTP is a jacketed hollow point but this point is quite flat and shallow, whereas the Hornady 100 gr is a soft point but it is a steep radius and comes to a 2mm flat instead of a point. Both of these projectiles would only have a short distance to deform before they reached an impact surface area equal to that of the projectile diameter. This tip style can be seen in the cross section of each of the projectiles in Figure 6.1-3.

The second grouping is that of the longer hollow point designs the .22 cal 55 gr Barnes, .22 cal 90 gr Berger and .30 cal 155 gr Berger. If a trend line was plotted along the velocity step test points then all the other hollow point projectiles also fall on or very close to this line at their relative impact velocities. The cross section Figure 6.1-3 shows the cavity at the front of each of these projectiles, consequently the projectile would deform more easily upon impact until the solid cross section is reached. This is a considerably longer distance than that of the shorter projectiles and also would have less resistance to deform as there is only the jacket component to deform at the start of the impact.

From the results there are two different penetrations that need to be modeled, that of the short and solid projectiles and also the longer hollow point style. Both these styles show very different behaviors and it would not be possible to predict them using the one model.

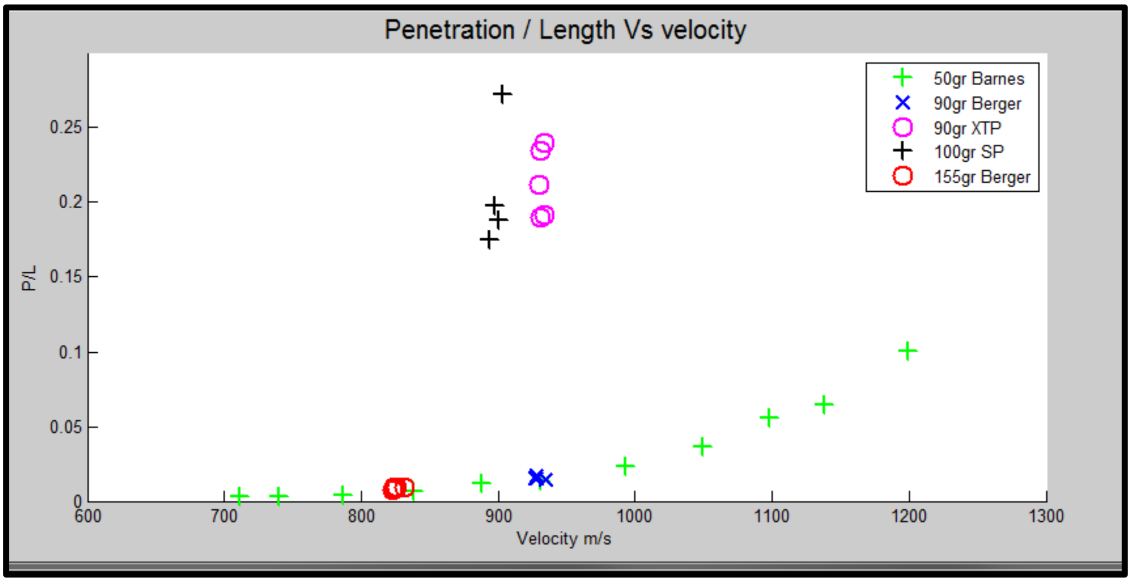

Figure 6.1-2 P/L Vs velocity

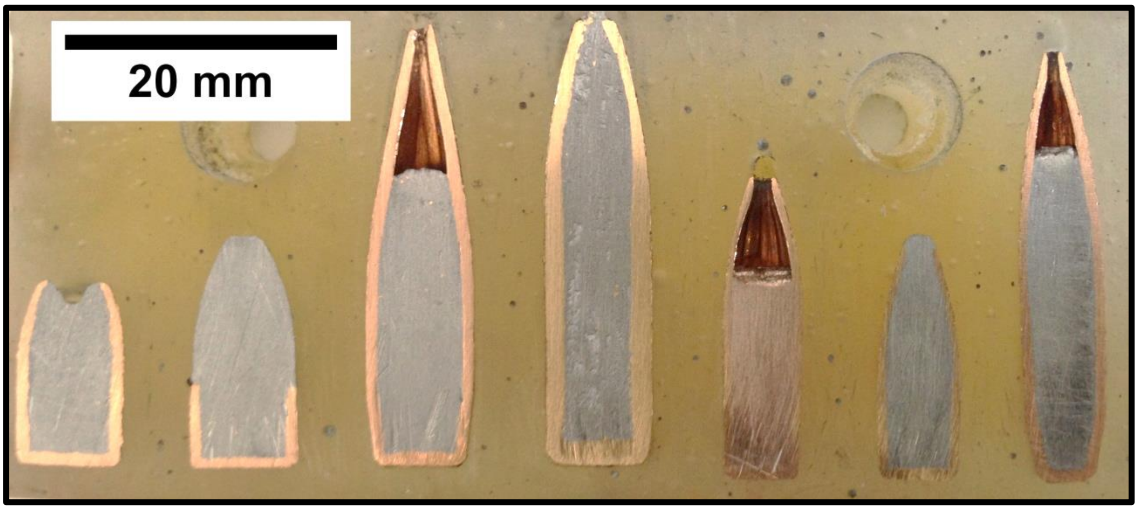

Figure 6.1-3 Projectile cross section from left .30 cal (90 gr XTP, 100 gr SP, 155 gr Berger, 200 gr Woodleigh) .22 cal (50 gr Barnes, 55 gr Speer, 90gr Berger)

6.1 Numerical modeling of Penetration

Two numerical simulations were used to compare against the experimental data, the Allen Rogers formula for eroding rods and the Alekseevskii Tate penetration model. These models were chosen as it is believed that they will give a good prediction of the penetration using the selected projectiles. The models were run in Matlab using constants identified during the literature review. The material properties used for the model inputs were:

$Y_p = 24\ MPa$ (Børvik, et al., 2009) $Y_t = 1400\ MPa$

$\rho_p = 10660\ kg/m^3$ (Børvik, et al., 2009) $\rho_t = 7850\ kg/m^3$

6.1.1 Allen Rogers penetration model

The Allen Rogers Model for penetration is as follows (Equation 6.1-1):

$$\frac{P}{L} = \frac{V - \mu\sqrt{V^2+Q}}{\mu\sqrt{V^2+Q} - \mu^2 V} \qquad \text{where:} \quad Q = 2\sigma \times \frac{1-\mu^2}{\rho_t}$$

$$\text{and} \quad \mu = \sqrt{\frac{\rho_t}{\rho_p}}$$

$\sigma = 3 \times Y_t\ (starting\ point)$ (Dekel & Rosenberg, 2012)

Equation 6.1-1 Allen Rogers Equations

Running this in Matlab and adjusting the value for σ from $3Y_t$ to $2.12Y_t$ moved the model curve for penetration into line with the penetration for the .30 cal 90 gr

Hornady XTP and the .30 cal 100gr Hornady SP. This also roughly matched with the starting point for penetration using the .22 cal 50 gr Barnes projectile in the velocity test (Figure 6.1-1)

