Stabilization of a Paintball

The Design and Implementation of Gyroscopic Stabilization to a Paintball

A Major Qualifying Project proposal to be submitted to the faculty of Worcester Polytechnic Institute in partial fulfilment of the requirements for the Degree of Bachelor of Science

Submitted by:

Kyle Dedmon
Stephen Parsons
Andrew McCarthy

Submitted to:

Project Advisor:

Prof. Eben C. Cobb

Acknowledgements

Upon completion of this project we feel there are many individuals deserving of our thanks. Professor Eben Cobb, thank you for the opportunity to research this topic and advise our project. Brendan Powers, thank you for all the help you provided helping us machine our prototypes. Your feedback and instruction with GibbsCAM, materials and machines was extremely valuable in helping us successfully machine our parts. Professor Olinger, thank you for assisting us with the wind-tunnel testing.

Abstract

The goal of our project was to improve the current paintball firing system which is widely used both recreationally and competitively by millions of players. Our project aimed to increase the accuracy and range of the paintball system by researching, designing, building, and testing prototypes that could be incorporated into systems currently available to consumers through the use of gyroscopic stabilization and improved aerodynamic profile. The prototype designs created by this project could be refined and improved so they could be implemented in the paintball community, ultimately improving the quality and scope of its uses.

Executive Summary

The game of paintball is enjoyed globally by millions of players. One major flaw which plagues these players is the inaccuracy of the markers and projectiles they fire. Throughout the course of history, firearms have continuously evolved to be more effective and this always includes improving the accuracy and range of projectiles and, in lethal applications, the deadliness of these rounds. Paintball has been established for a long time and it is logical for a progression to occur within the game similar to that seen with actual firearms.

The goal of this project is to attempt to make an advance to the game of paintball in these particular problem areas. This project focuses on aerodynamic principles, new designs, and production and testing of working prototypes to determine if this is indeed feasible. Ultimately, we hope to lay a foundation for a product which can successfully be integrated with current equipment into the massive paintball community.

We began our work by researching areas relevant to the areas we hoped to improve. From this research, several plausible bullet designs were selected and initial design specifications were developed for the construction of the barrel. As the project progressed the group adapted to meet various machining challenges in order to successfully manufacture the desired prototypes so that they could be tested for effectiveness and determine if they were indeed affecting the accuracy of the paintball marker.

The bullets were tested in the wind tunnel facilities to determine aerodynamic properties. Based on performance in the wind tunnel and other considerations such as safety factors and practicality, several prototypes were selected to be tested further. The barrel was subsequently tested in conjunction with the final projectile prototypes to determine what combination, if any, impacted the accuracy in a positive way.

The results of the test firing of prototype rounds were mixed. The equipment was compatible with a current paintball marker and the prototypes did indeed fire. However, due to manufacturing capabilities the rounds were not durable enough to withstand the forces imparted upon it through rifling. Theoretically, the improvements to the barrel and projectile shape would improve the spread of a group of rounds but the testing was unable to verify this because the rounds did not all perform adequately.

This project attempted to redesign a conventional paintball round and improve the overall accuracy of a paintball marker by examining aerodynamic principles. Creating new round shapes and barrel designs provided several manufacturing challenges which led to the creation of a new barrel making process and several molds which could be used to produce more rounds. Although the testing was not as successful as we would have liked the project was valuable because it provided knowledge which could be improved upon and eventually lead to applications within a massive industry in need of this type of progression.

Table of Contents

Acknowledgements ..... **i**
Abstract ..... **ii**
Executive Summary ..... **iii**
Table of Contents ..... **iv**
Table of Figures ..... **vi**
Table of Tables ..... **vii**
Table of Equations ..... **vii**
Introduction **1**
Background **3**
2.1 Paintball *3*
2.1.2 History of Paintball 3
2.1.3 Equipment Used for Paintball 5
2.2 Paintball Marker *5*
2.2.1 Components of a Paintball Marker 5
2.3 The Manufacture of Barrels *6*
2.3.1 Rifling History 8
2.4 Rifling Processes *10*
2.4.1 Cutting 10
2.4.2 Broach Rifling 11
2.4.3 Button Rifling 13
2.4.4 Hammer Rifling 14
2.5 Projectile Design Considerations *15*
2.5.1 Tangential or Spitzer Ogive 15
2.5.2 Elliptical Ogive 16
2.5.3 Cone 17
2.5.4 Double-Sided Projectiles 18
2.5.5 Tear-drop shape. 19
2.6 Safety Factor *19*
Methodology **20**
3.1 Identify Areas for Improvement *21*
3.1.1 Paintball Shape 21
3.1.2 Barrel Characteristics 21
3.2 CAD/CAM for Bullets and Barrel *22*
3.3. Build and Test Prototypes *22*
3.3.1 Machining Prototype Rounds 23
3.3.2 Wind Tunnel and Drag Force Testing 24
3.4 Selection of a Firing Platform *27*
3.5 Creation of a Rifling Cutter *40*
3.6 Creation of Ammunition *41*
3.7 Creation of the Barrel *43*
3.8 Test Firing *46*

Results and Analysis **48**
4.1 Wind Tunnel and Drag Force Testing *48*
4.2 Results from Test Firing *49*
Conclusions and Recommendations **51**
5.1 Conclusions *51*
5.2 Recommendations *52*
Appendix A: CO_2 Phase Diagram **54**
Appendix B: Moulton's Calculations **55**
Appendix C: Calculating Reynolds Number **59**
Appendix D: THE RIFLING G-CODE **60**
Appendix E: CAD Drawings of Projectile Shapes **61**
Glossary **63**
Works Cited **65**

Table of Figures

Figure 1: Professional paintball players 3
Figure 2: Paintball equipment 4
Figure 5: Gun Barrel Reamers 7
Figure 4: A Deep Hole Drill Tip 7
Figure 6: A Spitzer Round (left) and a Minie Ball (right) 9
Figure 7: A Complete Rifling Cutter 11
Figure 8: A Rifling-Cutter Hook 11
Figure 9: A Rifling Broach 12
Figure 10: A Rifle Button 13
Figure 11: Geometry of an ogive projectile 15
Figure 12: Numbered Sizing of multiple spitzer ogive rounds 16
Figure 13: Geometry of elliptical ogive (left) and numbered sizing of elliptical ogive rounds (right) 17
Figure 14: Geometry of cone-shaped round 17
Figure 15: Bullet with boattail 18
Figure 16: Drag measuring device in wind tunnel 24
Figure 17: Voltage readout 25
Figure 18: Force measuring device (base) 25
Figure 19: Force measuring device calibration 25
Figure 20: Round mounted on force measuring device 25
Figure 21: Tippmann A-5 at rest 28
Figure 22: Tippmann A-5 in its first stage of firing 29
Figure 23: Tippmann A-5 in its second stage of firing 30
Figure 24: Tippmann A-5 in its third stage of firing 31
Figure 25: Tippmann A-5 in its first stage of reloading 32
Figure 26: Tippmann A-5 in its second stage of reloading 33
Figure 27: Tippmann A-5 in its third stage of reloading 34
Figure 28: Shocker Sport at rest 36
Figure 29: Shocker Sport in its first stage of firing 37
Figure 30: Shocker Sport in its second stage of firing 38
Figure 31: Shocker Sport in its first stage of reloading 38
Figure 32: Shocker Sport in its second stage of reloading 39
Figure 33: Photograph of Ammunition Molds 42
Figure 34: Paintball marker mounted in gun vice 46
Figure 35: Target for spherical rounds (left) and ellipsoidal rounds (right) 46
Figure 36: mV/g calibration graph 48
Figure 37: Drag Coefficient of cylindrical bodies in axial flow 49
Figure 38: Ellipsoidal round after firing (left) and a closeup of the rifling marks (right) 50
Figure 39: CO_2 Phase Change Diagram 54
Figure 40: Front view of all projectile shapes 61
Figure 41: .5E Elliptical Ogive 61
Figure 42: .75E Elliptical Ogive 61

Figure 43: 1E Elliptical Ogive ... 62
Figure 44: 3S Spitzer Ogive ... 62
Figure 45: 6S Spitzer Ogive ... 62
Figure 46: Cone ... 62
Figure 47: Double Ogive ... 62
Figure 48: Ellipsoid ... 62
Figure 49: Teardrop Shape ... 62

Table of Tables

Table 1: Force and Cd values for projectiles ... 49

Table of Equations

Equation 1: Coefficient of drag equation ... 24
Equation 2: Angular Momentum ... 55
Equation 3: Newtonian Equation relating Torque and Angular Acceleration ... 55
Equation 4: Moment of Inertia of a Cylinder about its Transverse Axis ... 56
Equation 5: Extended Description of Transverse Angular Acceleration ... 56
Equation 6: Necessary Spin for Stabilization ... 58
Equation 7: Reynold's Number Equation ... 59

Introduction

The game of paintball is enjoyed by millions of participants across the world. The game provides entertainment and competition in a friendly and safe environment. The success of the game lies in the ability to replicate dangerous situations with non-lethal weapons. The game has succeeded in creating markers which can simulate actual firearms and situations which mimic real scenarios but there is still room for improvement. Improving the accuracy of the markers would create an even more realistic experience which would benefit the current participants and also expand the applications of the game.

The inaccuracy of the paintball marker is a result of the current system setup. Current gunpowder based firearms rely on more aerodynamic projectile shapes, grooved barrels and much greater projectile speed. The current paintball marker is not equipped with a grooved barrel. There is no other paintball shape except for a standard circular ball. Also, the ball becomes unstable after being fired due to the shape and firing ballistics. If these areas could be improved it is possible that the accuracy of a paintball marker could be improved to more closely resemble the accuracy of a firearm.

The problem of a relatively inaccurate paintball system has been a part of the game since its inception. The original markers were not intended for use on human beings or intended to act as a substitute for firearms. As such they were never completely designed to maximize aerodynamic capabilities or properties. As the game has evolved companies have experimented with curved barrels or systems utilizing multiple sleeves for barrels. The design of paintball rounds has rarely been manipulated since almost all barrels are standardized to fit the same size and shape rounds.

Creating more aerodynamic projectile shapes and complimentary grooved barrels could allow the paintball marker to fire consistently and accurately. It is important to create equipment which builds off of current systems and complies with rules and regulations already established among the paintball community. The rounds and barrel will utilize the same firing system and even attach to the same body found within some of the most popular marker models. Rounds will travel at the same speed as current rounds and have the same volume.

Paintball has established an extremely large community and is a popular form of entertainment for millions. If a system could be devised which could fire more accurate rounds it could become useful for applications other than entertainment. Law enforcement and military could use an accurate non-lethal system in an operational setting or a training environment. Current players who participate professionally would benefit greatly from more accurate and consistent firing as well. As such, there are immense marketing and expansion opportunities if an accurate paintball firing system could be created.

Increasing the accuracy of a paintball firing system would benefit millions of current users and probably attract many more. This technology could be utilized by different applications and revolutionize an already sizable community. Improved accuracy could transform a recreational and leisurely game and continue to provide an important substitute to firearms.

Background

The purpose of this chapter is to track the evolution of the game of paintball and gain insight on the equipment used by players. This chapter will explore the roots of the game as well as the expansion and growth of the game as a recreational activity or competitive sport. Also, this chapter will explore specific areas of equipment design which may be improved upon in order to continue the progression of paintball. The specific equipment which will be investigated includes the barrel, round shape and aerodynamic capabilities of current equipment.

2.1 Paintball

Paintball is played and enjoyed by participants of varied age and experience. Paintball teams are formed to compete professionally for prizes and fame similar to that found in any other team sport. However, paintball also acts as a leisurely recreational activity played in many backyards. The numerous opportunities make paintball attractive to a large audience and as the game continues to progress it continues to gain popularity.

Figure 1: Professional paintball players

2.1.2 History of Paintball

Paintball began in 1976 as a duel between men interested in stalking and hunting each other. These men, Charles Gaines and Hayes Noel, used paintball guns designed for marking cattle and trees. They determined that the guns would be effective for hunting each other and they would also spare the men from serious harm. The men began to hunt each other through the woods until one was able to successfully strike the other with a paint marker. They decided to name the game, "National Survival Game," and this is commonly thought of as the birth of modern day paintball.

The men were eager to share their experience and began to offer group games of, "Survival." One of the members present in these initial large scale games was a writer for *Sports Illustrated*, Bob Jones. Once the word spread, paintball began to rapidly expand during the 1980's and the first National Survival Championship Game was played in 1983 for a grand prize of $3,000. The sport expanded to cities and countries across the globe and it remains popular today as a competitive sport.

As the sport expanded the desire for common rules began to emerge. There were initially many variations of games and many times, users played by rules created by their groups. However, in order for the sport to be standardized, groups commonly utilized the game styles, "Capture the Flag," and "Elimination." Capture the Flag requires one team to acquire the flag of the opposing team and return it to their home base before the opposing team is able to capture their flag. Elimination style games are the most popular game variation for competitions. Elimination games are played until all members of one team are struck or, "marked," by a paintball from the opposing players. Other common rules are practiced by almost all users in order to ensure the safety of players. One such rule allows the player to surrender without being struck and another limits the maximum velocity of paintballs to 300 ft/s.

Figure 2: Paintball equipment

2.1.3 Equipment Used for Paintball

In order to play paintball a participant must attain a significant amount of equipment. As a minimum each player needs a gun or, “marker,” paintballs, a propellant, and a mask equipped with eye protection. There is additional equipment some players choose to employ such as paint grenades or camouflaged clothing accessories. Once a player has acquired this equipment the last task is finding a place to play. Facilities are available both indoors and outdoors which can be rented at the players expense.

2.2 Paintball Marker

Patrick Henry once stated, “The great object is that every man be armed. Everyone who is able may have a gun.’’ For those who do not own firearms or are unable to do so, a paintball marker provides a means to satisfy the desire to own a gun. A paintball gun is a valuable substitute for firearms because of the obvious benefit of being non-lethal. The inherent difference in purpose is responsible for other differences between firearms and paintball guns such as components that make up each gun and how each gun functions.

2.2.1 Components of a Paintball Marker

A paintball gun is comprised of several components which work together to produce the result of firing projectiles. Most paintball guns are formed from the following parts, a hopper, a body, a barrel and a propellant. The body is usually formed from aluminium and contains the firing elements, the trigger frame, bolt and valve. The hopper acts as a device designed to hold and load ammunition for the marker. The propellant stores and releases compressed gas to provide force to launch the projectiles. The barrel is responsible for releasing the projectile and affects the aim of the paintball.

2.3 The Manufacture of Barrels

The manufacture of most components of a rifle or a paintball marker can be envisioned by any experienced machinist and can be replicated in any well-equipped shop. However, the barrel presents a challenge to make with accuracy that allows shots to land within a 6.94E-5 degree arc.

The first step in machining a barrel is to make sure the outer profile is perfectly straight. When the rod stock arrives, it has a matte surface finish and a diameter tolerance of about ±.01 inch. The straightness tolerance is roughly .005 $inch_{lateral}/inch_{axial}$. In order to make the stock absolutely straight and tightly sized, the stock must be placed in a spindle with a tailstock and intermediate. This prevents chatter and allows the entire part to be straightened in a single operation, eliminating mating lines or potential straightness discrepancies from forming.

The next step is to drill a hole down the long axis of the barrel. This is not done in a traditional manner with a traditional drill. A traditional helical drill has a tendency to wander after traveling more than three diameters deep. Also, at that depth there is no way for the chips to be extracted and they tend to bind up on the cutting surfaces. This makes the tool ineffective and also places the tool and operator at risk of catastrophic failure. Instead, a special deep-hole drill, commonly called a gun drill, is purchased for the specific undersized bore diameter (-.005 inch) and tailored to the material used. The tool takes the cutting head of a traditional helical drill, uses a single flute, and places it at the end of a long rod. The helical flute is replaced by a straight flute that runs along the entirety of the rod. There is a hole (or two) 120º offset from the cutting edge that runs the length of the drill. This feature carries high pressure oil (between 500-1000 PSI) to the end of the gun drill to flush away swarf back along the single flute of the drill.

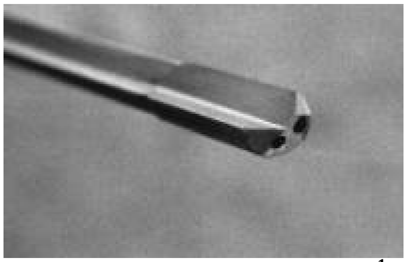


Figure 3: A Deep Hole Drill Tip[1]

The deep hole drill is placed in a guide hole while being supported by multiple bushings on intermediate rests so that its unbalanced form does not destroy it when spun at its nominal speed between two and five thousand RPM. Once in place, the coolant is activated, followed by the spindle, and lastly the (slow) feed. This allows the gun drill to basically scrape away the surface of the material until it has worked its way through the barrel.

After this operation is complete a special barrel reamer is run through the barrel.

Figure 4: Gun Barrel Reamers[1]

The special barrel reamer is similar to a chucking reamer but with greater overall length and appropriate stiffening. The reamer is generally spun at 500 RPM at a feed of approximately 1 inch per minute with 200 PSI coolant flushing away chips. In many production barrels this will create the surface finish of the bore. In this case the reamer should have a nominal diameter equal to the intended bore diameter. However, many specialty barrels require honing process to

[1] http://www.drillmasterseldorado.com/reamers.htm

take off additional material. If this is the case, the reamer should be .001 inches smaller in diameter than the intended bore diameter.

The final step is to hone the barrel to the desired finish, often 4 RU. This is achieved by waiting until after all rifling operations are completed and then gently placing a bore-diameter-undersized steel rod through the bore and pouring molten lead down the rod to fill up the barrel. Once lead cools, the rod is pulled out of the barrel and twisted at the twist rate of the rifling. Then, the lead negative-mold that has been extracted is covered in abrasive paste and slid through the barrel repeatedly, successively stepping down the roughness of the paste until the bore and groove diameters have met nominal size and have reached their desired surface finish. This process also helps to set the groove diameter to be constant and free of burrs throughout the length of the barrel.

2.3.1 Rifling History

Rifling was first put into firearms in 1492 by German gunsmiths with the intent of creating a depository for carbon fouling during firing to allow for longer firing without needing to clean the weapon. In the American Revolutionary War, Continental forces employed snipers who utilized Kentucky long rifles. After officers were sniped off and Armies stifled about leaderless, the power of a spinning projectile became apparent. However, it was not widely adopted until the American Civil War largely due to the fact that military tactics had not deemed it necessary. By the time of the Civil War, the creation of the French Minié ball (Figure 6) made rifles even more accurate compared to earlier spherical rounds. In 1898, the conical Minié round was replaced with an ogive-shaped round created by the Germans, called the “Spitzer,” as shown on the left of Figure 6.

Figure 5: A Spitzer Round (left) and a Minie Ball (right)

While the spitzer round has remained largely unchanged since its invention, it was found merely by trial-and-error, as was much of ballistics study at the time. In 1926, a US Army ordnance officer by the name of Major Forest Ray Moulton published a mathematical analysis of exterior ballistics supported by empirical data collected during World War I, called "Methods in Exterior Ballistics." It has since been referred to for all matters concerning external and internal ballistics. It has been challenged and confirmed by empirical data from nearly every arms-producing country in the world, and was republished in 1962. Since then, external ballistics theory has not changed with the exception of some super-long-range artillery, and has allowed designers to predict results before ever firing a round. His calculations are discussed in Appendix B.

2.4 Rifling Processes

The cutting of rifling in a barrel is a difficult task. There are four different ways that a manufacturer forms rifling. These are cut-rifling, broach-rifling, button-rifling, and hammer-rifling. Invented in that order, they have different advantages and disadvantages as well as different requirements to implement.

2.4.1 Cutting

The first and oldest way to create rifling is by cutting the rifling. The gunsmith does this by creating a custom tool that is similar in construction to a miniature wood plane that is fixed to a long rod. That tool, known as a "hook," is then placed into an axial slot on a short rod with the same diameter as the bore. A screw pushes on the hook to set it so that it emerges .0001 inch above the bore diameter. The complete tool is pulled or pushed through the barrel while the barrel is twisted, both at very controlled rates. The standard feed rate is 46 in/min for aluminum, 12 in/min for carbon steel, and 7 in/min for stainless steel, with the spindle speed set appropriate to the desired twist rate. The whole process is performed in the presence of pressurized lubricant/coolant to flush away swarf, prevent thermal stresses, and to lubricate. This is typically oil, but can sometimes be tapping fluid or synthetic coolant. The tool is returned to its starting position, indexed to the next groove, and repeats until all grooves have been cut to a depth of .0001 inches. Then, the operator twists the control screw to add .0001 inches of height to the hook and repeats the process until all grooves are cut to the desired depth. With a typical groove depth being somewhere between .0025 inches and .004 inches, this method requires hundreds of passes to form rifling. Figure 7 and Figure 8 depict a hook and a completed rifling-cutter containing a hook.

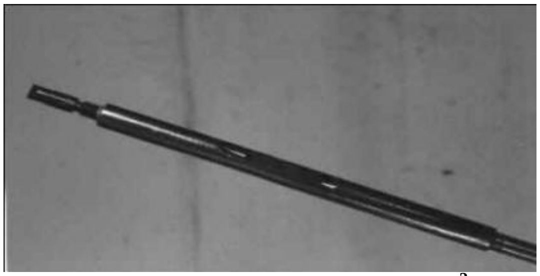


Figure 6: A Complete Rifling Cutter[2]

Figure 7: A Rifling-Cutter Hook[3]

Although the process of cut rifling is tedious, it does have advantages. The first major advantage is that it does not require much special equipment. The tools can be made in most shops, and the process can be done on many lathes. The second advantage is that this can make a barrel of any caliber and any twist rate with the same tool. The third advantage is that it is highly accurate because it is a relatively low-stress process and does not require any heat treatment for stress-relief.

2.4.2 Broach Rifling

The second method to come about was broach rifling. Broach-rifling works similar to cut-rifling and shares its low-stress accuracy. Broach-rifling works by placing multiple hooks, all with successively taller heights behind one another in the desired spiral pattern on a rod. This spiral of hooks is indexed around the rod at equal intervals. Figure 9 shows a completed rifling broach designed to make five grooves.

---

[2] http://www.firearmsid.com/Feature%20Articles/RifledBarrelManuf/BarrelManufacture.htm

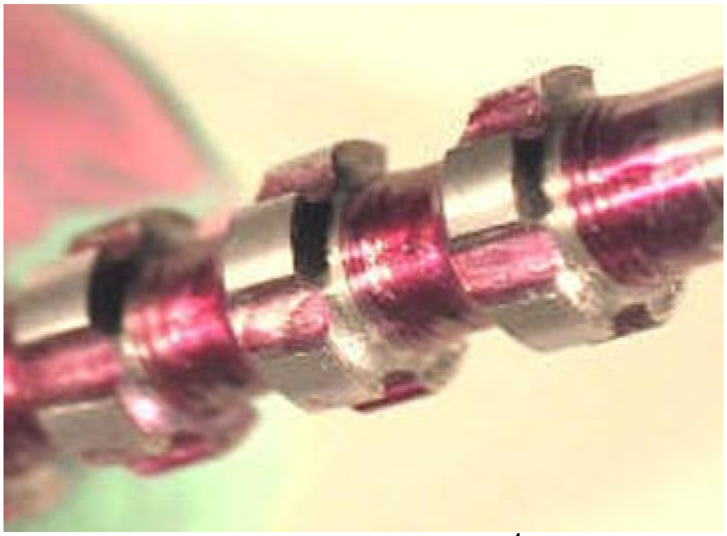


Figure 8: A Rifling Broach[4]

The tool is pushed or pulled through the barrel blank with identical speeds and feeds as cut-rifling, with pressurized coolant. It essentially performs the same function as a rifling cutter's many passes in just one pass. This makes the manufacture of barrels significantly quicker. However, there are also disadvantages to this strategy. First, a barrel broach can only be used for a barrel of a single caliber and twist rate. Second, this broach can only be made by a manufacturer who has access to 4-axis machining. Third, because of the large amount of material removal, it requires a large amount of force to operate while also maintaining a steady speed and feed. This is usually not available in general-purpose lathes or milling centers and requires a dedicated machine.

---

[3] http://www.firearmsid.com/Feature%20Articles/RifledBarrelManuf/BarrelManufacture.htm
[4] http://www.pyramydair.com/blog/images/rifling-broach-web.jpg

2.4.3 Button Rifling

The third way to make rifling is to button-rifle. A rifle button is a football-shaped portion of hardened steel or carbide that has a negative of the desired rifle pattern cut into it. Typically, it also has a front and/or rear guide sized to bore diameter surrounding it. It is mounted on a long, high-strength steel rod.

Figure 9: A Rifle Button[5]

A rifle button, when pulled or pushed through a barrel, cold-forges rifling grooves into the bore of the barrel. This process is even faster than broaching, requires less replacement of tools, work-hardens the barrel, and requires less skill to accomplish. However, it needs even more force than broaching, requiring a dedicated machine. Also, the residual stresses it leaves in the barrel needs to be relieved to maintain accuracy.

---

[5] http://www.pyramydair.com/blog/images/rifling-button-web.jpg

2.4.4 Hammer Rifling

The final technique for making barrel rifling is hammer rifling. Hammer rifling involves sliding an oversized barrel over a hardened mandrel with the negative images of the inside of the barrel. Once it is locked into place, a series of massive hammers compress the barrel into the mandrel to cold-forge the rifling and elongate the barrel by up to 20 percent. This is the fastest method for making barrels. It can also make different barrel designs if a different mandrel is made. However, it leaves extensive stresses in the barrel which needs to be relieved. This also requires a tremendous investment to install.

2.5 Projectile Design Considerations

For the shape of the new projectile, consideration was given to any shape that had undergone investigation in the fields of ballistics and aerodynamics. Ballistic science focuses especially on bullets, gravity bombs, and rockets; therefore, many of our shapes mimic projectiles in those fields. A circular front profile was chosen to limit the difficulty presented in producing projectiles with fins or any other added structure.

2.5.1 Tangential or Spitzer Ogive

In ballistics and aerodynamics, an ogive is a curved, pointed surface used to form the front of a projectile, generally a bullet, missile, shell, or aircraft.

The tangential, or Spitzer, ogive is a shape where the radius of the circular front of the projectile meet the shank of the projectile at zero angle, as shown in Figure 11. This is a very common ogive for high velocity rifle bullets.

The sharpness of this ogive is expressed by the ratio of its radius to the diameter of the shank, or R/D from Figure 11. A value of one half would be a hemispherical nose, and larger values would be progressively sharper. Values from 4 to 10 are commonly used in rifles, with 6 being the most common.

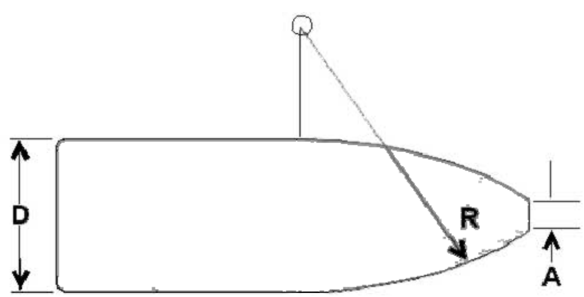


Figure 10: Geometry of an ogive projectile

We chose to design and test a 3-S and 6-S projectile, 3 and 6 referring to the respective R/D ratio, and S identifying it as a Spitzer Ogive. Although our rounds will never approach speeds close to a rifle round, we still chose to test a 6-S projectile due to its aerodynamic shape. Although 3-S is not a commonly used shape in firearms, it was still tested to see if the pointed, but much less sharp nose would be beneficial.

The downside to this shape is that due to its sharper nose, the centre of gravity is further aft. This makes the projectile less stable, causing the round to be pushed more than it is pulled. This means smaller perturbations may potentially cause the round to want to flip around. Gyroscopic stabilization solves this problem; however, due to the slow speed of paintball rounds, our spin rate will be smaller than a typical rifled projectile.

Figure 11: Numbered Sizing of multiple spitzer ogive rounds

2.5.2 Elliptical Ogive

The elliptical ogive is similar to a Spitzer ogive; however, the nose is more rounded. The profile of this shape is half of an ellipse, with the minor axis being the diameter of the shank, and the major axis being the length of the nose.

The value that designates this shape is the ratio of the length of the nose to the diameter of the shank, or B/D in Figure 13. Akin with the Spitzer, a value of one half would be a hemispherical nose. A ¾-E bullet is the most common pistol round shape, 1-E is common in round nose rifle rounds, and the ½-E shape is used in some pistol rounds. All three of these shapes were used in our testing. Since these shapes are used in pistols, it is closer to the speed paintballs travel at, but still significantly faster.