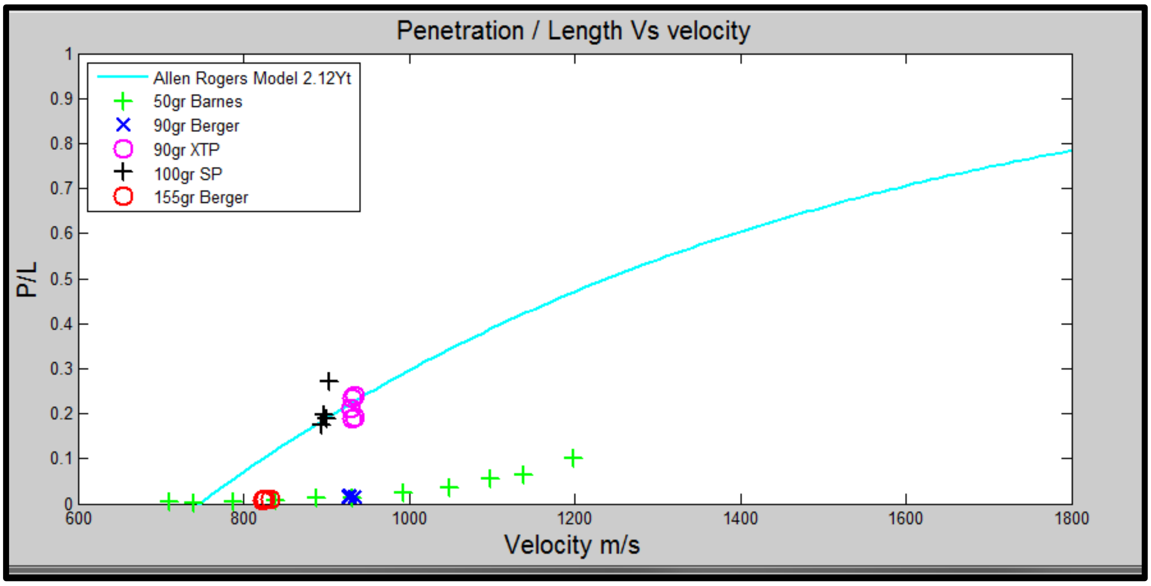

Figure 6.1-1 Allen Rogers model comparison

6.1.2 Alekseevskii-Tate penetration model

Using determined values from testing or previous data the following formulas can be utilized (Equation 6.1-2):

$$\frac{1}{2}\rho_p(V-U)^2 + Y_p = \frac{1}{2}\rho_t U^2 + R_t \quad \textbf{eq. 1}$$

$$\rho_p \ell \frac{dV}{Dt} = -Y_p \quad \textbf{eq.2}$$

$$\frac{d\ell}{Dt} = -(V-U) \quad \textbf{eq. 3} \qquad V_C = \sqrt{\frac{2(R_t - Y_p)}{\rho_p}} \quad \textbf{eq. 4}$$

Equation 6.1-2 Alekseevskii Tate Equations

Substituting different values for R_t to match up with the data found the best match to be $2.12Y_t$ which the same as the value of σ used in the Allen Rogers model. Again this curve only matches with the .30 cal 90 gr Hornady and the .30 cal 100gr Hornady. The model was solved numerically in Matlab using velocity increments of 10 m/s and a time step of 1×10^{-7} s. This took thirty one minutes to compute but using a time step that was greater than that yielded some erratic results.

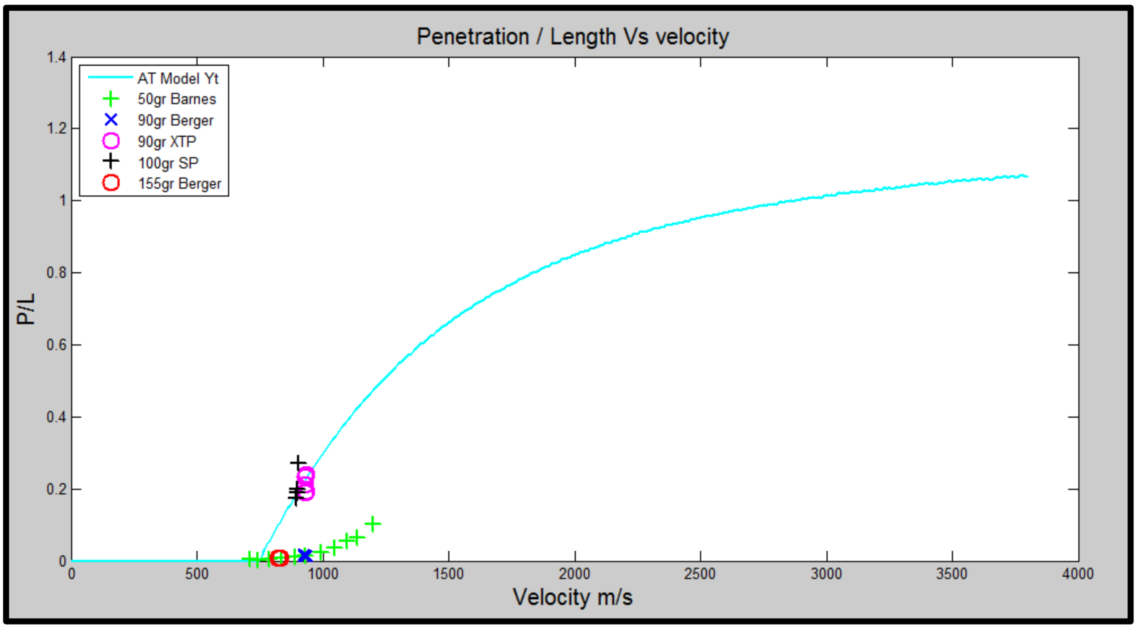

Figure 6.1-2 Alekseevskii Tate Model Rt = 2.12 Yt

It can be seen from the model graphs that neither of the models used can predict the behavior of the hollow point style projectiles. This difference is probably due to the ease of deformation of the projectile tip upon impact before it reaches a solid cross section. The equation for a line of best fit as matched in Matlab is Equation 6.1-3:

$$\frac{P}{L} = 8.9 \times 10^{10} V^3 - 2 \times 10^{-6} V^2 + 0.0015V - 0.38$$

Equation 6.1-3 Hollow point velocity trend line

This could be used to predict penetration of 12 mm Bisalloy 500 plate using hollow point projectiles up to an impact velocity of 1200 m/s. This matched trend line is shown in Figure 6.1-3. The AT model also shows a much steeper penetration rate, which when comparing to the level of penetration in the test plates would be a more accurate representation, as the plates are very close to complete penetration at the impact velocities used. To confirm that the AT model is a reasonable match for the two short .30 cal projectiles, velocity step tests would be required to be carried out so that the AT model accuracy can be confirmed at a number of different impact velocities.

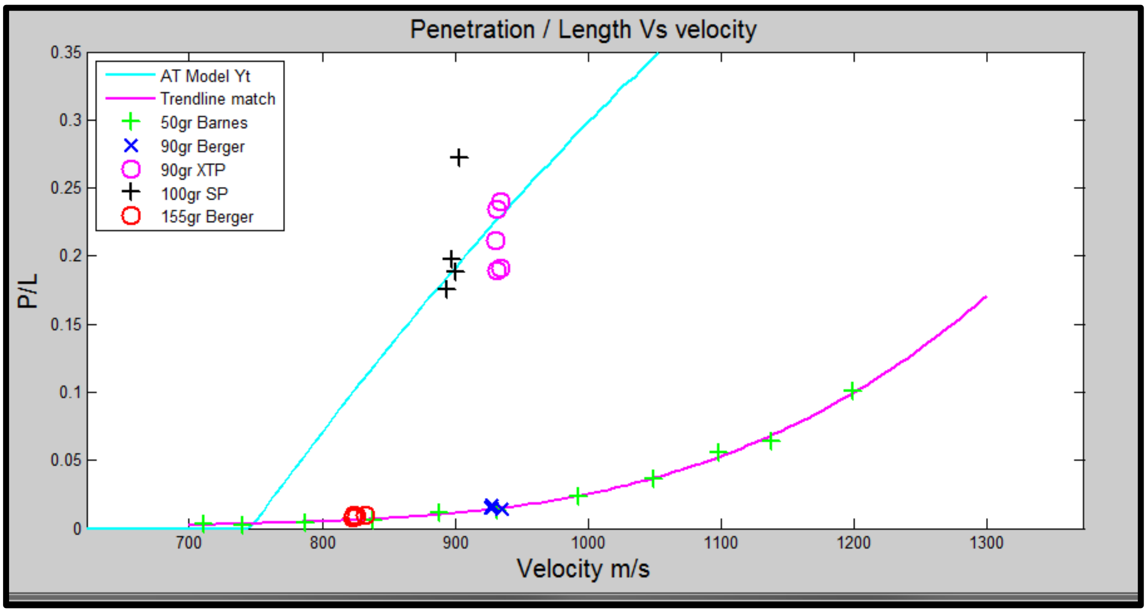

Figure 6.1-3 Penetration with Trend line and AT model

6.2 Air pocket and L/D ratio

The L/D ratios of each projectile show that projectiles with a lower L/D ratio penetrate further into the targets. This supports the previous claims (Dekel & Rosenberg, 2012) that a projectile with a low L/D ratio is more efficient than one with a larger ratio and that the Alekseevskii Tate model does not account for the effect of the L/D ratio. In these experiments due to the construction of the longer projectiles, it is most likely the air pocket and reduced density at the front of the projectile, which is having a far greater effect on this trend. The percentage of the length of the air pocket is between 22-33 % for the hollow point style and 0-7 % for the short .30 cal projectiles (Table 6.2-1).

Table 6.2-1 L/D and air pocket percent

Projectile type	L / D	% length air chamber
.22 cal 50 gr Barnes varmint grenade 930 m/s	3.83	32
.22 cal 90 gr Berger BTHP 929 m/s	5.64	22
.30 cal 90 gr Hornady XTP 932 m/s	1.69	0.00
.30 cal 100 gr Hornady SP 898 m/s	2.09	7
.30 cal 155 gr Berger Hybrid 826 m/s	4.16	33

6.3 Target plate Behaviour

Penetration on the target plates ranged from minimal damage to near complete penetration. Both erosion and plugging failure mechanisms could be seen on some of the impacts. In the case of the .22 cal 50 gr velocity step test the impacts started with no damage and began to show erosion at 930 m/s. At 1200 m/s deformation of the back of the plate could be seen indicating that plugging failure is present in its early stages. The most damage that occurred to the plates was with the .30 cal 100 gr Hornady soft point. The impact craters showed an area where erosion has occurred for approximately 2 mm and then failure via plugging for the rest of the penetration depth Figure 6.3-1 and Figure 6.3-2.

From the experimental testing it can be seen that using long hollow point projectiles with impact velocities' less than 930 m/s result in minimal damage or deformation to the test plates. For the short solid and semi flat pointed .30 cal 90 gr and 100 gr Hornady this threshold is much lower and velocity step testing needs to be carried out for these projectiles to confirm this threshold.

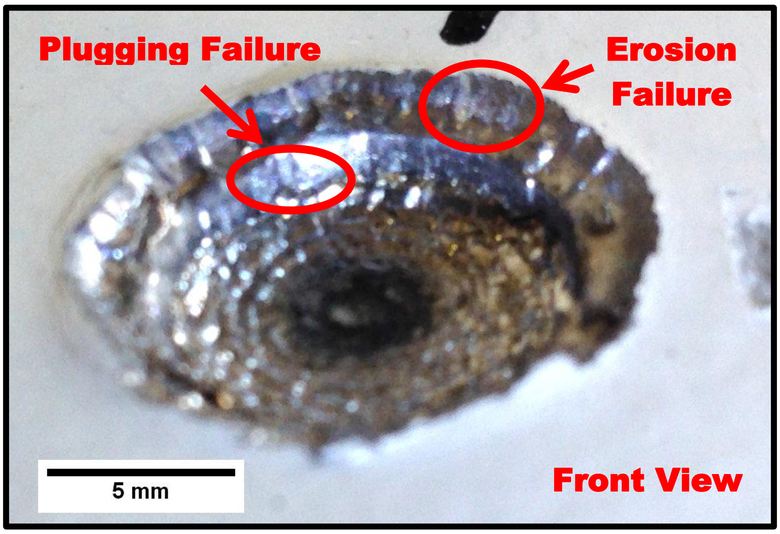

Figure 6.3-1 Crater failure zones front view

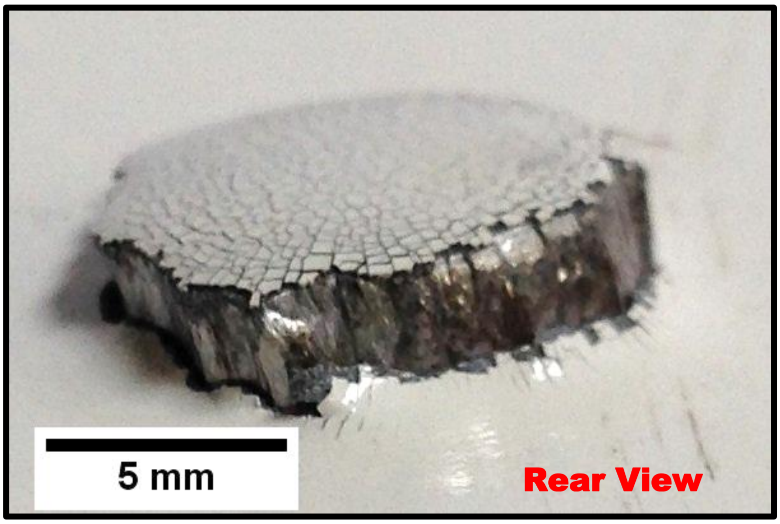

Figure 6.3-2 Crater failure zones rear view

Chapter 7. Conclusion

7.1 Threshold Levels

From the velocity step test it can be seen that the long ogive hollow point projectiles, produce far less damage at a given velocity than the equivalent weight in a short and blunt tip projectile. As a rule of thumb long ogive hollow point projectiles with an L/D ratio of greater than 3.8, will only cause minimal damage to targets at impact velocities up to 900 m/s and would be fine for use on targets.

For all projectiles the threshold level of V_c (Dekel & Rosenberg, 2012) seems to be an accurate prediction of the velocity where damage will start to occur to the plates. Using 12 mm Bisplate 500 and lead or lead-copper jacket projectiles this value is approximately 740 m/s (2430 ft/s).

7.2 Experimental Vs Model

In conclusion the models were not successful in predicting the penetration of the long ogive hollow point style projectiles(.22 cal 55 gr Barnes, .22 cal 90 gr Berger and .30 cal 155 gr Berger). For the short and Blunt .30 cal 90 gr Hornady XTP and the .30 cal 100 gr Hornady SP projectiles the impacts did fall on the model line for both the Alekseevskii Tate and the Allen rogers models but to make an accurate prediction as to their accuracy requires some more experimental velocity step tests on these projectiles.

7.3 Future Work

Further testing on the .30 cal 90 gr Hornady XTP and the .30 cal 100 gr SP using a velocity step test will give more data to be able to predict the accuracy of the models used in this project for predicting penetration.

Further testing on long ogive solid or soft point projectiles to compare the difference in penetration to the hollow point designs would be beneficial as it may be found that they behave in the same manner for penetration. This data could then be used to develop a formula that can accurately predict the penetration of the long ogive hollow point projectiles and similar soft point designs.

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Appendix A. Project specification

UNIVERSITY OF SOUTHERN QUEENSLAND
FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project Specification

For: Lachlan Orange

Topic: Penetration of projectiles on hardened steel plate and the relationship to mass, velocity and diameter

Supervisors: Chris Snook

Enrolment: ENG4111 Sem 1, 2013 & ENG4112 Sem 2, 2013

Project Aim: To investigate the effect of different projectiles and predict levels of penetration for a given size, weight and velocity on armoured steel plate.