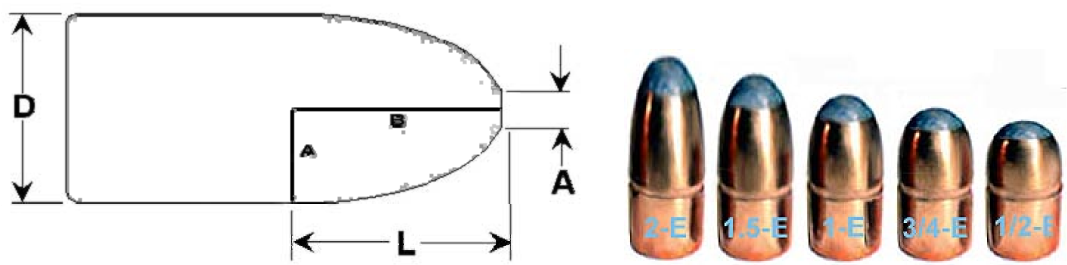


Figure 12: Geometry of elliptical ogive (left) and numbered sizing of elliptical ogive rounds (right)

2.5.3 Cone

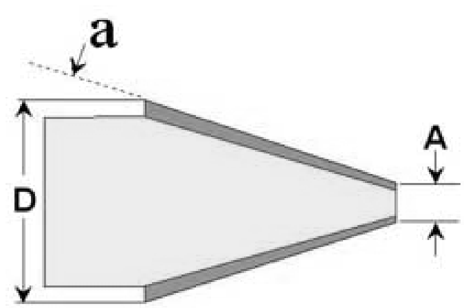


Figure 13: Geometry of cone shaped round

The cone nose is a simple shape common in rockets and rifle bullets. It consists of two lines joining the shank at an angle, designated as a in Figure 14. For bullets, this value is commonly 9 to 12 degrees and is sometimes referred to as a spire point bullet. They are very similar to spitzer bullets of the same axial length; however, they take a straight path to the shank, cutting off some of the volume and making a lighter bullet. The projectiles tested in this project are of the same volume so do not benefit from reduced weight characteristics. Cones of 9 to 12 degrees are rather sharp; so, a 30 degree cone was chosen to be tested.

2.5.4 Double-Sided Projectiles

Bullets generally have a flat base or a slight boat-tail, shown in the bottom of the bullet in Figure 15. At the base of projectiles, there originates a pressure drag which is termed "base drag." This drag is caused by turbulence in the air which has been displaced by the front of the bullet and fills in the area behind the base. This drag is most consequential in subsonic flow. The boat-tail design would be most effective in low-speed pistol rounds, but weight and length restrictions limit its use. It is most often found in longer rifle rounds where its use causes little improvement.[6]

Figure 14: Bullet with boattail

Streamlining the aft portion of a projectile gives the air a smoother path to travel with less turbulence. Conventional bullets are limited in the use of these shapes because it creates bullets too long, taking up space generally used for powder. This problem does not arise with paintball projectiles, making double-sided rounds a viable option. An ellipsoid was chosen to be tested along with a double-sided ogive projectile.

Problems with a streamlined aft section arise in rifling. Air is more likely to seep into the grooves of the rifling if it can easily flow along the rear of the projectile. There is also less contact with the barrel, which may cause rounds to receive less of the spinning force. For this reason, an ellipsoid with an added shank was chosen to be tested.

---

[6] Hoerner, Sighard F. Fluid-Dynamic Drag. 3-18 – 3-21

2.5.5 Tear-drop shape.

Both ogive shapes and the cone have centres of gravity ahead of the midpoint of the axial length of the projectiles. This means that, without spin, the projectiles would tend to flip over and want to travel with their aft portion forward. With the double-sided rounds, the centre of gravity is in the centre of the projectile, creating better stability without spin. The tear-drop shape is a ½-E round with an angled shank which eliminates base drag and creates a centre of gravity more towards the nose of the projectile.

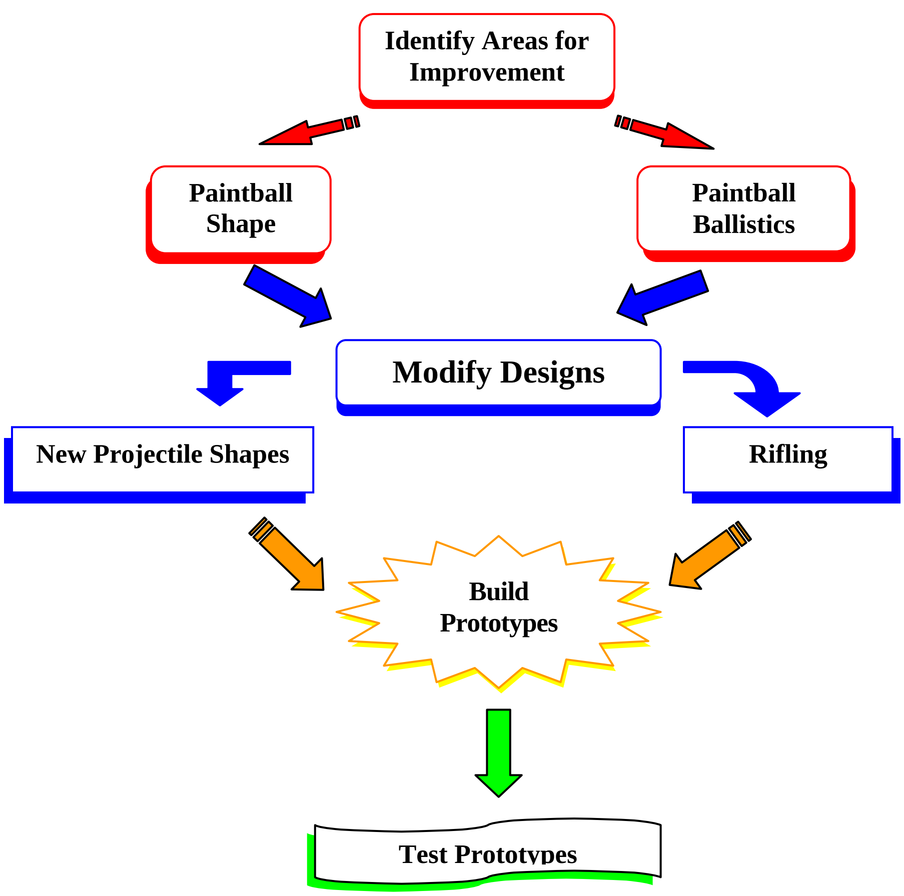
2.6 Safety Factor

Before selecting our final bullet design prototype it was necessary to consider safety factors associated with the game of paintball. Since the rounds would theoretically be fired with the intention of accurately striking human beings it was important to consider certain safety factors related to bullet design. It was not practical to implement a round with an extremely pointed nose or sleek, sharp shape which could possibly impale or break the skin of an opposing player. Since injury and unnecessary pain are undesired side effects of paintball it was important to select a design which minimized additional damage incurred by the current circular paintball design. As a result a balance between aerodynamic performance in the wind tunnel and appropriate safety considerations was selected. The final selection was a more user friendly oval shaped round similar to a circular round but with better aerodynamic properties.

Methodology

This project designed a series of paintball rounds and a complimentary barrel to determine if an improved paintball firing system based on aerodynamic and ballistic principles could be fired more accurately. These prototypes were modified from specifications common to popular paintball markers and comply with rules and regulations observed by participants. We achieved this goal by completing the following objectives described within this chapter and depicted below:

- Design new, more aerodynamic paintball shapes and a grooved barrel which are compatible with common current paintball equipment
- Build prototypes of the paintball rounds and barrel
- Test the prototypes to determine the success of the modifications



3.1 Identify Areas for Improvement

In order to create a more accurate system it was important to determine which areas of the current system could be improved upon. We decided the two areas which impact the accuracy of the projectile were the shape of the paintball rounds and the components that affect the ballistics of the paintball, namely the barrel. We chose to focus on these two elements for several reasons. First, it would be possible to make these changes compatible with the current systems and this was important since it would not require rebuilding the entire conventional paintball marker. Also, these elements have the most drastic impact on the projectile trajectory so they have the best chance of improving the accuracy.

3.1.1 Paintball Shape

There were many factors which affected the design of the new paintball round shapes. The new paintball rounds were going to be shaped more aerodynamically than the ordinary circular paintball round but they were going to have the same volume. This required modifying common aerodynamic shapes with changes in order to match the volume requirement.

3.1.2 Barrel Characteristics

The current paintball barrel system works well at launching projectiles through a sealed tube; however, our shapes would become unstable without the added stability of rotating the round. The rotation of the round serves two purposes, gyroscopic stability and drag reduction. Hoerner describes the drag reduction due to rotation in the following exerpt:

> "The influence of rotation on drag reduction seems to be fourfold. First, the boundary layer is thickened because of the added speed component… however, this causes

increased drag on streamlined bodies. Second, the thickened boundary layer is likely to cause separation and additional form drag in the afterbody. Third, on account of centrifugal forces in the rotating boundary layer, separation from the base appears to be increased. Fourth, the added velocity component affects the stability of the boundary layer, thus reducing the critical Reynolds number of sensitive bodies such as spheres."[7]

3.2 CAD/CAM for Bullets and Barrel

Different forms of software were utilized in order to create a prototype design that was ready to be machined. Virtual part models were created using Pro-Engineer and SolidWorks. These files were imported into GibbsCAM and machining operations were added using specifications appropriate for the materials and machines which would be used. The post file was created using GibbsCAM after all machining operations were rendering properly and the prototype was ready to be created. These files can be found in Appendix D and Appendix E.

3.3. Build and Test Prototypes

After the finalized bullet and barrel designs were selected, the next step was to produce prototypes of each component and test the effectiveness of these parts. The parts were manufactured for the most part at the WPI machine shop using CNC lathes and various other finishing tools located within the shop. The testing was performed at several locations including the wind tunnel and an open field.

[7] Hoerner, Sighard F. Fluid-Dynamic Drag. 3-13

3.3.1 Machining Prototype Rounds

The process of machining the ten wind-tunnel prototype paintball rounds was basically an assembly line operation. The first step was to cut two inch diameter PVC piping into sections approximately eight inches long using a bandsaw. Next, the PVC sections were placed into a CNC lathe loaded with the CAM software for each round shape. The tool offsets were programmed before each round could be created and the software for a round was run. The machine produced a round which was ready to be drilled, tapped and pressed.

The rounds needed to be mounted on the force balance system present in the wind tunnel so it was necessary to create a system to hold them into place. Each round needed to be drilled using the vertical drill press so that a steel rod could be inserted. The steel rods were drilled and set screws were inserted into each rod. The final step was to insert the rod and set screw combination into the round using the arbour press.

3.3.2 Wind Tunnel and Drag Force Testing

There were two purposes to the wind tunnel testing that was being performed. One was to determine the drag force that the projectiles would be exposed to under normal firing conditions. The second was to determine which shapes received the least drag and were, therefore, the most aerodynamic.

The wind tunnel being used was not capable of, nor would it be particularly safe, testing our rounds at full speed, around 90 m/s. The following equation is used to calculate drag:

Figure 15: Drag measuring device in wind tunnel

Equation 1: Coefficient of drag equation

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 S}$$

Where C_D is the coefficient of drag, D is the drag force, ρ is the fluid density, V is the velocity, and S is the sectional area.

So, in order to get an accurate drag reading, we would have to increase the size of the projectiles that would be tested to compensate for the lower speed. The maximum speed of the wind tunnel used was 55 m/s; however, as a safety precaution and to decrease instability in our testing device, we chose to operate at half of that speed, or 27.5 m/s. This is roughly ¼ of the speed our final projectiles would be travelling at. This would mean our V value in the equation would be multiplied by ¼, meaning the area S would need to be multiplied by 16 to compensate. Since $S = \pi r^2$, r would have to be increased by a factor of 4 to increase S by a factor of 16. This meant that, to test our rounds, we would have to scale them up by a factor of 4.

The testing device works by measuring the distance that the unit has moved. The upper portion of the device is mounted on metal strips which can bend, allowing the device to move slightly when force is applied. The device shown in Figure 18 measures the distance between its tip and the metal sheet directly in front of it in Volts. As the force increases, the distance will increase, and so will the voltage. The voltage is displayed on the device shown in Figure 17.

Figure 16: Voltage readout

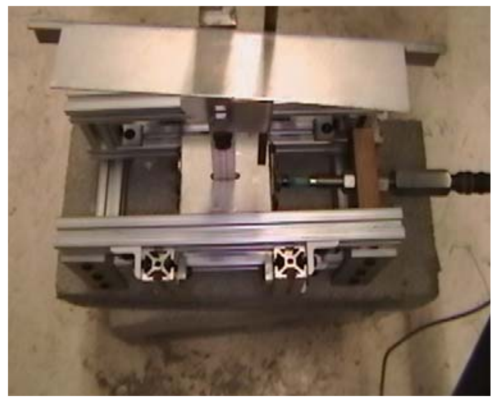


Figure 17: Force measuring device (base)

To translate these voltage readings to force measurements, the device had to be calibrated. This was done with the pulley system shown in Figure 20. Voltage readings were taken while hanging various weights from the pulley system. Values for weight were then plotted against their voltage values. The slope of this trend line would then show how changes in voltage translated to changes in force.

To test the force on each shape,

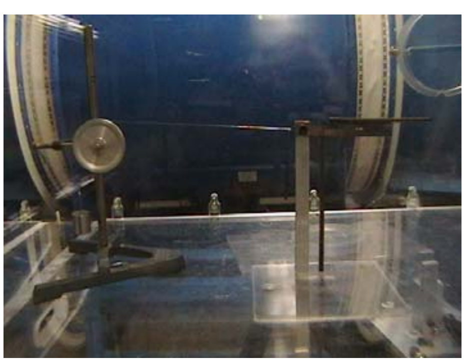


Figure 18: Force measuring device calibration

Figure 19: Round mounted on force measuring

measurements were taken while the wind tunnel was running with nothing on the device, and then measurements were taken while the wind tunnel was running with a round placed on the device, shown in Figure 19. The difference between these two values was then recorded. This value is converted to Newtons using the calibration value determined earlier. This value is the drag force, and is roughly the same force the tested shape would encounter if it was travelling at 300 ft/s and was 0.5 in. in diameter.

This drag force value can also be used to determine the coefficient of drag using the formula at the beginning of the section. The values calculated can be compared with those from historical data to confirm the validity of our testing.

3.4 Selection of a Firing Platform

Many different paintball markers were available for our testing, but ultimately the 2004 Shocker Sport was chosen as the firing platform for the barrel testing. It was chosen for multiple reasons relating to its unique firing mechanism. These reasons are the closed bolt firing position, the controlled firing volume, low firing pressure, and ease of adaptation.