Sponsorship: None at Present

Programme: **Revision A 12th of March 12, 2013**

1. Research terminal ballistics and plate penetration from existing research
2. Source equipment and decided on appropriate samples for testing
3. Estimate penetration levels for chosen testing samples using formulas from theory
4. Testing of plates in field and data collection
5. Comparison of testing data with theory
6. Compare and discuss results

   If time permits

7. Develop formula to simulate penetration for specific plates

Lachlan Orange | Std No. 0050010100 | Tuesday, March 12, 2013

Revision A | ENG4111/4112 Project Specification | Page 1 of 1

Appendix B. Risk Assessment

Current controls and Risk

2. RISK DESCRIPTION	3. CAUSES	4. IMPACTS	5. CURRENT RISK CONTROLS	6. LIKELIHOOD	6. CONSEQUENCE	6. RATING	9. WHO	9. WHEN
Travel								
Falling asleep whilst driving	Fatigue. Driving too long without rest. Failing to stop when tired.	Injury to personnel Damage to plant / equipment	Take a break every 2 hours. Avoid driving whilst tired. Alternate drivers if possible. Drive to suit conditions. Avoid driving during natural sleep cycle Use vehicle in roadworthy condition.	D - Unlikely	3 - Moderate	Medium	Testing crew	During all travel
Distractions, other drivers	Other Fatigued drivers. Decreased visibility. Wildlife on road. Mobile phone.	Injury / fatality to personnel. Damage to vehicles, injury/ fatality to public	Stay alert whilst driving. Drive to suit conditions. Use vehicle in roadworthy condition. Keep a good safety margin between traveling vehicles. Turn off mobile phone and or have hands free connected.	C - Possible	4 - Major	High	Testing crew	During all travel
vehicle failure / breakdown	Poor maintenance Debris on road Faulty components	Damage to vehicle Stranded in remote area	Use vehicle in safe and roadworthy condition. Prestart inspections, Regular services. Keep emergency water supply. Travel with communication devices such as CB radio and mobile phone. Notify of planned departure and return.	C - Possible	2 - Minor	Medium	Testing crew	During all travel

Current controls and Risk

2. RISK DESCRIPTION	3. CAUSES	4. IMPACTS	5. CURRENT RISK CONTROLS	6. LIKELIHOOD	6. CONSEQUENCE	6. RATING	9. WHO	9. WHEN
Material Procurement								
Procurement of incorrect material	Ordering incorrect material. Wrong supply material. Wrong design calculations.	Delay to testing. Financial loss.	Double checking of orders. Obtain written quotations. Obtain technical data sheets for suitability review.	C - Possible	2 - Minor	Medium	Researcher	During research and procurement phase
Damage to items during transport	Poor packaging. Unaccredited freighters. Poor delivery instructions.	Delay to testing.	Specify packaging requirements. Use insured couriers. Signature on delivery.	C - Possible	2 - Minor	Medium	Researcher	During research and procurement phase
Short supply of items	Late procurement. Demand shortages. Wrong Quantity ordered.	Delay to testing. Financial loss.	Double check order Qty. Order % extra for spares. Order items as soon as they are selected for use. Use readily available products when possible.	C - Possible	2 - Minor	Medium	Researcher	During research and procurement phase

Current controls and Risk

2. RISK DESCRIPTION	3. CAUSES	4. IMPACTS	5. CURRENT RISK CONTROLS	6. LIKELIHOOD	6. CONSEQUENCE	6. RATING	9. WHO	9. WHEN
Load development								
Primer detonation during loading	Faulty primers. Flash hole blockage. Obstruction in primer pocket. Factory crimp not removed, rough handling.	Injury to personnel. Damage to equipment.	Correct storage before use. Clean case and visually inspect. Check for factory crimp. Use correct primers. Do not force if resistance is encountered. Use safety glasses and hearing protection.	D - Unlikely	3 - Moderate	Medium	Researcher	During loading phase
Powder over charge	Too much powder. Wrong powder.	Injury to personnel / damage to equipment.	Calibrate scales and confirm powder weight and type in reloading manual. Work up loads from known safe powder weight. Check for pressure signs during load development. Confirm cartridge overall length. Use correct sizing and seating dies. Wear eye protection.	C - Possible	4 - Major	High	Researcher	During loading phase
Case crushed in press	Too much powder. Wrong powder. Wrong weight projectile. Wrong diameter projectile. Faulty projectiles. Wrong reloading dies.	Injury to personnel / damage to equipment	Calibrate scales. Confirm powder weight and type. Weigh powder and projectiles. Measure projectile diameter. Work up loads from known safe level. Confirm cartridge overall length and use correct sizing and seating dies. Wear eye protection.	D - Unlikely	3 - Moderate	Medium	Researcher	During loading phase

Current controls and Risk

2. RISK DESCRIPTION	3. CAUSES	4. IMPACTS	5. CURRENT RISK CONTROLS	6. LIKELIHOOD	6. CONSEQUENCE	6. RATING	9. WHO	9. WHEN
Range testing								
pressure over load	Too much powder. Wrong powder. Wrong weight projectile. Wrong diameter projectile. Faulty projectiles. Barrel obstruction.	Injury to personnel/ fatality / damage to equipment	Calibrate scales. Confirm powder weight and type in reloading manual. Weigh powder and projectiles. Measure projectile diameter. Check barrel clear before firing. Work up loads from known safe powder weight. Check for pressure signs during load development. Confirm cartridge overall length in reloading manual. Use correct sizing and seating dies Wear eye protection.	C - Possible	4 - Major	High	Researcher	During loading and testing phase
Obstruction in barrel	Failure to check barrel clear	Injury to personnel/ fatality / damage to equipment	Check barrel clear before use	E - Rare	4 - Major	Medium	Researcher	During loading and testing phase
Squib load (failure to discharge from barrel)	Selection of incorrect powder. Moisture entrapment. Wrong powder weight. Faulty primers. Flash hole blockage.	Damage to equipment	Labelled powder containers. Correct storage before use. Clean case and visually inspect. Calibrate scales. Weigh projectiles. Segregate projectiles from each other.	D - Unlikely	2 - Minor	Low	Researcher	During loading and testing phase

Current controls and Risk

2. RISK DESCRIPTION	3. CAUSES	4. IMPACTS	5. CURRENT RISK CONTROLS	6. LIKELIHOOD	6. CONSEQUENCE	6. RATING	9. WHO	9. WHEN
Damage to instruments	Shrapnel. Rough handling. Environmental conditions.	Damage to equipment , Financial loss	Ballistic protection for instruments down range. Shelter at range bay. Test on clear day. Take care with sensitive equipment.	C - Possible	2 - Minor	Medium	Test crew	During loading and testing phase
Failure to gather data with instruments	Not knowing how instruments work or how to use. Flat batteries. Faulty or not large enough memory cards.	Financial loss Research delay	Read instruction manuals. Take spare batteries. Receive training on equipment use. Determine requirements for storing data.	D - Unlikely	2 - Minor	Low	Test crew	During loading and testing phase
Ricochets	Bad impact angles. Uneven impact surface. Hard uneven ground. Unsafe distance to test plates.	Injury to personnel / damage to equipment	Angle plates towards ground slightly to direct ricochets down. Use flat plate and avoid repeat impacts in damaged area. Use ballistic protection when at short distances.	D - Unlikely	3 - Moderate	Medium	Test crew	During testing phase

Appendix C. SSAA Millmerran Atmospheric conditions

Table C-1 Millmerran Atmospheric conditions

Millmerran SSAA captains mountain Atmospheric conditions			
Value	SI units	Imperial	Imp value
Altitude (m)	425	1394	ft
Relative humidity (%)	16	16	%
Barometric press (hPa)	1022	30.18	inHg
Wind (m/s)	5	16.405	ft/s
Wind direction	11	11	
Temperature (Deg C)	21	69.8	°F

Appendix D. Stability Calculations

Table D-1 Prelim Stability Calculations

Prelim Calculations for calibre selection							
Calibre (inch)	Make	Weight (grains)	Length (mm)	Target velocity (m/s)	Energy (J)	Rifling twist rate inches per turn	SG (miller stability formula
0.22	Berger	90	32.1	975.0	2772	8.0	1.075
0.30	Berger	155	32.5	975.0	4774	12.0	1.436

Appendix E. Consumables & Equipment

E 1. Reloading Consumables

- ADI AR2209 Powder, ADI AR2206H Powder.
- Remington 9.5 & 9.5M primers.
- .224 dia 50 gr Barnes varmint grenade projectiles.
- .24 dia 55 gr Speer soft point projectiles.
- .224 dia 90 gr Berger BTHP projectiles.
- .308 dia 90gr Hornady XTP projectiles.
- .308 dia 100gr Hornady SP projectiles.
- .308 dia 155 gr Berger Hybrid projectiles.
- Remington .308 Winchester cartridges.
- Lapua .22-250 AI (fire-formed) cartridges.