In order to understand the advantage of the Shocker, it is necessary to understand how a typical firing system works. There are hundreds of different designs for paintball marker valves. For this example the Tippmann A-5 is being used, due to the fact that most other designs follow a similar system or suffer from the same flaws. Figure 21 shows a Tippmann A-5 at rest. The black outline represents the cast-iron receiver and ergonomic fixtures of the marker. All orange parts represent parts made of HDPE. Moving from left to right is the ball-detent, made for keeping the ball in place while in the rest position. To the right and slightly above that is the bolt. Moving on, there are orthogonal orange lines representing the valve housing. The final plastic component is the trigger, located furthest to the right.

All grey components represent pieces made from stainless steel. The most notable are the large body in center constituting the valve wall, and the long horizontal bar known as the connection rod. The large lime green component is made from aluminum and is known as the hammer. The pink component is known as the sear and is also made of stainless steel, but is colored differently to be distinguished. Likewise, a guide pin for the drive spring (a red zigzag) is placed within the hammer that is colored pink for visibility. The yellow area is pressurized CO_2, running a pressure between approximately 500 PSI and 2200 PSI, depending on ambient temperature (in accordance with Appendix A: CO_2 phase change diagram), supplied by a high-pressure gas bottle. All zigzag markings are springs, while all blue lines represent o-rings.

However, the blue-swirled circle represents a COTS .68 caliber paintball. All dark-green components are made from brass with the rightmost component being called the valve pin. The red component is a COTS carbon steel pipe bushing using NPT threads.

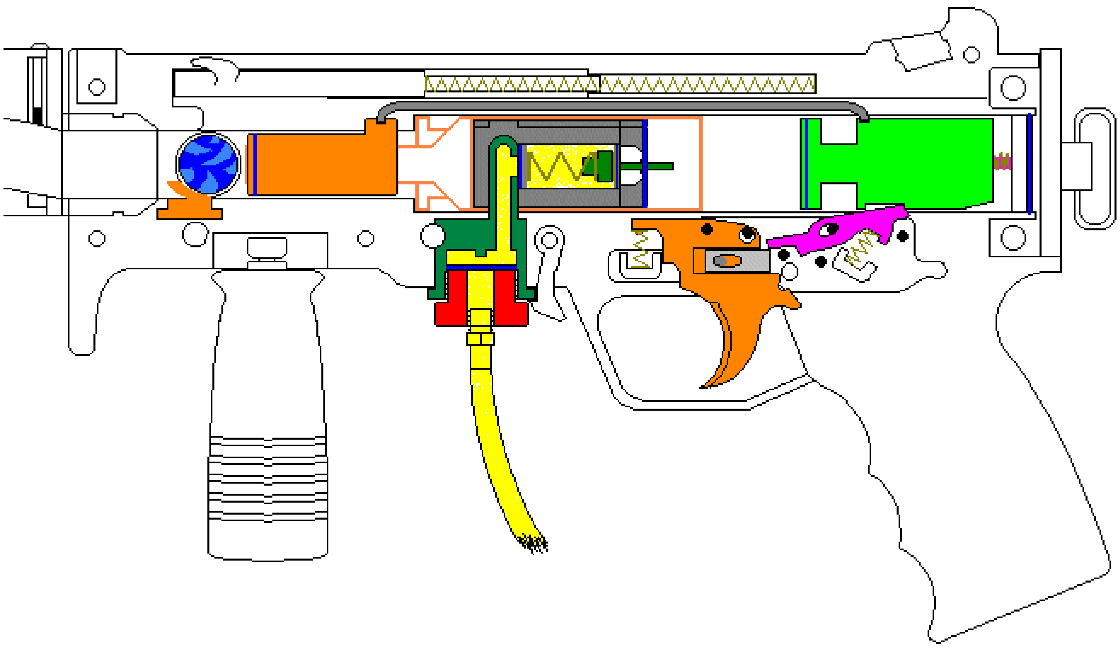


Figure 20: Tippmann A-5 at rest

Figure 22 shows a Tippmann A-5 in its first stage of firing. Note that the orange trigger has been tilted, causing the pink sear to release the hammer, powered by the red drive spring.

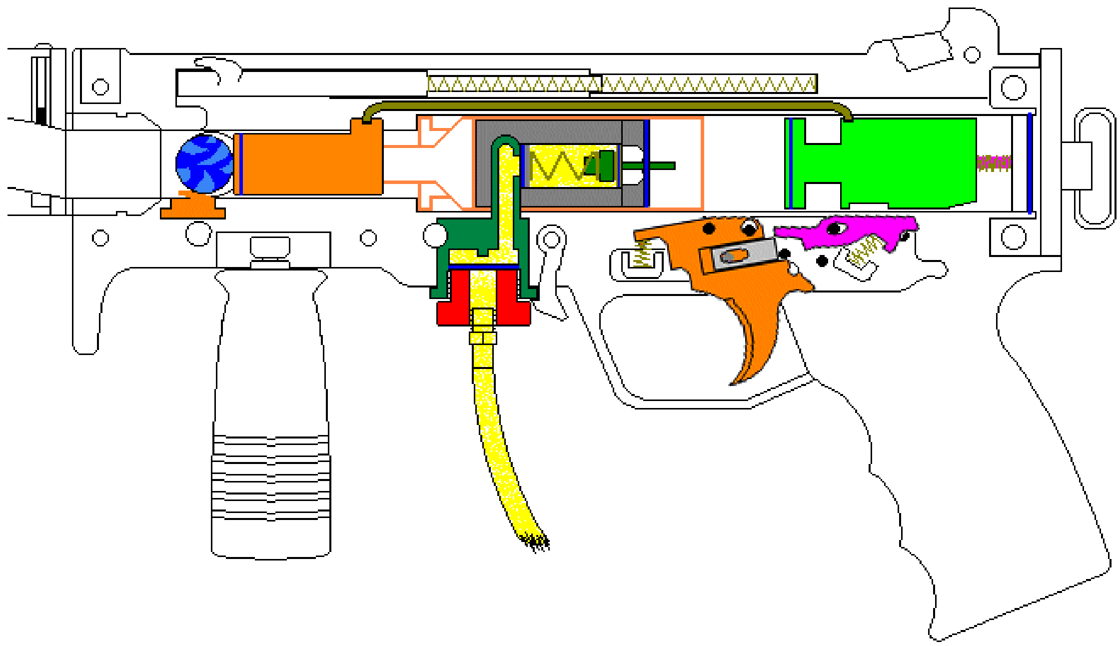


Figure 21: Tippmann A-5 in its first stage of firing

Figure 23 shows a Tippmann A-5 in its second stage of firing. A number of changes have taken place. The force of the drive spring has pushed the hammer forward. Likewise, the connection rod has forced the bolt and paintball into the barrel, forming a seal between the barrel and valve assembly. Also, the kinetic energy of the hammer has temporarily overcome the tension of the valve spring holding the valve pin shut. This has caused the pressurized gas to flood out through the newly opened hole.

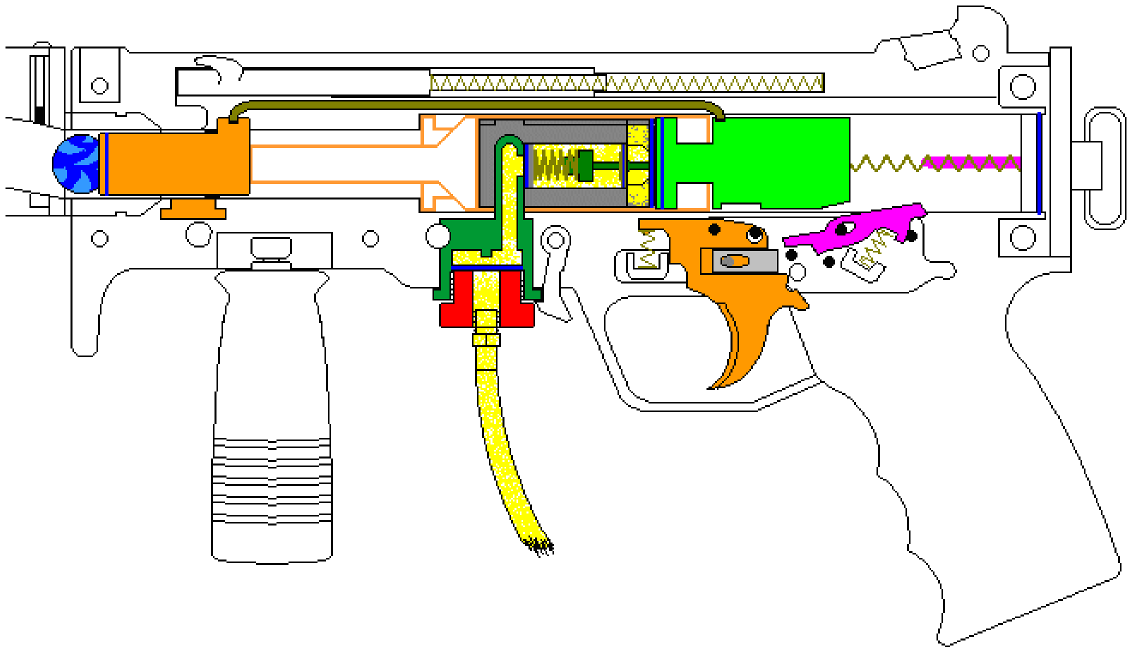


Figure 22: Tippmann A-5 in its second stage of firing

Figure 24 shows the Tippmann A-5 in its third and final stage of firing. The cutaway of the valve has been covered by the stainless steel wall of the valve. Note that the pressurized CO_2 wrapped around the valve, followed the valve housing through the bolt, and expelled the paintball down the barrel.

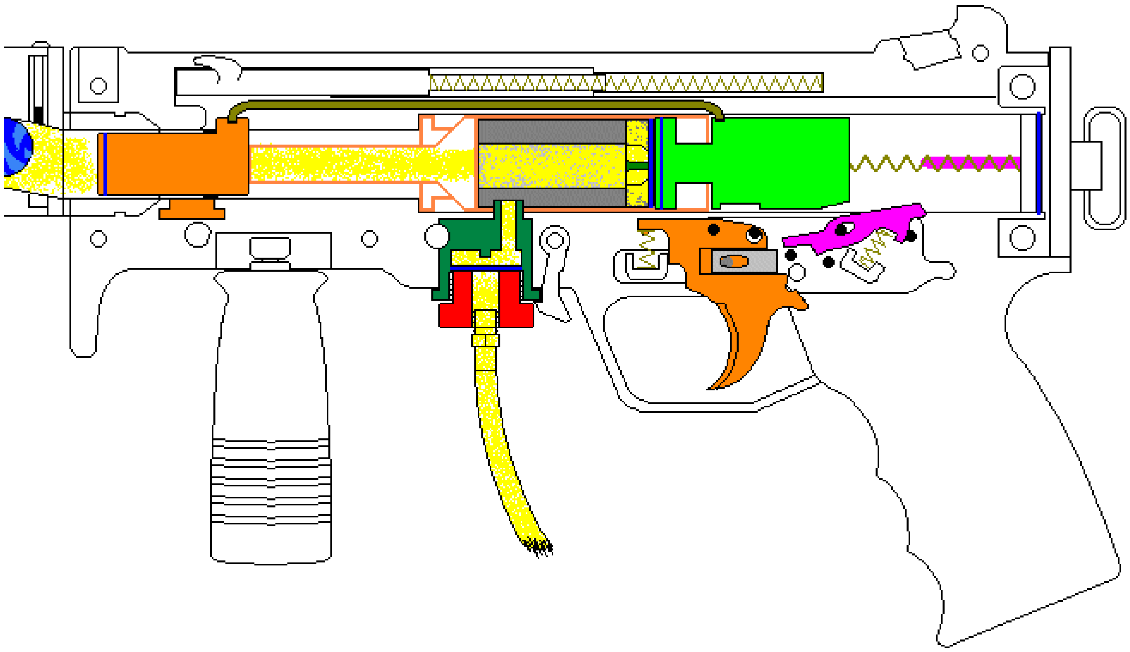


Figure 23: Tippmann A-5 in its third stage of firing

Figure 25 shows the Tippmann A-5 in its first stage of reloading. It is important to note that there is no time delay or manual input between firing and reloading stages in most designs. Note that the hammer has been repulsed by the expanding gas leaking through the hole left by the valve pin, and is retreating. The sear is in place in its original position to catch the hammer when it returns and prevent it from cycling again prematurely.

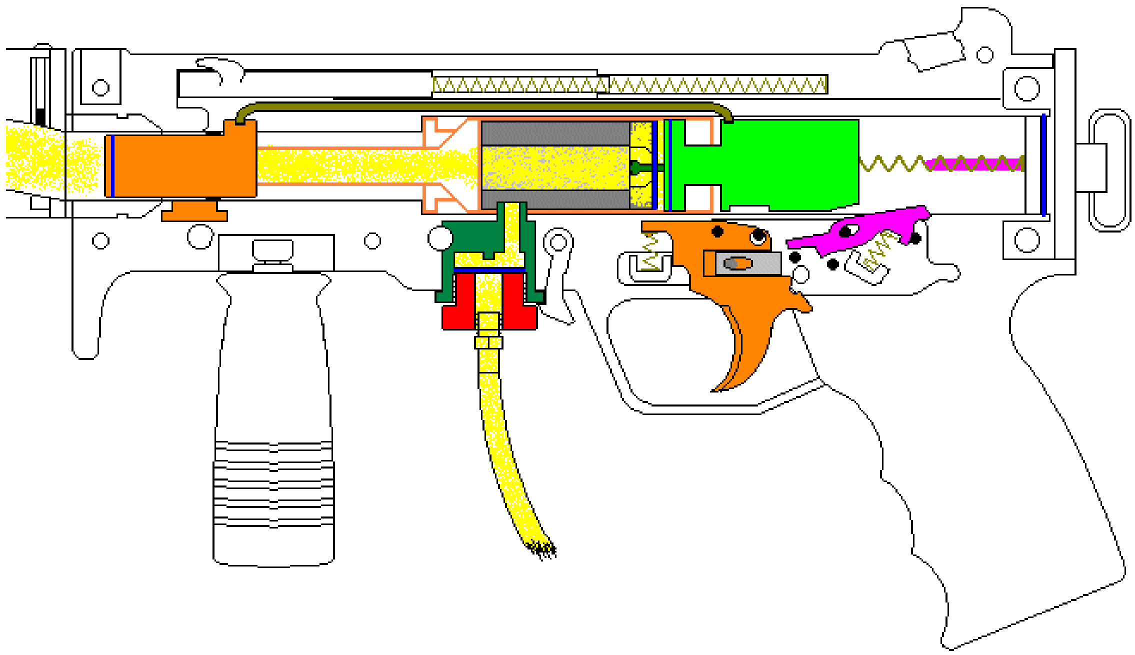


Figure 24: Tippmann A-5 in its first stage of reloading

Figure 26 shows the Tippmann A-5 in its second stage of reloading. Note the valve spring has moved the valve pin back to the rest position, closing the valve. This has left the hammer to complete its cycle on its own momentum and allowed the valve to recharge. The sear has been pushed down by the bevel in the hammer and is scraping along the bottom of the hammer. With the movement of the hammer came the movement of the bolt, which broke the seal with the barrel, allowing all remaining pressure to escape. A paintball is also slipping into the chamber through a hole in the receiver through gravitational pull, or in some cases, a spring- or gas-powered feed system.

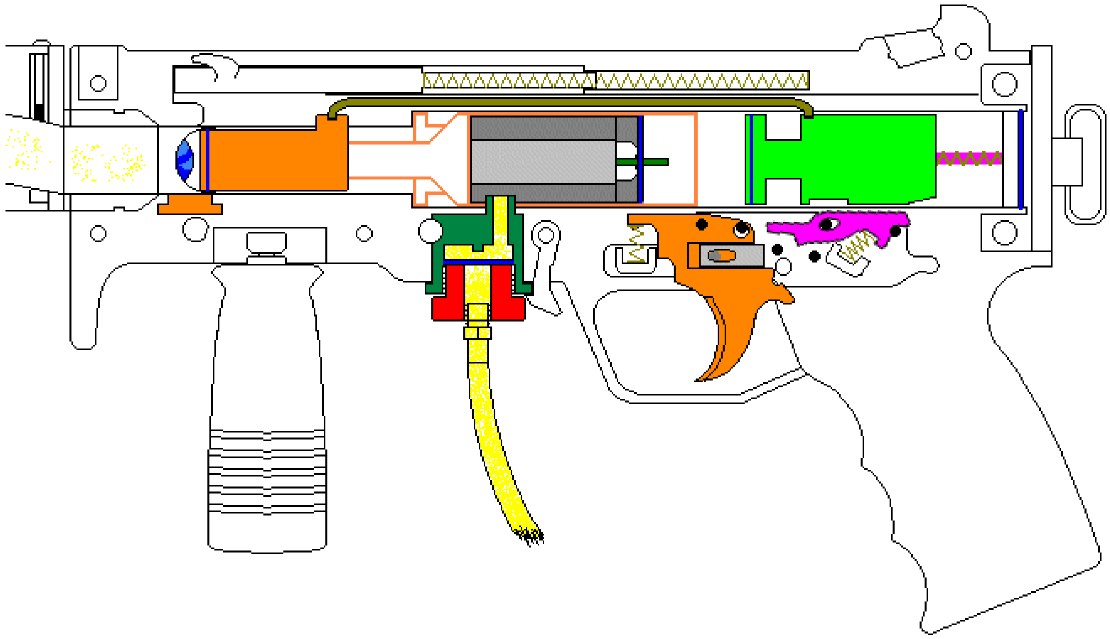


Figure 25: Tippmann A-5 in its second stage of reloading

Figure 27 shows the Tippmann A-5 in its third and final stage of reloading. This stage takes place immediately before the rest state. The hammer and bolt have moved to the rear of the rest position and allowed the sear to engage a slot in the hammer without simultaneously engaging the trigger. This allows the trigger-sear mechanism to function as a semi-automatic, and cycle once per trigger pull. Before the paintball marker returns to its rest position, a number of actions will take place. The hammer and bolt will move forward, making the sear reengage the trigger, the valve will recharge, a new paintball will fall into place, and the ball detent will spring back into place to keep the ball from rolling down the barrel.

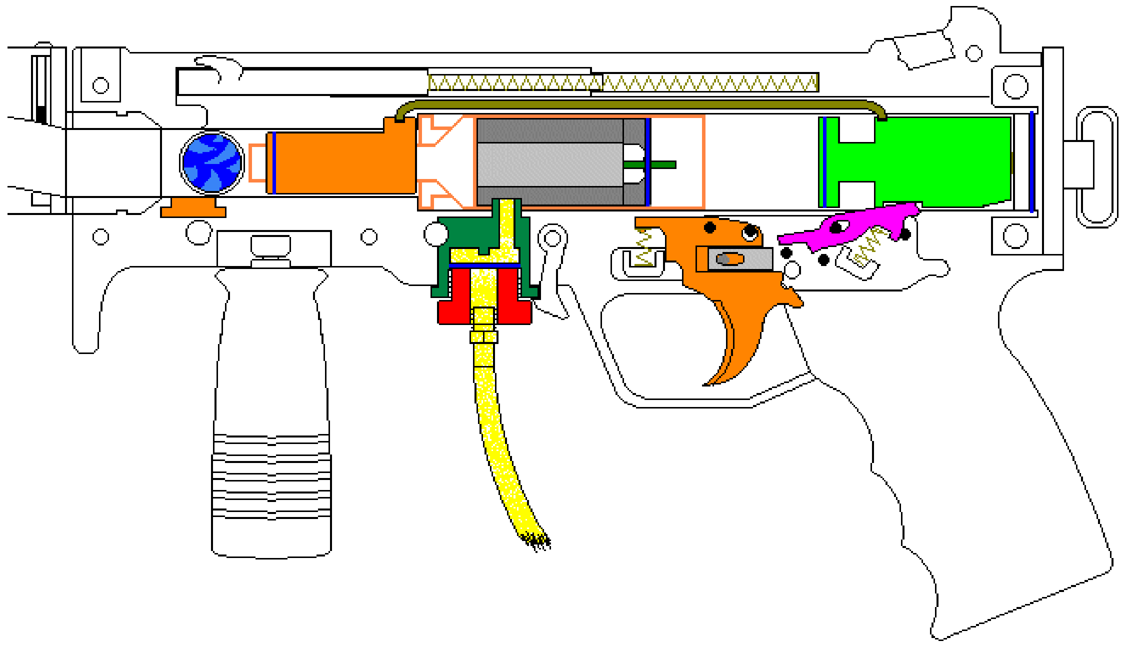


Figure 26: Tippmann A-5 in its third stage of reloading

The accuracy disadvantages of this system are numerous. First, the mechanical trigger-sear mechanism creates a great deal of friction at many joints, making for a heavy trigger-pull which can cause the marker to inadvertently jerk. Second, the entire machine depends on the movement of a heavy cylinder of aluminum bucking back and forth inside the marker. This causes a shift in the center of gravity, which causes the whole marker to bounce even in the steadiest hands in the midst of the firing sequence.

These factors can be mitigated by using a bench-rest; however, there are three factors that can not. The first is that the rate at which the gas reaches the ball is controlled by a set screw that is placed partially through the long neck of the valve housing. This provides a poorly regulated and disrupted airflow onto the rear of the ball. This leads to inconsistent muzzle velocities and unintended spinning.

Second, the volume of CO_2 released during the firing sequence is dependent entirely upon the force with which the hammer strikes the valve pin. The velocity component is dependent on the amount of friction encountered by the hammer during its sliding. This is subject to change in any sliding part where the hole is as loosely-fitting as cast iron, especially if factors such as temperature change or fouling take place.

Finally, the biggest disadvantage is that the hammer slams into the valve upon firing. This causes a transfer of momentum into the firing platform and audible vibrations throughout the paintball marker. These vibrations are normally ignored in a firearm because a bullet moves supersonic and outruns these vibrations. However, in a paintball marker, these vibrations cause the barrel to whip at the muzzle, resulting in an unpredictable terminal direction of the barrel when the ball is last in contact with it.

While hundreds of paintball markers mitigate one or more of these many inaccuracy factors, all failed to successfully solve two major issues. The first issue was how to control the volume of gas expelled, and the second was how to keep from moving a heavy hammer to start a high-energy firing cycle. Produced from 1995 to 2002, the Shocker Sport solved all of these issues.

Figure 28 shows the Shocker Sport at the rest position. There are 4 different levels of the Shocker shown here, partitioned by tan-designated aluminum. The bottom level contains two solenoid-controlled valves and an unseen computer board and battery pack to coordinate them; one marked 4000 and the other marked 3000. Above that is the power tube, indicated by a small white arrow. Above that is the valve tube containing the valve mechanism straddling the gas chamber. Placed on top is the bolt tube containing the bolt, barrel, and ammunition feeder. It is important to note that in reality, the power tube and valve tube are next to one another, not stacked.

Unlike the previous drawing, all components are machined aluminum. The exceptions are as follows. All green sections are made from PTFE. Although not shown, the bolt head has an array of Venturi tubes, similar to magician's levitator. All light-blue areas are pressurized air or nitrogen, running between 200 and 500 PSI, depending on the setting of the regulator and desired velocity. Gas is supplied through the white arrow in the rear, indicating a COTS NPT attachment leading to the gas regulator. All dark pink sections indicate O-rings. There is a series of black circles located to the rear of the valve mechanism, which indicates a cutaway view of a spring. The large grey circles in the upper right represent paintballs.

Note that at the rest position a paintball is already loaded into the barrel and ready to fire, eliminating all the need for any motion of the bolt before firing. Also, the gas is required to be low-pressure regulated air or nitrogen, a gas that is far from a phase change and acts in an ideal manner. This allows for consistent and predictable input into the valve.

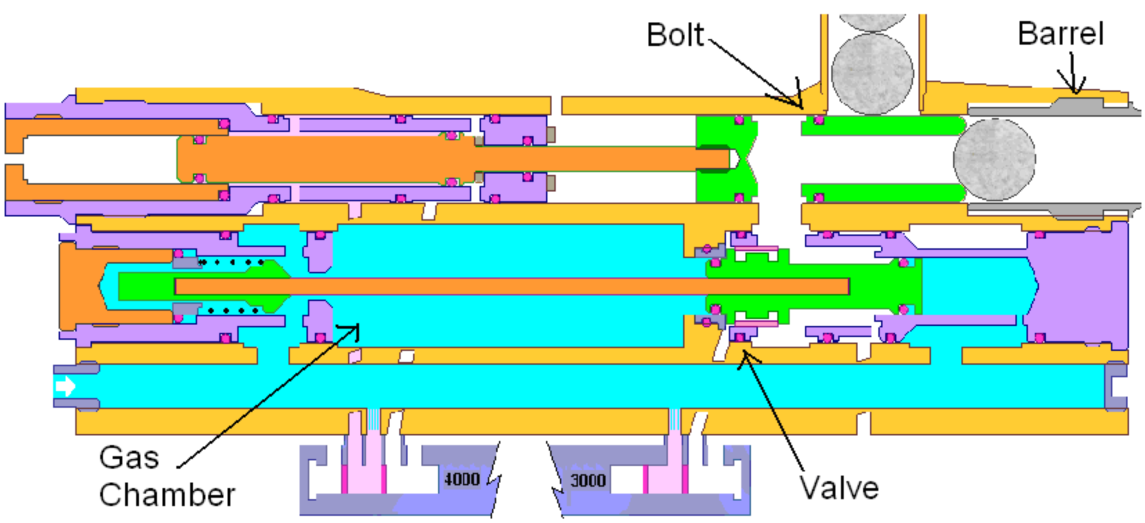


Figure 27: Shocker Sport at rest

Figure 29 shows the Shocker Sport in its first phase of firing. Note that the 3000-solenoid valve, known as the valve solenoid, is charged. This creates a small channel between the power tube and the valve. In essence, this provides a small pilot push on the valve. Meanwhile, the rear of the valve mechanism has closed off the gas chamber in order that the gas enclosed is the only gas expelled.

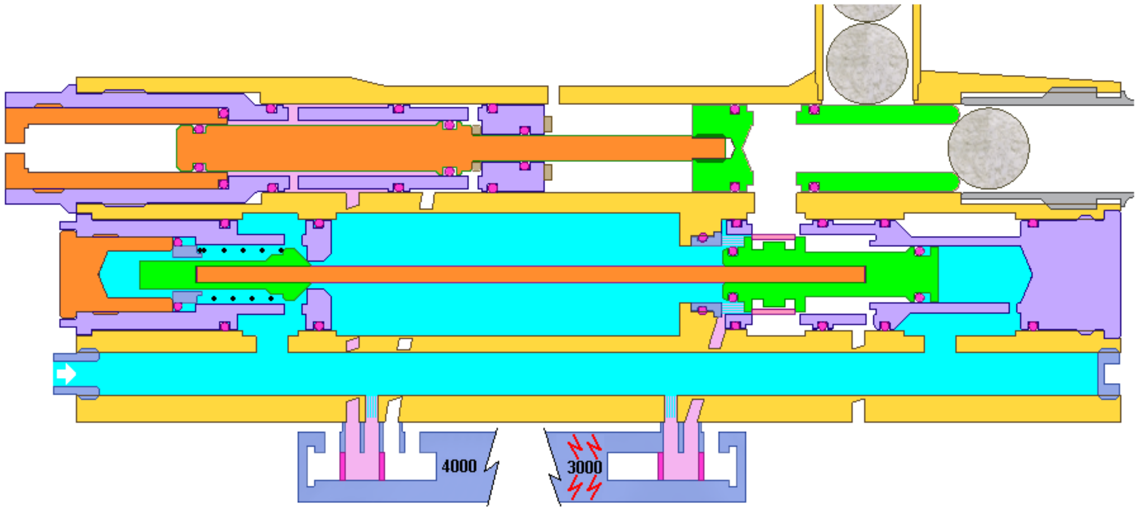


Figure 28: Shocker Sport in its first stage of firing

Figure 30 shows the Shocker Sport in its second stage of firing. The paintball is expelled by the fixed volume of air that has been released. Note that the valve solenoid remains powered in order to freeze the marker in its pre-firing state until the round is completely expelled. After the round has left the barrel, firing is complete.