E 2. Target materials

- 6 x 12mm Bisalloy 500 150x150 mm square targets.
- Paper target for sight in.
- Steel target mounting frame.
- Lexan protection screen.
- Camera protection box, camera front armour plate cover.

E 3. Testing equipment

- Test rifle 1 .22 caliber chambered in 22-250AI with 1 in 8 twist barrel.
- Test rifle 2 .30 caliber chambered in .308 Win with standard 1 in 12 twist barrel.
- CED M2 chronograph for primary velocity measurement.
- Reloading Dies for 22-250 AI and 308 Winchester and associated reloading equipment.
- IPhone for measuring weather conditions and also to run JBM ballistics calculator.
- Metrology equipment, digital calipers, tape measure and laser range finder.

- Ballistic unit for holding steel plates and providing protection for the camera.
- Generator, power leads.
- Cameras 2 x GoPro video cameras and laptop.
- PPE: enclosed shoes, eye protection and hearing protection (ear muffs and plugs)

Appendix F. Load Development sheets

Table F-1 .22 cal 50 gr Barnes Varmint Grenade

.22 cal 50gr Barnes Varmint Grenade #22496 load sheet							
Setup data			**Load data**		**Atsmospheric Data**		
Projectile diameter (mm)		5.689	Cartridge	22-250AI	Altitude (m)	425	
Projectile style		FBHP	Case type	Lapua	Relative humidity (%)	16%	
Ballistic coefficient		0.183	Primer type	Remington 9.5m	Barometric press (hPa)	1022	
Projectile length (mm)		21.800	COAL (mm)	62.9	Wind (m/s)	5	
Target velocity (m/s)		1248	Projectile wt (gr)	100.0	Temperature (Deg C)	21	
Distance from muzzle to chrono (m)		2.0	Projectile brand	Barnes	Powder measure Mem No.	MEM-018	
Shot no.	**Powder type**	**Powder wt (gr)**	**muzzle velocity (m/s)**	**COAL (mm)**	**OGAL (mm)**	**Notes**	
1	AR2209	37.5	1100.0	62.9	55.0	OGAL on 2-22 insert	
2	AR2209	40.0	1143.0	62.9	55.0		
3	AR2209	40.5	1155.0	62.9	55.0		
4	AR2209	41.0	1164.0	62.9	55.0		
5	AR2209	41.5	1167.0	62.9	55.0		
6	AR2209	42.0	1184.0	62.9	55.0		
7	AR2209	42.5	1199.0	62.9	55.0		
8	AR2209	43.0	1204.0	62.9	55.0		
9	AR2209	43.5	1223.0	62.9	55.0		
10	AR2209	44.0	1235.0	62.9	55.0		
11	AR2209	44.5	1240.0	62.9	55.0		
12	AR2209	45.0	1252.0	62.9	55.0	Slight pressure signs	
13	AR2206H	20.0	771.0	62.9	55.0	Low pressure loads	
14	AR2206H	22.0	828.0	62.9	55.0	Low pressure loads	
15	AR2206H	24.0	870.0	62.9	55.0	Low pressure loads	
16	AR2206H	26.0	914.0	62.9	55.0	Low pressure loads	
17	AR2206H	28.0	980.0	62.9	55.0	Low pressure loads	
18	AR2206H	30.0	1020.0	62.9	55.0	Low pressure loads	

Table F-2 .22 cal 55 gr Speer

.22 cal 55gr Speer FBHP #1047 load sheet							
Setup data			**Load data**		**Atsmospheric Data**		
Projectile diameter (mm)		5.689	Cartridge	22-250AI	Altitude (m)	425	
Projectile style		FBSP	Case type	Lapua	Relative humidity (%)	16%	
Ballistic coefficient		0.512	Primer type	Remington 9.5m	Barometric press (hPa)	1022	
Projectile length (mm)		32.080	COAL (mm)	60.96 OGAL 52.38	Wind (m/s)	5	
Target velocity (m/s)		Various	Projectile wt (gr)	55.0	Temperature (Deg C)	21	
Distance from muzzle to chrono (m)		2.0	Projectile brand	Speer	Powder measure Mem No.	MEM-	
Shot no.	**Powder type**	**Powder wt (gr)**	**muzzle velocity (m/s)**	**COAL (mm)**	**OGAL (mm)**	**Notes**	
1	AR2209	40.0	954.0	61.0	52.4	OGAL on 2-22 insert	
2	AR2209	41.0	954.0	61.0	52.4	Jacket failure	

Table F-3 .22 cal 90 gr Berger BTHP

.22 cal 90gr Berger BTHP #22426 load sheet						
Setup data			Load data		Atsmospheric Data	
Projectile diameter (mm)		5.689	Cartridge	22-250AI	Altitude (m)	425
Projectile style		BTHP	Case type	Lapua	Relative humidity (%)	16%
Ballistic coefficient		0.512	Primer type	Remington 9.5m	Barometric press (hPa)	1022
Projectile length (mm)		32.080	COAL (mm)	68.97	Wind (m/s)	5
Target velocity (m/s)		964	Projectile wt (gr)	90.0	Temperature (Deg C)	21
Distance from muzzle to chrono (m)		2.0	Projectile brand	Berger	Powder measure Mem No.	MEM-017
Shot no.	Powder type	Powder wt (gr)	muzzle velocity (m/s)	COAL (mm)	OGAL (mm)	Notes
1	AR2209	30.5	831.0	69.0	55.8	OGAL on 2-22 insert
2	AR2209	31.0	841.0	69.0	55.8	
3	AR2209	31.5	854.0	69.0	55.8	
4	AR2209	32.0	860.0	69.0	55.8	
5	AR2209	32.5	871.0	69.0	55.8	
6	AR2209	33.0	880.0	69.0	55.8	
7	AR2209	33.5	884.0	69.0	55.8	
8	AR2209	34.0	895.0	69.0	55.8	
9	AR2209	34.5	906.0	69.0	55.8	
10	AR2209	35.0	917.0	69.0	55.8	
11	AR2209	35.5	919.0	69.0	55.8	
12	AR2209	36.0	927.0	69.0	55.8	
13	AR2209	36.5	939.0	69.0	55.8	
14	AR2209	37.0	921.0	69.0	55.8	
15	AR2209	37.5	947.0	69.0	55.8	
16	AR2209	38.0	955.0	69.0	55.8	Slight pressure signs

Table F-4 .30 cal 90 gr Hornady XTP

.30 cal 90gr Hornady XTP #31000 load sheet						
Setup data			Load data		Atsmospheric Data	
Projectile diameter (mm)		7.823	Cartridge	.308 Winchester	Altitude (m)	425
Projectile style		XTP FBHP	Case type	Remington	Relative humidity (%)	16%
Ballistic coefficient		0.136	Primer type	Remington 9.5	Barometric press (hPa)	1022
Projectile length (mm)		13.230	COAL (mm)	61.14	Wind (m/s)	5
Target velocity (m/s)		1007	Projectile wt (gr)	90.0	Temperature (Deg C)	21
Distance from muzzle to chrono (m)		2.0	Projectile brand	Hornady	Powder measure Mem No.	MEM-020
Shot no.	Powder type	Powder wt (gr)	muzzle velocity (m/s)	COAL (mm)	OGAL (mm)	Notes
1	AR2206H	30.0	611.0	61.1	58.0	
2	AR2206H	34.0	583.8	61.1	58.0	
3	AR2206H	37.0	650.3	61.1	58.0	
4	AR2206H	39.0	680.8	61.1	58.0	
5	AR2206H	42.0	760.0	61.1	58.0	
6	AR2206H	44.0	818.0	61.1	58.0	
7	AR2206H	46.0	870.0	61.1	58.0	
8	AR2206H	48.0	910.0	61.1	58.0	
9	AR2206H	49.0	921.0	61.1	58.0	
10	AR2206H	50.0	966.0	61.1	58.0	
11	AR2206H	51.0	991.5	61.1	58.0	
12	AR2206H	51.5	984.5	61.1	58.0	
13	AR2206H	52.0	1014.0	61.1	58.0	Target velocity reached