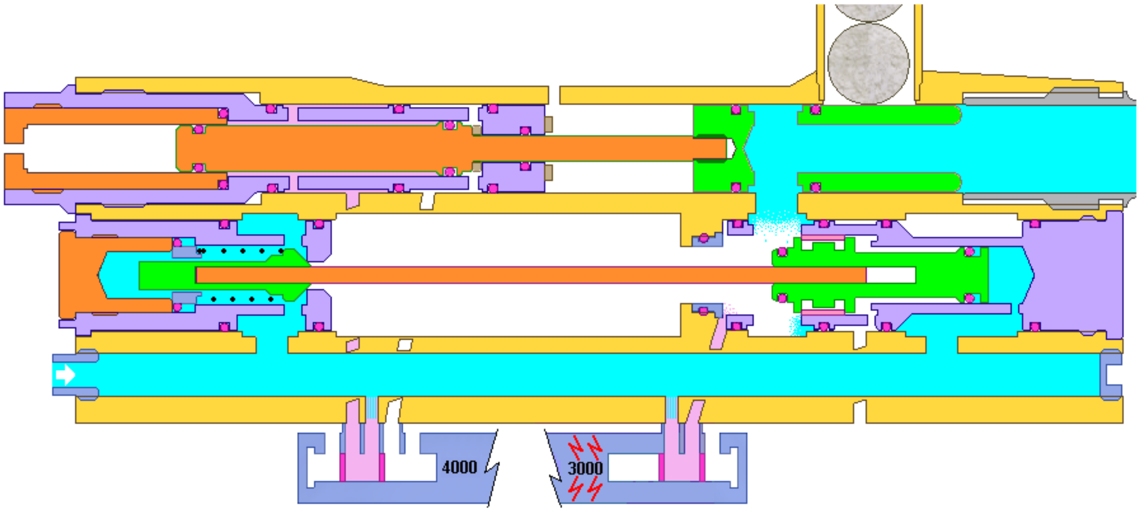


Figure 29: Shocker Sport in its second stage of firing

Figure 31 shows the Shocker Sport in its first stage of reloading. Note that the valve solenoid has had its power cut off, allowing pressure from the power tube to push the whole assembly to the rear. This, in turn has opened the gas chamber to refilling from the power tube. Meanwhile, the 4000-solenoid valve, also known as the bolt solenoid has vented the pressure on one side of the bolt and pressurized the other side of a three-way valve, pushing the bolt to the rear. This has allowed another paintball to feed.

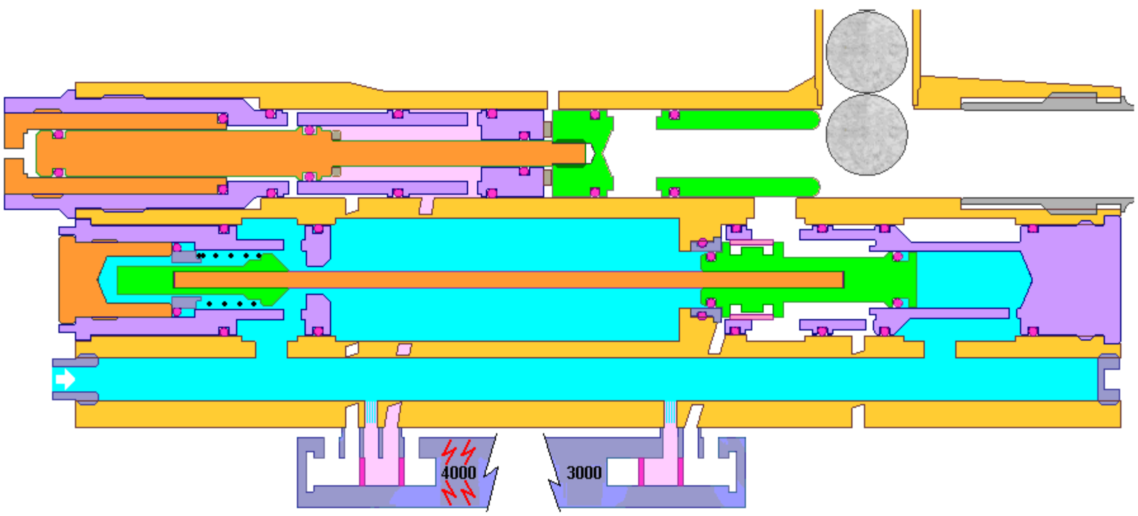


Figure 30: Shocker Sport in its first stage of reloading

Figure 32 shows the Shocker Sport in its second stage of reloading. Note that the bolt solenoid has been discharged, which allows gas from one side of the three way valve to vent while re-pressurizing the other. Before returning to the resting position, the bolt has to move all the way to the front.

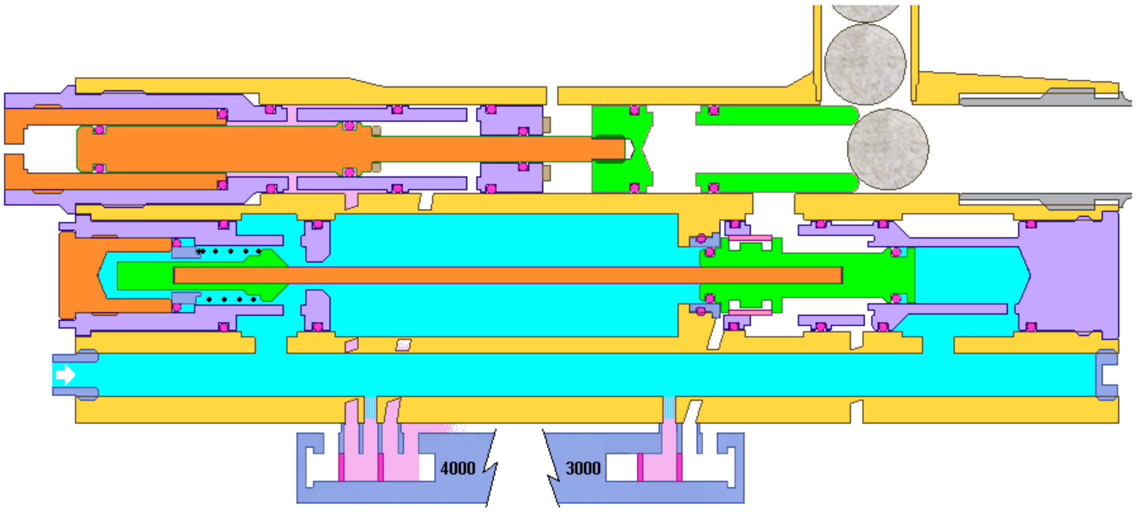


Figure 31: Shocker Sport in its second stage of reloading

While this system gave many gaming advantages such as firing rate and reliability, it mitigates all the factors of inaccuracy inherent in other markers. By controlling the entire system by computer, the trigger pull could be set to no more than a mouse-click. By making the valve smaller, operating using gas pressure, well-lubricated, internalized, and made from lightweight PTFE, the amount of impact and center-of-gravity shift that is produced is negligible. With a consistent input and isolated gas chamber, the amount of volume could be predicted, and velocity can be changed with regulation of the gas pressure alone. The addition of Venturi tubes onto the bolt-face made for laminar flow in the barrel to prevent unintentional spinning of the ball. Additionally, the Shocker Sport is nearly twice as heavy as the Tippmann A-5, allowing any vibrations that are created to be greatly dissipated.

3.5 Creation of a Rifling Cutter

Given the fact that button and hammer rifling were far beyond the capability of WPI's machine shop and the means of our project, the only options remaining were to create a broach or cutter system. However, considering that only one barrel was to be built, investing time into a mass-production tool such as a broach was impractical, and a simpler tool would be favorable. Thus, the rifling would need to be cut using a rifling cutter.

A rifling cutter hook is traditionally made from high-speed steel or carbide in order that it can cut hardened steel. However, for this application, the material would be aluminum, which is significantly softer. This allowed the cutting tool to be made from a more widely available and easily machinable material. We used a 14-inch long, .5-inch OD, .25-inch ID, piece of 4130 steel that had remained from the manufacture of wind tunnel prototypes to make up the body. This was subsequently machined down to a .487 inch diameter on all areas except the head.

While a customized cutting bit was beyond our means and technology, a stainless steel set screw roughly seven times as hard as aluminum, would easily cut our material. Thus, the rod would have a set screw's base emitting from it to scrape the surface of the barrel to form the rifling. During rifling, the set screw used Loctite threadlocker to keep from twisting back into the cutter, which would be reapplied every time the screw was stepped to a greater height.

In order to keep the bit coaxial and concentric with the ID of the barrel, a front and rear guide near to the bit were needed. They were quarter inch bands of OD .494, or .001 under bore diameter in accordance with the Machinery's Handbook[8]'s slip fits. Between the two bands

---

[8] Jones, Franklin D., and Henry H. Ryffel. Machinery's Handbook. Machinery's Handbook. 28th ed. 2008

would be a quarter inch band of .490, into which a 6-32 through hole would be placed through the long axis of the tool.

3.6 Creation of Ammunition

After the completion of wind tunnel testing, we decided on which shape the projectiles would best take to incorporate internal, external, and terminal ballistics. Then, we needed a way to create these rounds in a relatively quick manner to make testing possible. While the traditional method for making paintball ammunition would theoretically make rounds in our needed shape the machinery to do this was well beyond our means.

There were three different designs for rounds that we wanted to test, all with the same outside shape but with different insides. The first was a solid round. This round would be essentially a light bullet and would prove the maximum accuracy of the barrel. The next type of round was the liquid-filled. This round would be made through the same process as a paintball and would test what affect the rifling would have on it. The final type of round would be a finned round. This round would be similar to a liquid-filled round, but would have a fin protruding into the liquid fill so as to agitate it when spun and make all the mass spin.

In order to make these rounds, we decided to use a casting process, as it was inexpensive and easy to manufacture. Though the rounds would not be marketable, they would be able to demonstrate the objectives. This required the creation of several molds. Figure 33 shows a photograph of the 4 molds that we made using SolidWorks, GibbsCAM, and a VM-3 CNC vertical milling machine.

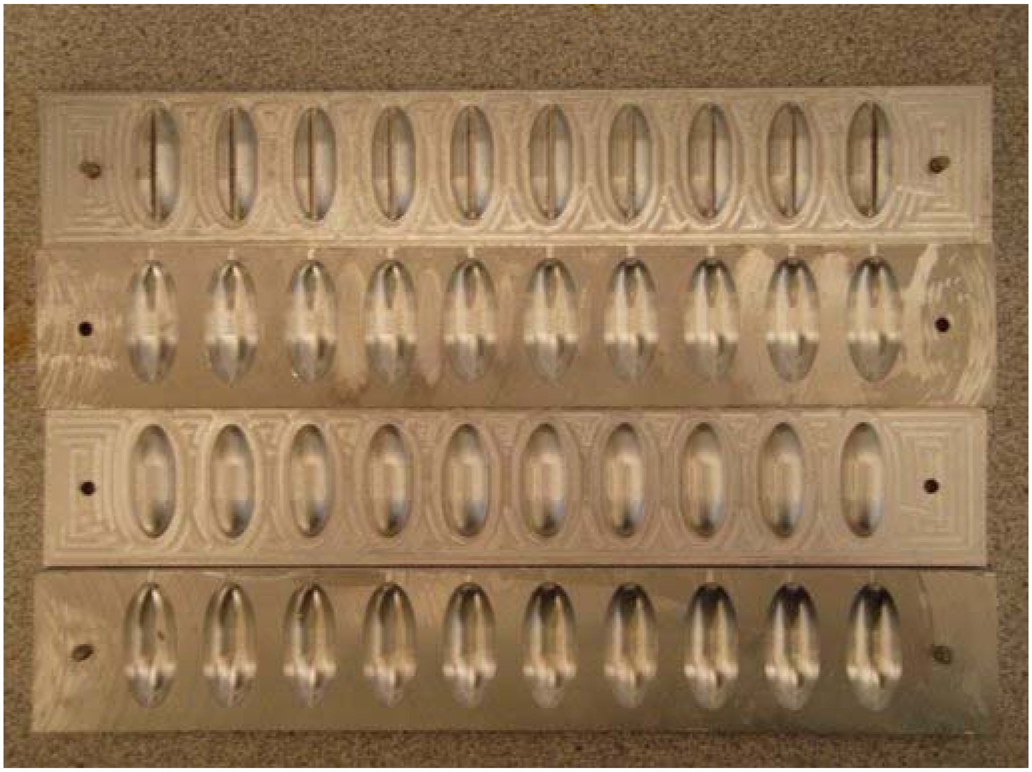


Figure 32: Photograph of Ammunition Molds

Note in Figure 33 that numbers 2 and 4 are concave, while 1 and 3 are convex. Also, 1 and 4 have dowel pins protruding from them, while 2 and 3 have holes to match. When creating solid rounds, 2 and 4 are placed together and filled with liquid wax through a syringe entering through a notch in the top and then cooled. When creating liquid filled rounds, the holes of 3 are lined up with the pins of 4 and liquid wax is placed into the mold and cooled. This would create half of a round, would be matched up with another similar half, and would be placed inside of 2 and 4. While inside there, a syringe would inject them with hot water, causing the wax to melt and the seam between the two halves to form. Finned rounds were produced the same way, except using numbers 1 and 2 initially to make round-halves. Note that number 1 is similar to number 3, but has a slit going through it to form the fin within the round.

3.7 Creation of the Barrel

Because the barrel presented so many manufacturing challenges, it took the longest time to create. Creation of a barrel takes many steps, including deep-hole drilling, reaming, polishing, rifling, and profiling.

Due to the fact that WPI's machine shops did not have the capability to run pure oil coolant through the spindle at 1000 PSI, it was impossible to deep-hole drill the barrel ourselves. Rather than set up some sort of contraption that may have accuracy issues, we instead opted to contract it out. Two rods of aluminum round was turned down to .995 inch OD and faced off to be just over 10 OAL, and sent to Gartman Arms in Wrentham, MA. At Gartman Arms, the rods had a .494 inch hole cut down the entire length of the barrel.

Then, in order to ream it, we ordered a .495 reamer, and placed it in a VM-3 vertical milling machine. We centered the reamer by performing a bore touch-off on the freshly made hole. We used copious coolant that was programmed to aim at the entrance hole to the barrel, rather than the head of the reamer. The coolant would then wick down the reamer and flush away the flake-like chips that the reamer was producing. The reamer was spun at 500 RPM at a rate of 1 inch per minute, and fed in two inches (length of the cutting head) at a time, and then fed outwards, and then repeated. This was repeated for each two inch section for the entire length.

Following that, the barrels were polished. This was done using a section of threaded plastic rod and a rag due to their low hardness that would not scratch the barrel and their quick availability. The rag was smeared with a paste of polish and wrapped tightly on the barrel, and then run through the same program as the reamer. After the cycle was finished, a less abrasive polish was smeared on a new section of rag and the cycle repeated. This process was used for three successively less abrasive polishes and gave the inside of the barrel a mirror finish.

Finally, we needed to rifle one of the barrels, while leaving the other smoothbore for testing purposes. The barrel that needed to be rifled had all but the last two inches turned down to .9 inch in order to create a step where the future rifling would be. This would give the spindle something to push against during the rifling process. In order to rifle this barrel, the rifle cutter had to be mounted in a collet, which in turn, had to be tightly screwed into a machine tool holder mounted on the turret of the SL-20 lathe. The SL-20 was selected to be used because it had fine spindle control and could turn at the slow, controlled rate used in making rifling. With the rifling tool being 14 inches long there was very little clearance between the end of the tool, and the head of the spindle. Thus, in order to load the barrel for rifling, the turret would have to be turned into place, the barrel loaded behind the spindle, and then the tool loaded. Then, once that was complete, the barrel would be pulled forward to the point that the chuck teeth engaged the step. Then, the turret was slowly handle-jogged forward until the front guide had been placed into the bore, with the cutting tooth just outside the barrel. Before running the program, the tool was coated in AlumTap aluminum cutting solution. Finally, with the optional-stop on, the rifling program (written in Appendix D) was run. Every time an optional stop was met, more AlumTap was applied to the tool. Once the end of the program was met, the set screw was stepped up to its new height by adding an additional .0001 inch, threadlocked into place. This process was repeated without removing the barrel or tool from their position.

Finally, once threading was completed, the external profile of the barrel was cut. This was done by first observing a barrel made for the Shocker Sport under the optical comparator and measuring its threads. These threads were found to be two different threads that were 8 TPI with a major diameter of .92, but with a depth-of-cut equal to a UNC 16 TPI screw. Then, a GibbsCAM lathe program was written that would rough at the recommended feed and speed of the Machinery's Handbook[9] that would leave .001 inches of material on the shaft. Then, the lathe was programmed to follow the profile of the barrel at a 10 percent feed rate to leave a clean surface finish.

[9] Jones, Franklin D., and Henry H. Ryffel. Machinery's Handbook. Machinery's Handbook. 28th ed. 2008

3.8 Test Firing

The test firing process was developed to compare our barrel and projectiles against the traditional spherical round altering as few variables as possible. We tried to keep the barrel and round as the only variables. The same marker, distance, target size, velocity, and volume were used.

Figure 34: Target for spherical rounds (left) and ellipsoidal rounds (right)

For the first set of tests, a target was placed at a distance of 50 ft, shown in Figure 34. The marker was placed in a gun vice placed on a solid surface to ensure there would be no movement of the marker after the recoil of a shot, shown in Figure 35. The first barrel placed on the marker was the traditional barrel for spherical rounds. A custom fitting allowed the barrel to keep a tight seal on the balls to ensure optimal performance of the balls. Each round was loaded into the chamber with the barrel off, then the barrel was screwed in and the round was fired. A chronometer was placed on the end of the barrel to measure the speed of each round in order to ensure consistency and also to analyze what effect any minor changes in velocity had on the rounds. The target for the spherical rounds was a paper target that the rounds were able to penetrate without breaking. This made it easy to mark each shot and determine a grouping. Ten shots were fired on the target.

Figure 33: Paintball marker mounted in gun vice

The next test was the rifled barrel and the ellipsoidal rounds. We planned to reuse the ellipsoidal rounds since they were difficult to manufacture. To do this, the target for the ellipsoidal rounds, shown in Figure 34, was an easily penetrated tissue paper mounted on a sleeping bag to create a cushion for the projectiles to land on. The marker remained in the same position as before and the barrels were swapped. The ellipsoidal projectiles were loaded in the same manner as the spherical ones, with the barrel off. A round was fired, and then adjustments were made to the marker to get the projectile to hit the target. If the velocity of the round was to high or low, adjustments could be made to the pressure. Ten shots were to be fired. This same process would be repeated for the smooth barrel with ellipsoidal rounds. After this set of tests was complete, the target would be moved 25 ft and the process repeated. The targets would be moved out another 25 ft for the third set of tests. The targets could then be analyzed to determine which round and barrel combination caused the smallest grouping at various distances.

.

Results and Analysis

4.1 Wind Tunnel and Drag Force Testing

Figure 21 shows the calibration of the force measuring device. Each weight was tested several times and a trendline was made to determine that there was a 2.9 millivolt increase for every gram of force applied to the device.

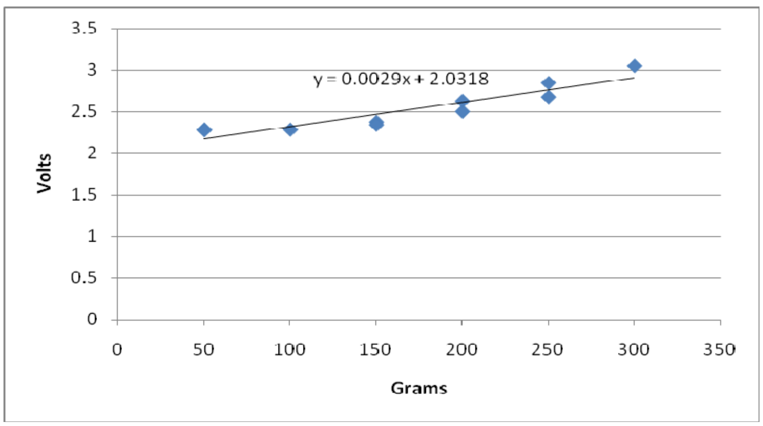


Figure 23 shows the voltage that was measured while running the tunnel in volts. These values were then converted to grams using the conversion factor from the graph above. A Newton force value is also shown which was used in determining the rifling spin rate. The Coefficient of Drag could then be calculated using the equation,

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 S}$$

where D is the Drag value in Newtons, ρ is the density of air (1.2 kg/m^3), V is the velocity of the wind tunnel (27.5 m/s), and S is the area of the front view of the projectile (0.002027m^2). The coefficient of drag is used to check and make sure our testing matches up with historic data. Cylindrical bodies in axial flow, shown in Figure 22, with length to diameter ratios similar to ours (between 1.5 and 3) should have C_d values ranging from 0.2 to 0.4, which they do. Our cone should have a C_d value ranging from 0.2 to 0.5, which it did.[10]

Shapes with lower C_d and Drag force values are the most aerodynamic.

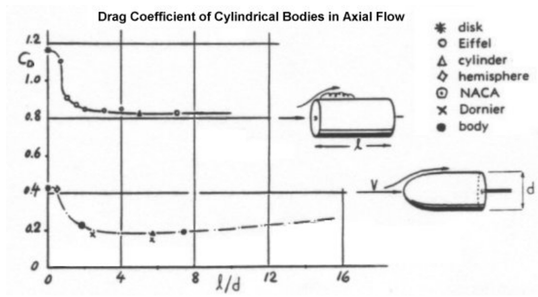


Figure 36: Drag Coefficient of cylindrical bodies in axial flow

Volts	grams	Newtons	C_d	Shape
0.0792	27.33	0.2681	0.2915	cone
0.0825	28.45	0.2791	0.3035	.75E
0.0830	28.62	0.2808	0.3053	6S
0.0837	28.88	0.2833	0.3081	3S
0.0840	28.97	0.2842	0.3090	double ogive
0.0935	32.24	0.3163	0.3439	tear
0.1065	36.72	0.3603	0.3917	1E
0.1250	43.10	0.4228	0.4598	ellipsoid w/o shank
0.1367	47.13	0.4623	0.5027	.5E
0.1378	47.53	0.4663	0.5070	ellipsoid w/ shank

Table 1: Force and Cd values for projectiles

4.2 Results from Test Firing

The test setup we developed was successfully able to create a grouping at 50 ft with spherical rounds as a base to determine the success of our rounds and barrel. Once we began firing ellipsoidal rounds out of the rifled barrel, problems began to arise. The rounds were successfully fired out of the barrel at speeds in the range of a standard paintball; however, consistency could not be upheld. Rounds would begin to fall apart as they were loaded. Other

[10] Hoerner, Sighard F. Fluid-Dynamic Drag. 3-22

rounds seemed to get damaged while traveling down the barrel. This would then cause the rounds to spiral out of control in the air. Several wounds were able to accurately hit the target, but we were not able to manufacture enough rounds to test either barrel enough times.

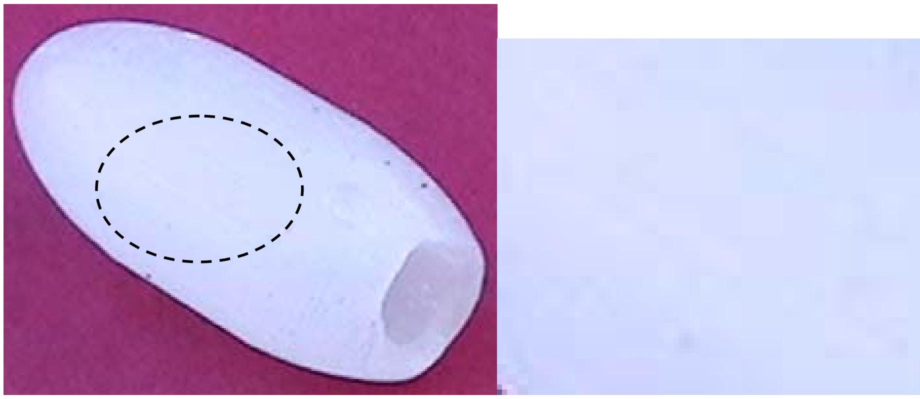


Figure 37: Ellipsoidal round after firing (left) and a closeup of the rifling marks (right)

The rifling process did work. Figure 38 shows the markings left on the ellipsoidal rounds as the rifling cut into them and caused them to turn. The turning also explains the helical trajectory that damged rounds took after leaving the barrel.

Figure 38 also shows that some rounds caved in at the back under the pressure of the CO_2. Although this may seem like a negative characteristic at first, rounds that had this type of damage withstood testing for longer with better accuracy than whole rounds. This implies that having a smooth aft portion of the projectile may lead to a more streamlined profile in the air, it may allow gas to leak through the grooves of the barrel during the firing process. Having this "pocket" behind a projectile allows the gas to more easily push the projectile forward.

Conclusions and Recommendations

Our project set out to develop and test a modification to a well established firing system in hopes to improve accuracy and range. This chapter will discuss what our project was able to prove and recommend future endeavors that could be taken to further develop this firing system

5.1 Conclusions

After a long development and some testing, we were able to conclude that there is potential to increase paintball accuracy through modified rounds and rifled barrels. We analyzed various shapes and through considerations for both safety, aerodynamics, and manufacturing, chose a shape that successfully travelled, with rotation, to a small target at 50 ft away. However, we were not able to consistently replicate that firing in order to merit an actual conclusion on whether this system is actually more accurate.

We concluded that a system could easily be integrated into current paintball equipment. The only changes necessary would be to swap out a barrel and load a different type of projectile. If this system were further developed, the paintball community would be able to easily reap the potential benefits.

Through unforeseen circumstances, we were able to prove that a projectile with a pocket for air, similar to that found in many bullets, would be able to travel down a barrel with more stability. A greater variety of projectiles would certainly bring further conclusions on this front.

5.2 Recommendations

The many different aspects of developing a complicated firing system creates a daunting task when trying to modify the means of launching a projectile. This leads to many problems throughout the platforms development and many recommendations for future investigation into the system.

When developing projectiles, it is important to remember that paintball projectiles must be unlike other projectile. Although some shapes may be more aerodynamic, they may pose a safety risk for a game developed to mimic firearms without the dangers. It is also important to consider the ease of manufacturing such projectiles. Since paintballs are meant to break, the chosen shape must be strong enough to withstand the forces applying while they are being fired, and must also be weak enough to shatter when making contact with a person. The process used to create the rounds was not reliable enough to produce a significant amount of rounds for testing. The area with the largest room for improvement was the quality of the test rounds. A shape and material must be chosen that can withstand the pressure of the gas combined with the cutting and turning force from the rifling. The method for developing that round must also be reliable enough to create enough rounds to show a consistent grouping on a target. This requires enough rounds to get the marker position correctly along with the rounds considered for the grouping.

Creating a rifled barrel was the most difficult task. It is not a common process in most machine shops, so it requires a lot of problem solving for the inevitable incapability of the facilities in use. The tools and processes used created a very successful rifled barrel. The most significant area for improvement for the barrel would be to better smooth out the interior.

During testing, some roughness in the rifling may have caused a piece of some of the rounds to fall off, causing very erratic flight.

This project proved there is definitely potential to improve upon and revolutionize an already extremely popular recreational activity with little extra cost to the user. It is a difficult task, but one that seems as though it would work if the materials were correct.

Appendix A: CO_2 Phase Diagram

This diagram is used made specifically for paintball for use by airsmiths. In a paintball CO_2 tank, under normal conditions, there is a section of the tank that is liquid, and a section that is gas. CO_2-powered paintball markers work on the idea of latent pressure, that pressure remains the same until all of a substance has changed phases.

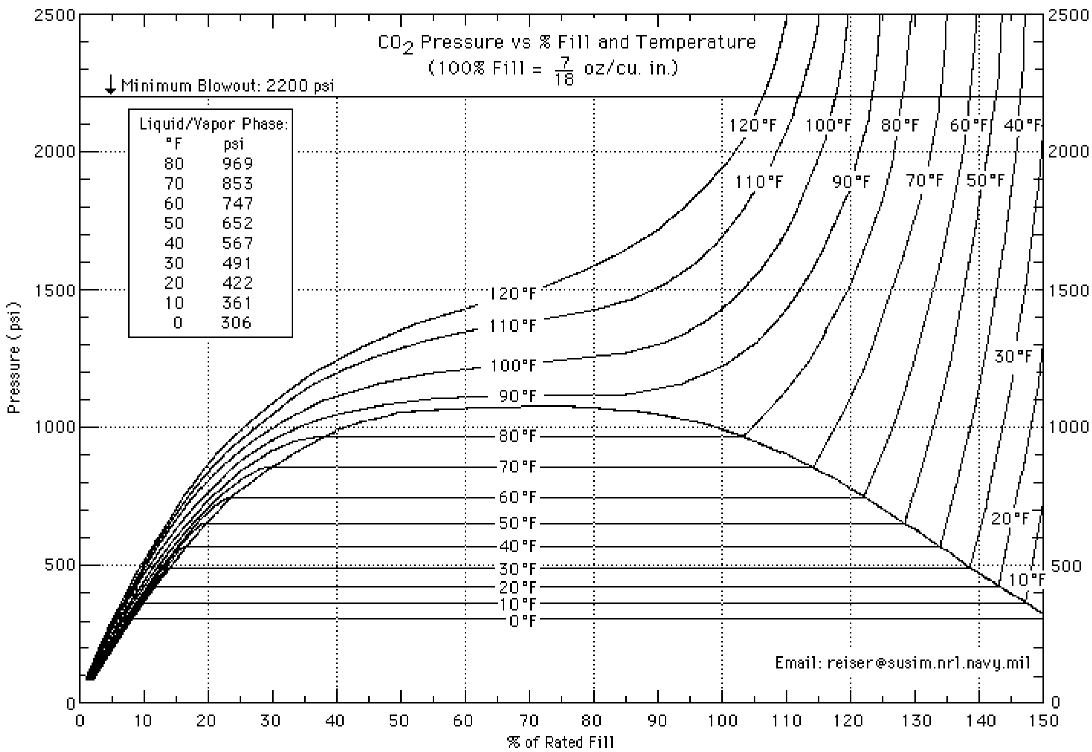


Figure 38: CO_2 Phase Change Diagram

Note that at 2200 PSI, a safety burst disk fails, and the bottle has a controlled release of the entirety of the contents. As is shown, in extreme temperatures or low tank fills, pressure is not consistent due to a lack of liquid within the bottle. It is also important to note that firing of the paintball marker cools the tank, moving its pressure to a different isobar.