Table F-5 .30 cal 100 gr Hornady SP

.30 cal 10gr Hornady Soft point #3005 load sheet							
Setup data				Load data		Atsmospheric Data	
Projectile diameter (mm)			7.823	Cartridge	.308 Winchester	Altitude (m)	425
Projectile style			FBSP	Case type	Remington	Relative humidity (%)	16%
Ballistic coefficient			0.152	Primer type	Remington 9.5	Barometric press (hPa)	1022
Projectile length (mm)			16.370	COAL (mm)	64.2	Wind (m/s)	5
Target velocity (m/s)			1000	Projectile wt (gr)	100.0	Temperature (Deg C)	21
Distance from muzzle to chrono (m)			2.0	Projectile brand	Hornady	Powder measure Mem No.	MEM-021
Shot no.	Powder type	Powder wt (gr)	muzzle velocity (m/s)	COAL (mm)	OGAL (mm)	Notes	
1	AR2206H	45.0	816.0	64.2	Not measured		
2	AR2206H	47.0	869.2	64.2	Not measured		
3	AR2206H	48.0	897.3	64.2	Not measured		
4	AR2206H	49.0	914.6	64.2	Not measured		
5	AR2206H	50.0	930.8	64.2	Not measured		
6	AR2206H	51.0	960.0	64.2	Not measured		
7	AR2206H	52.0	976.0	64.2	Not measured	Max case capacity reached	

Table F-6 .30 cal 155 gr Berger Hybrid

.30 cal 155gr Berger Hybrid #30426 load sheet							
Setup data				Load data		Atsmospheric Data	
Projectile diameter (mm)			7.823	Cartridge	.308 Winchester	Altitude (m)	425
Projectile style			BTHP	Case type	Remington	Relative humidity (%)	16%
Ballistic coefficient			0.483	Primer type	Remington 9.5	Barometric press (hPa)	1022
Projectile length (mm)			32.500	COAL (mm)	73.45	Wind (m/s)	5
Target velocity (m/s)			966	Projectile wt (gr)	155.0	Temperature (Deg C)	21
Distance from muzzle to chrono (m)			2.0	Projectile brand	Berger	Powder measure Mem No.	MEM-019
Shot no.	Powder type	Powder wt (gr)	muzzle velocity (m/s)	COAL (mm)	OGAL (mm)	Notes	
1	AR2206H	43.0	786.0	73.5	58.2		
2	AR2206H	44.0	809.8	73.5	58.2		
3	AR2206H	44.5	824.0	73.5	58.2		
4	AR2206H	45.0	842.0	73.5	58.2		
5	AR2206H	45.5	837.0	73.5	58.2		
6	AR2206H	46.0	863.7	73.5	58.2		
7	AR2206H	46.5	870.7	73.5	58.2	Slight pressure signs	

Appendix G. Test data record sheets

Table G-1 .22 cal 50 gr Berger test data

.22 cal 50gr barnes Varmint Grenade FB Test data record sheet

Setup data	Item 2	Load data		Atsmospheric data	
Projectile diameter (mm)	5.690	Cartridge	22-250 AI	Altitude (m)	425.0
Projectile style	FBHP	Case type	Lapua	Relative humidity (%)	16.0
Ballistic coefficient	0.183	Primer type	Rem 9.5m	Barometric press (hPa)	1022.0
Projectile length (mm)	21.800	Powder type	AR2209 or AR2206H	Wind (m/s)	5.0
Target velocity (m/s)	1248	Powder charge (gr)	Varied	Temperature (Deg C)	21.0
Target impact velocity (m/s)	1200	COAL (mm)	62.9mm or 55 OGA	Notes	Velocity step test
Target impact energy (J)	2332.8	Projectile wt (gr)	50.0		
Distance from muzzle to chrono (m)	2.0	Projectile brand	Barnes		
Distance from muzzle to Target (m)	25.0	Projectile length (mm	21.8		

Shot no.	Actual Muzzle Velocity (m/s)	Actual impact	% var in target	Actual impact energy (J)	% variation in impact energy	Flight time (s)	Estimated penetratio	Actual penetration	Crater Dia	% variation
1	745	711	N/A	817	N/A	0.04		0.07	6	
2	774	740	N/A	883	N/A	0.03		0.06	6	
3	822	787	N/A	999	N/A	0.03		0.09	6	
4	875	838	N/A	1134	N/A	0.03		0.14	6	
5	926	888	N/A	1272	N/A	0.03		0.25	6	
6	971	931	N/A	1401	N/A	0.03		0.3	7.6	
7	1035	993	N/A	1593	N/A	0.03		0.51	9	
8	1092	1049	N/A	1775	N/A	0.02		0.8	10.5	
9	1143	1098	N/A	1946	N/A	0.02		1.22	13	
10	1185	1138	N/A	2092	N/A	0.02		1.4	13.7	
11	1248	1199	N/A	2321	N/A	0.02		2.19	14.5	

.22 cal 50gr barnes Varmint Grenade FB Test data record sheet

Test Target Photo

Table G-2 .22 cal 90 gr Berger test data

.22 cal berger 90gr BTHP Test data record sheet

Setup data	Item 1	Load data		Atsmospheric data	
Projectile diameter (mm)	5.690	Cartridge	22-250 AI	Altitude (m)	425.0
Projectile style	BTHP	Case type	Lapua	Relative humidity (%)	16.0
Ballistic coefficient	0.512	Primer type	Rem 9.5m	Barometric press (hPa)	1022.0
Projectile length (mm)	32.080	Powder type	AR2209	Wind (m/s)	5.0
Target velocity (m/s)	944	Powder charge (gr)	38	Temperature (Deg C)	21.0
Target impact velocity (m/s)	930	COAL (mm)	69.0 or 55.8 OGAL	Notes	
Target impact energy (J)	2522.0	Projectile wt (gr)	90.0		
Distance from muzzle to chrono (m)	2.0	Projectile brand	Barnes		
Distance from muzzle to Target (m)	25.0	Projectile length (mm	32.1		

Shot no.	Actual Muzzle Velocity (m/s)	Actual impact	% var in target	Actual impact energy (J)	% variation in impact energy	Flight time (s)	Penetration Est (mm)	Penetration	Crater Dia	% variation
1	942	928	0.22%	2508	0.56%	0.03		0.55	9.00	
2	941	927	0.32%	2503	0.75%	0.03		0.5	7.00	
3	949	935	-0.54%	2546	-0.95%	0.03		0.46	7.50	
4	942	928	0.22%	2508	0.56%	0.03		0.5	7.00	
5	942	928	0.22%	2508	0.56%	0.03		0.5	7.00	

.22 cal berger 90gr BTHP Test data record sheet

Test Target Photo

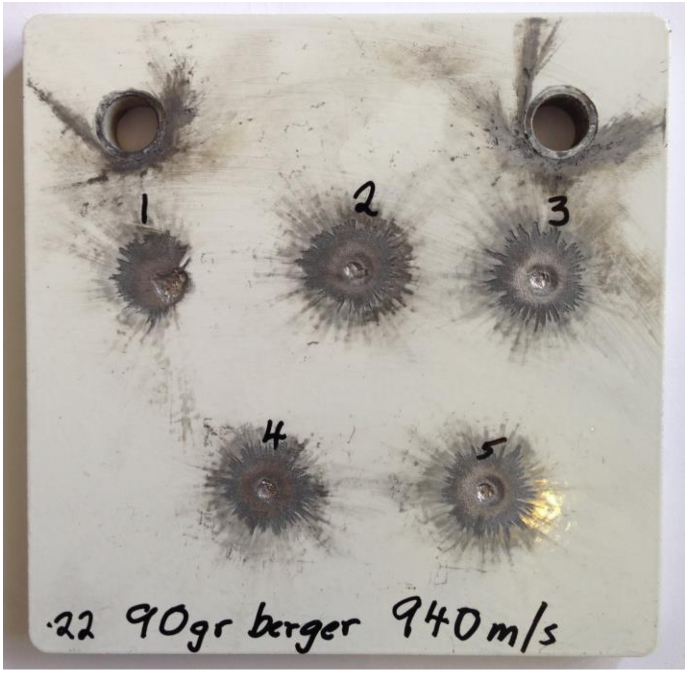

Table G-3 .30 cal 90 gr Hornady XTP test data

.30 cal 90gr hornady XTP Test data record sheet

Setup data	Item 5	Load data		Atsmospheric data	
Projectile diameter (mm)	7.823	Cartridge	.308 Winchester	Altitude (m)	425.0
Projectile style	JHP	Case type	Remington	Relative humidity (%)	16.0
Ballistic coefficient	0.136	Primer type	Rem 9.5	Barometric press (hPa)	1022.0
Projectile length (mm)	13.230	Powder type	AR2206H	Wind (m/s)	5.0
Target velocity (m/s)	983	Powder charge (gr)	52	Temperature (Deg C)	21.0
Target impact velocity (m/s)	930	COAL (mm)	61.14	Notes	
Target impact energy (J)	2522.0	Projectile wt (gr)	90.0		
Distance from muzzle to chrono (m)	2.0	Projectile brand	Hornady		
Distance from muzzle to Target (m)	25.0	Projectile length	13.2		

Shot no.	Actual Muzzle Velocity (m/s)	Actual impact	% var in target	Actual impact energy (J)	% variation in impact energy	Flight time (s)	Penetration Est (mm)	Penetration	Crater Dia	% variation
1	984	931	-0.11%	2513	0.36%	0.03		2.51	15	
2	985	931	-0.11%	2519	0.12%	0.03		3.10	15	
3	988	934	-0.43%	2534	-0.48%	0.03		2.53	15	
4	988	934	-0.43%	2534	-0.48%	0.03		3.17	15	
5	983	930	0.00%	2508	0.56%	0.03		2.80	15	

.30 cal 90gr hornady XTP Test data record sheet

Test Target Photo

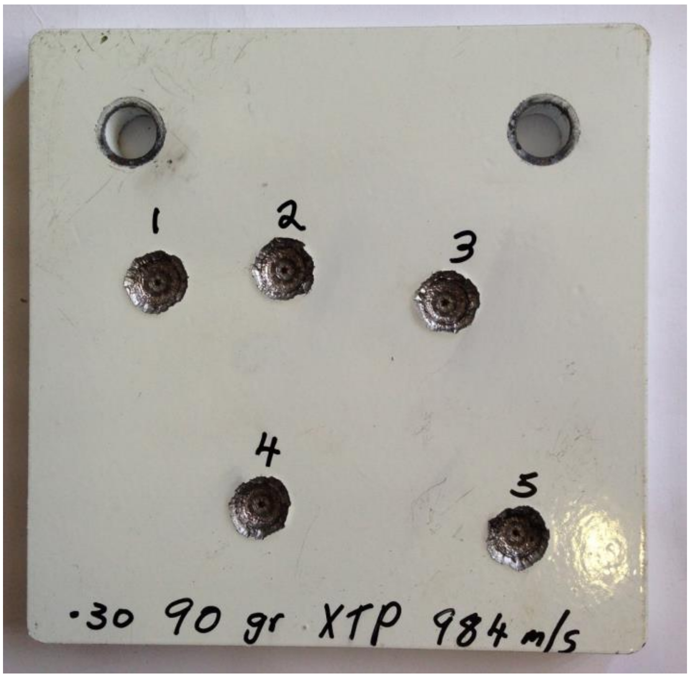

Table G-4 .30 cal 100 gr Hornady SP test data

.30 cal hornady 100gr SP Test data record sheet					
Setup data Item 4		**Load data**		**Atsmospheric data**	
Projectile diameter (mm)	7.823	Cartridge	.308 Winchester	Altitude (m)	425.0
Projectile style	SP	Case type	Remington	Relative humidity (%)	16.0
Ballistic coefficient	0.152	Primer type	Rem 9.5	Barometric press (hPa)	1022.0
Projectile length (mm)	16.370	Powder type	AR2206H	Wind (m/s)	5.0
Target velocity (m/s)	976	Powder charge (gr)	52	Temperature (Deg C)	21.0
Target impact velocity (m/s)	930	COAL (mm)	64.2	Notes: Only 4 shots as accuracy was severly unstable and unable to achieve all clean shots on plate.	
Target impact energy (J)	2802.2	Projectile wt (gr)	100.0		
Distance from muzzle to chrono (m)	2.0	Projectile brand	Hornady		
Distance from muzzle to Target (m)	25.0	Projectile length (r	16.4		

Shot no.	Actual Muzzle Velocity (m/s)	Actual impact	% var in target	Actual impact energy (J)	% variation in impact energy	Flight time (s)	Penetration Est (mm)	Penetration	Crater Dia	% variation
1	Not counted									
2	945	900	3.23%	2613	6.75%	0.03		3.08	15	
3	948	903	2.90%	2630	6.15%	0.03		4.46	15	
4	939	894	3.87%	2580	7.93%	0.03		2.87	15	
5	942	897	3.55%	2596	7.36%	0.03		3.24	15	

.30 cal hornady 100gr SP Test data record sheet

Test Target Photo

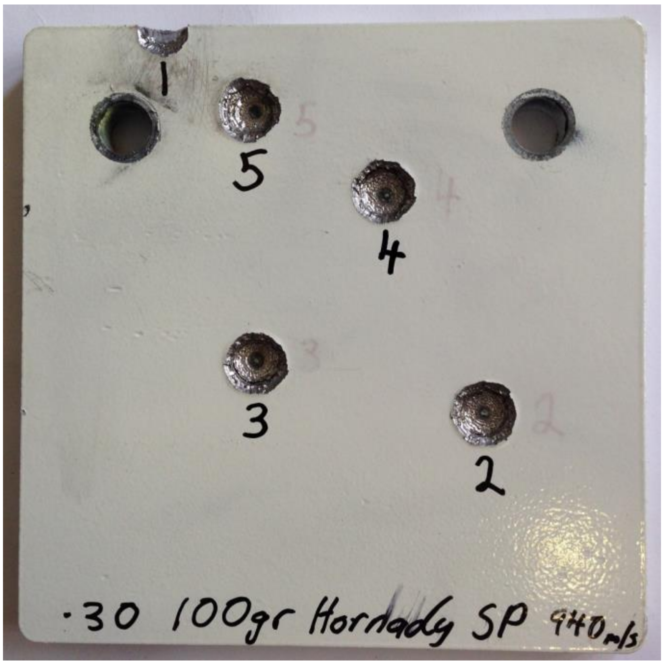

Table G-5 .30 cal 155 gr Berger Hybrid test data

.30 cal Berger 155gr Hybrid BTHP Test data record sheet

Setup data Item 3		Load data		Atsmospheric data	
Projectile diameter (mm)	7.823	Cartridge	.308 Winchester	Altitude (m)	425.0
Projectile style	BTHP	Case type	Remington	Relative humidity (%)	16.0
Ballistic coefficient	0.483	Primer type	Rem 9.5	Barometric press (hPa)	1022.0
Projectile length (mm)	32.512	Powder type	AR2206H	Wind (m/s)	5.0
Target velocity (m/s)	945	Powder charge (gr)	46.5	Temperature (Deg C)	21.0
Target impact velocity (m/s)	930	COAL (mm)	73.5 OGAL 58.2	Notes	
Target impact energy (J)	4343.5	Projectile wt (gr)	155.0		
Distance from muzzle to chrono (m)	2.0	Projectile brand	Hornady		
Distance from muzzle to Target (m)	25.0	Projectile length	32.5		