Appendix B: Moulton's Calculations

Major Forest Ray Moulton started from the previous calculations by Newton that defined how much resistance to transverse twist a longitudinal twist would produce. This is described by the angular momentum equation illustrated as Equation 1.

Equation 2: Angular Momentum

$$\mathbf{L} = I\omega$$

Where:

L represents angular momentum (rad-lbf-in^2/s)

I represents the moment of inertia around the rotating axis (lbf-in^2)

ω represents the angular velocity (rad/s)

However, this raised the question of why a highly-stabilized round would have a sporadic flight path. The answer lay in that a round needs to pitch at a slow rate to stay tangential to its parabolic flight path. The challenge that lay before Major Moulton was to find out just how much twist needed to be applied to a round to prevent yawing, but to allow for the pitch of the flight path. In order to do this, he defined what the strength of the force was that caused the round to pitch. Then, he turned to the Newtonian equation relating torque and angular acceleration, as exhibited in Equation 2.

Equation 3: Newtonian Equation relating Torque and Angular Acceleration

$$\alpha = \frac{\tau}{I}$$

Where:

α represents angular acceleration (rad/s^2)

τ represents torque (lbf-in)

I represents moment of inertia (slug-in^2)

He reasoned that the force that causes any oblong projectile to stay tangential to its path is the force of drag applied to the circumferential edge of the projectile. From there, he determined that the force of drag, multiplied by the moment arm, in this case being the radius of the projectile, would have to overcome the angular momentum caused by the rotation of the projectile, but only by a small amount.

He substituted α_T for α, I_T for I, and F_d*r for τ, where r represents radius of the projectile as viewed from the front in order to calculate the angular acceleration a projectile would go through during its flight. Assuming that a projectile is a cylinder (a good approximation), and I_T for a cylinder is as stated in Equation 3, and the force of drag, then the equation for α_T would be Equation 4.

Equation 4: Moment of Inertia of a Cylinder about its Transverse Axis

$$I_T = \frac{1}{12} * m * (3r^2 + h^2)$$

Where:

I_T represents the moment of inertia of a solid cylinder about its transverse axis (slug-in^2)

m represents the mass of the cylinder (slug)

r represents the radius of the cylinder (in)

h represents the height of the cylinder (in)

Equation 5: Extended Description of Transverse Angular Acceleration

$$\alpha_T = \frac{12 * C_d * \rho * v^2 * \pi * r^3}{m * (3 * r^2 + h^2)}$$

Where:

α_T represents the angular acceleration about a transverse axis (rad/s^2)

ρ represents the density of air (slug/in^3)

v represents the velocity of the round (in/s)

C_d represents the coefficient of drag (unitless)

r represents the radius of the round when viewed from the front

m represents the mass of the round (slug)

h represents the height of the cylinder (in)

All elements of α_T could be measured using simple instruments. However, the issue became discovering the optimal ratio between longitudinal angular momentum (L_L) and transverse torque (τ_T). By setting τ_T equal to L_L multiplied with a constant, C, he created the following equation:

$$\tau_T = C * L_L$$

Then, substituting in their Newtonian equivalents, the following equation is formed:

$$I_T * \alpha_T = C * I_L * \omega_L$$

Then, since α_T could be calculated by Equation 4, it would be made into a standalone variable:

$$\alpha_T = C * \omega_L * \left(\frac{I_L}{I_T}\right)$$

Finally, in order to find out the value of C, Moulton fired thousands of rounds of varying calibers and twist rates, and recorded the trueness of each flight. He noticed that there was actually a parabolic correlation between ω_T and α_T. What resulted was Equation (93) from Methods in Exterior Ballistics, defined here as Equation 5. It is important to note the less-than sign rather than an equal sign because it is safer to for the barrel to over-stabilize the round than to under-stabilized it.

Equation 6: Necessary Spin for Stabilization

$$\alpha_T < \frac{1}{4} * \omega_L^2 * (\frac{I_L}{I_T})^2$$

Where:

α_T represents angular acceleration about a transverse axis (rad/s^2)

$\acute{\omega}_L$ represents angular velocity about the longitudinal axis, ie twist rate (rad/s)

I_L represents the moment of inertia about the longitudinal axis (lbf-in)

I_T represents the moment of inertia about a transverse axis (lbf-in)

Appendix C: Calculating Reynolds Number

An important factor when researching the forces that our projectiles would undergo is the Reynolds Number. It is calculated using the equation:

Equation 7: Reynold's Number Equation

$$Re = \frac{\text{Dynamic pressure}}{\text{Shearing stress}} = \frac{\rho v_s^2/L}{\mu v_s/L^2} = \frac{\rho v_s L}{\mu} = \frac{v_s L}{\nu} = \frac{\text{Inertial forces}}{\text{Viscous forces}}$$

where:

v_s is the mean fluid velocity, 300 ft/s or 91.44 m/s

L is the characteristic length, ranging from 1 to 1.5 inches

μ is the (absolute) dynamic fluid viscosity, $3.75x10^{-7}$ lb*s/ft^2

ν is the kinematic fluid viscosity, defined as ν = μ/ρ, $1.58x10^{-4}$ ft^2/s or $15.11x10^{-6}$m^2/s

ρ is the density of the fluid, .0745 lb/ft^3 or 1.2 kg/m^3

This gives us a Reynolds number in an approximate range of 1.54 $x10^{-5}$ to 2.37 $x10^{-5}$.

Appendix D: THE RIFLING G-CODE

```
%
O1( SmoothRiflingCode.NCF )

G20G40G56G80G97G98m154;

G00C360.;
G01W-11.F46.4C218.6;
M01;
G01W11.F46.4C360.;
M01;
G00C300.;
M01;

G01W-11.F46.4C158.6;
M01;
G01W11.F46.4C360.;
M01;
G00C240.;
M01;

G01W-11.F46.4C98.6;
M01;
G01W11.F46.4C360.;
M01;
G00C180.;
M01;

G01W-11.F46.4C38.6;
M01;
G01W11.F46.4C360.;
M01;
G00C120.;
M01;

G01W-11.F46.4C338.6;
M01;
G01W11.F46.4C360.;
M01;
G00C60.;
M01;

G01W-11.F46.4C278.6;
M01;
G01W11.F46.4C360.;
M01;

G00C360.;

%
```

Appendix E: CAD Drawings of Projectile Shapes

The shapes for the projectiles were designed using Pro/Engineer software. The front profile of all the projectiles is the same, a 0.5in diameter circle, shown in Figure 25. All projectiles also have a volume of 0.1628 in^3, the same as current spherical paintballs. All dimension values are in inches and represent the size of a round that would potentially be fired out of our test barrel.

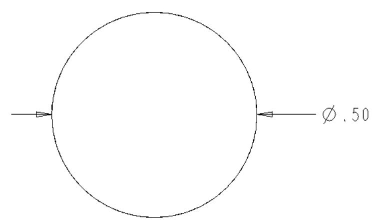


Figure 39: Front view of all projectile shapes

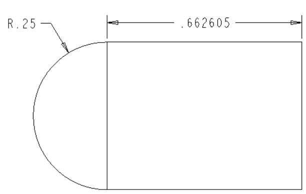


Figure 40: .5E Elliptical Ogive

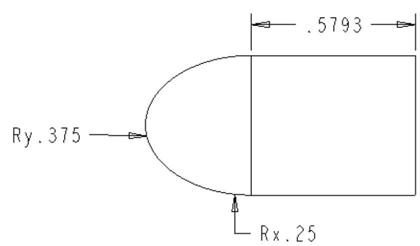


Figure 41: .75E Elliptical Ogive

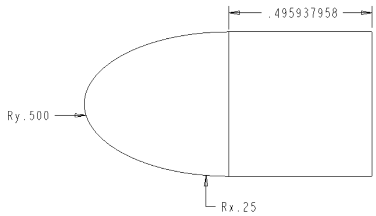


Figure 42: 1E Elliptical Ogive

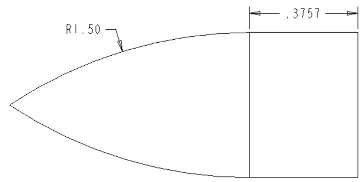


Figure 43: 3S Spitzer Ogive

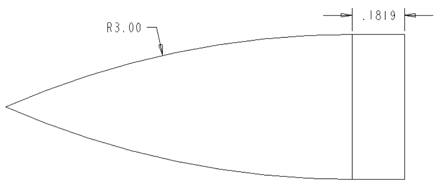


Figure 44: 6S Spitzer Ogive

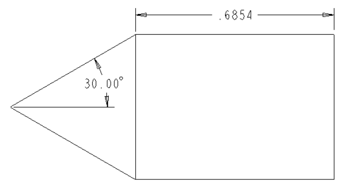


Figure 45: Cone

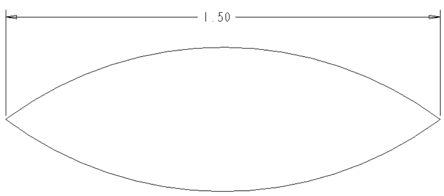


Figure 46: Double Ogive

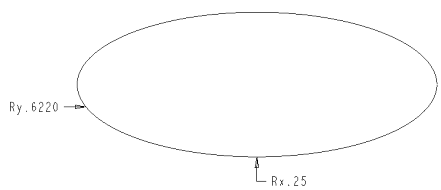


Figure 47: Ellipsoid

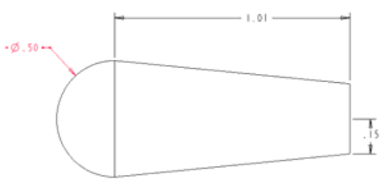


Figure 48: Teardrop Shape

Glossary

FPS: Feet Per Second; A common measurement of muzzle velocity.

COTS: Commercial-Off-The-Shelf; available for purchase without custom manufacturing.

NPT: National Pipe Thread; a standardized 60-degree thread pattern with a 1.7899-degree taper used in the United States to hold pressurized vessels together.

HDPE: High Density Polyethylene; a common plastic used for its ease of manufacture, high strength, low cost, and light weight

Bench-rest: A testing position for a paintball marker in which the marker is placed in a vice on a steady firing platform, such as a bench or table.

Muzzle Velocity: The speed of the paintball when it exits the barrel. As a matter of safety, all paintball markers are tested once per game by using a radar chronograph to ensure that it is not in excess of 300 feet per second.

Airsmith: A technician who builds and repairs paintball markers and accessories.

PTFE: Polytetrafluoroethylene; developed by DuPont and commonly marketed under name "Teflon." Having a density of 0.0795 lb/in^3, it is lightweight and has very low coefficients of friction.

Venturi Tubes: An array of holes cut in a pattern so that it reduces the Reynolds number of passing flow to the point that turbulent flow becomes laminar.

Internal Ballistics: The study of how a projectile interacts with the barrel, the bolt, and the propellant.

External Ballistics: The study of how a projectile interacts with the flight medium, in most cases, air.

Terminal Ballistics: The study of how a projectile impacts with its target.

Caliber: A measure of the diameter of a projectile, when viewed from the front, measured in decimal-inches. For example, 68 caliber means that the projectile is .68 inches in diameter.

Barrel: A pressure vessel that carries a projectile along a tubular path, powered by pressure on one side of the projectile and atmospheric pressure on the other.

Bore Diameter: Diameter of a barrel measuring from the top of one land to the top of the opposing land

Groove Diameter: Diameter of a barrel measuring from the bottom of one groove to the bottom of the opposing groove.

OAL: Overall Length. The total length of the object

OD: Outer Diameter. The distance across a round object as measured from the outside

ID: Inner Diameter. The distance across a round hole

Threadlocker: An adhesive solution that is activated when oxygen is not present. It is used to make an inner thread and an outer thread in stick to one another, and thus lock a screw into place.

TPI: Threads Per Inch. It is a measurement of how tight the twist on a screw is

UNC: United National Coarse. It is the large-thread, low-TPI standard threading system in America and all places that use Imperial Units.

Works Cited

1. Jones, Franklin D., and Henry H. Ryffel. Machinery's Handbook. Machinery's Handbook. 28th ed. 2008

2. Francis, Mouton R. Methods in Exterior Ballistics. Chicago: University of Chicago Press, 1926.

3. 1998-1999 Special Edition. Ed. John Amodea. 1999. Paintball Competitions and Ratings International. 26 Aug. 2007 <http://www.pcri.net/specialedition4.htm#paintballs4>.

4. Pelletier, B. B. How are barrels rifled? 2 Oct. 2006. Pyramyd Air. 15 Apr. 2008 <http://www.pyramydair.com/blog/2006/09/how-are-barrels-rifled-part-1.html>.

5. Voils, Dan. Marker Animations. ZDS Paintball. 14 Apr. 2008 <http://www.zdspb.com/tech/misc/animations.html>.

6. Kolbe, Geoffrey. "Making of a Rifled Barrel." 2000. 7 Apr. 2008 <http://www.firearmsid.com/Feature%20Articles/RifledBarrelManuf/BarrelManufacture.htm>.

7. Hoerner, Sighard F. Fluid-Dynamic Drag. Hoerner Fluid Dynamics, 1958.