Shot no.	Actual Muzzle Velocity (m/s)	Actual impact	% var in target	Actual impact energy (J)	% variation in impact energy	Flight time (s)	Penetration Est (mm)	Penetration	Crater Dia	% variation
1	838	824	11.40%	3537	18.57%	0.03		0.30	9	
2	846	832	10.54%	3474	20.02%	0.03		0.30	9	
3	840	826	11.18%	3424	21.17%	0.03		0.29	9	
4	837	823	11.51%	3400	21.72%	0.03		0.24	9	
5	840	826	11.18%	3424	21.17%	0.03		0.29	9	

.30 cal Berger 155gr Hybrid BTHP Test data record sheet

Test Target Photo

Appendix H. Matlab Code

H 1. Allen rogers Model

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%Lachlan Orange Thesis Penetration modelling%
% Module 1 %
clc;
clear;
% load import from file%
load PLR
%Density of Target kg/m3%
Pt=7850
%Density of Penetrator kg/m3%
Pp=10660
%Allen rogers model data%
%value for mu Rod/target density ratio%
mu=sqrt(Pt/Pp)
% yield strength of plate MPa%
Yt=1400*10^6
%Value for dynamic strength MPa%
s=2.12*Yt
%Value for Q%
Q=2*(s)*((1-(mu^2))/Pt)
% Diameter and length arrays .22 50,.22 90,.30 90,.30 100,.30 155 %
D=[5.69,5.69,7.82,7.82,7.82];
L=[21.8,32.08,13.23,16.37,32.51];
%define velocity span m/s%
V=[100:10:1800];
%define start value for n%
n=1
%Define Vc%
Vc=sqrt(2*s*10^6/Pp)
%Define matrix for allen rogers model%
PL=zeros(length(V),2);
while n <=length(V)
PL(n,1)=V(n);
%formula for normalised penetration allen rogers%
PL(n,2)=(V(n)-mu*sqrt((V(n)^2)+Q))/(mu*sqrt((V(n)^2)+Q)-((mu^2)*V(n)))
n=n+1;
end
%create fugure for plot%
figure('name','P/L Vs velocity trends')
%Plot V,P?L values on graph%
plot(PL(:,1),PL(:,2),'c','LineWidth',2,'MarkerSize',11)
hold on
%plot 50gr barnes%
plot(PLR(1:11,4),PLR(1:11,10),'+g','LineWidth',2,'MarkerSize',11)
%plot 90gr berger%
plot(PLR(12:16,4),PLR(12:16,10),'xb','LineWidth',2,'MarkerSize',11)
%plot 90gr XTP%
plot(PLR(17:21,4),PLR(17:21,10),'om','LineWidth',2,'MarkerSize',11)
%plot 100gr SP
plot(PLR(22:25,4),PLR(22:25,10),'+k','LineWidth',2,'MarkerSize',11)
%plot 155gr Berger for %
plot(PLR(26:30,4),PLR(26:30,10),'or','LineWidth',2,'MarkerSize',11)
axis([600,1800,0,1])
title('Penetration / Length Vs velocity','FontSize',15)
xlabel('Velocity m/s','FontSize',15),ylabel('P/L','FontSize',15)
```

```
legend('Allen Rogers Model 2.12Yt','50gr Barnes','90gr Berger','90gr
XTP','100gr SP','155gr Berger','location','NorthWest')

figure('name','P/L Vs velocity')
hold on
%plot 50gr barnes%
plot(PLR(1:11,4),PLR(1:11,10),'+g','LineWidth',2,'MarkerSize',11)
%plot 90gr berger%
plot(PLR(12:16,4),PLR(12:16,10),'xb','LineWidth',2,'MarkerSize',11)
%plot 90gr XTP%
plot(PLR(17:21,4),PLR(17:21,10),'om','LineWidth',2,'MarkerSize',11)
%plot 100gr SP
plot(PLR(22:25,4),PLR(22:25,10),'+k','LineWidth',2,'MarkerSize',11)
%plot 155gr Berger for %
plot(PLR(26:30,4),PLR(26:30,10),'or','LineWidth',2,'MarkerSize',11)
axis([600,1300,0,.3])
xlabel('Velocity m/s'),ylabel('P/L')
title('Penetration / Length Vs velocity','FontSize',15)
legend('50gr Barnes','90gr Berger','90gr XTP','100gr SP','155gr Berger')
```

H 2. Alekseevskii Tate Model

```
%Lachlan Orange Thesis Penetration modelling%
% Model to match hollow point projectiles %
%trendline added%
clc;
clear;
% load import Penetration testing data from file%
load PLR
%Density of Target kg/m3%
Pt=7850;
%Density of Penetrator kg/m3%
Pp=10660;
%Yield strength of penetrator%
Yp=24*10^6;
% yield strength of plate MPa%
Yt=1400*10^6;
%Value for targets resistance to penetration%
Rt=Yt*2.12;
%Define critical velocity Vc%
Vc=sqrt(2*(Rt-Yp)/Pp);
% Diameter and length arrays .22 50,.22 90,.30 90,.30 100,.30 155 %
D=[5.69,5.69,7.82,7.82,7.82];
Li=[21.8,32.08,13.23,16.37,32.51];
%define velocity span m/s%
Vi=[0:5:3000]; %ideal 5 m/s step
%Define time step%
t=.00001; %ideal .00001
%define initial length%
Li=1;
%define start value for n%
n=1;
%set variable in toolbox;
u=sym('u');
%Define matrix for AT model%
PL=zeros(length(Vi),2);
% while loop for each velocity
while n<=length(Vi)
    V=Vi(n);
    L=Li;
    P=0;
    Ldot=0;
    Vdot=0;
```

```
            while L>0 && V>=Vc
            %formula 1 AT model%
            U=solve(.5*Pp*(V-u)^2+Yp==.5*Pt*u^2+Rt,u);
                if double(U(1))>=0 && double(U(1))<=V
                    U=double(U(1));
                elseif double(U(2))>=0 && double(U(2))<=V
                    U=double(U(2));
                end
            %formula 2 AT model%
            Vdot=(-Yp/(L*Pp))*t;
            %formula 3 AT model%
            Ldot=-(V-U)*t;
            %formula 4 AT model%
            Pdot=U*t;
            %add values%
            V=V+Vdot;
            L=L+Ldot;
            P=P+Pdot;
            end
            if P==0 && n>1
                PL(n,2)=PL(n-1,2);
            else
        PL(n,2)=P;
            end
        PL(n,1)=Vi(n);
         NUM=['Last velocity calculated ',num2str(PL(n,1))];
        disp(NUM)
        n=n+1;
end
%plot trendline%
VT=[700:5:1300];
PT=(8.8737*10^-10)*VT.^3 - (1.9812*10^-6)*VT.^2 + 0.0015017*VT -
0.38258;
%plot AT model lines
figure('name','P/L Vs velocity trends')
%Plot x,t values on graph%
plot(PL(:,1),PL(:,2),'c','LineWidth',2,'MarkerSize',11)
hold on
%Plot trendline values on graph%
plot(VT,PT,'m','LineWidth',2,'MarkerSize',11)
%plot 50gr barnes%
plot(PLR(1:11,4),PLR(1:11,10),'+g','LineWidth',2,'MarkerSize',11)
%plot 90gr berger%
plot(PLR(12:16,4),PLR(12:16,10),'xb','LineWidth',2,'MarkerSize',11)
%plot 90gr XTP%
plot(PLR(17:21,4),PLR(17:21,10),'om','LineWidth',2,'MarkerSize',11)
%plot 100gr SP
plot(PLR(22:25,4),PLR(22:25,10),'+k','LineWidth',2,'MarkerSize',11)
%plot 155gr Berger for %
plot(PLR(26:30,4),PLR(26:30,10),'or','LineWidth',2,'MarkerSize',11)
%axis([0,1200,0,1.5])
title('Penetration / Length Vs velocity','FontSize',15)
xlabel('Velocity m/s','FontSize',15),ylabel('P/L','FontSize',15)
legend('AT Model Yt','Trendline match','50gr Barnes','90gr Berger','90gr
XTP','100gr SP','155gr Berger','location','NorthWest')
```