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Abstract

This report details the process undertaken in order to design a small prototype two-stage gas gun capable of firing small projectiles at low supersonic speeds. This project has run serval times before but the goal of firing projectiles at supersonic velocities has never been reached. This project aims to achieve this goal through simplification of the design.

The process begins with the theory behind gas guns being discussed and the relevant information utilized to aid in the design of this prototype. Analytical and numerical analysis of the gun is performed to illustrate the effect that certain parameters have on the overall performance. Optimisations using both of these models were used to aid in the design of serval components. Concepts designs are shown, a final detailed design is described, and design decisions are explained regarding each component.

This report then goes on to describe the testing procedure and discusses the results. The findings are analysed and any trends that appeared are described. Finally, a conclusion is drawn that the project was an overall success as the main goal of firing projectiles at supersonic speeds was reached. The project as a whole was a successful iteration of this ongoing gas gun project and any recommendations that could help with the subsequent iteration are made.

Acknowledgements

First and foremost, I would like to thank my supervisor Mr Trevor Cloete for pushing me to achieve my best and for allowing me to grow and learn as an engineer throughout this project. Under his guidance I was able to achieve my best and his endless patience allowed me to independently formulate solutions.

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Project Brief

In order to improve the design of protective structures, such as sporting helmets and body armour, it is important to have detailed knowledge of the way structures respond to projectile impact events. To do this, a laboratory scale projectile launcher is required. The Blast Impact and Survivability Research Unit (BISRU) has a gas gun to launch sabot mounted projectiles to high subsonic speeds (up to 270 m/s) using air at a pressure of 30 bar. However, supersonic speeds are not attainable due to limiting factors, such as the initial pressure and temperature of the driving gas. Producing static high gas pressures and temperatures is expensive and potentially dangerous. An alternative is to use a two-stage gas gun, where a reservoir filled with relatively low-pressure gas is used to accelerate a free piston. The kinetic energy of the piston is then used to rapidly compress a second volume of gas to high pressures and temperatures, which is immediately used to accelerate the projectile. Previous prototype two-stage gas guns developed at BISRU have produced gas at a high temperature and pressure but proved to be over complicated and failed to meet the required performance. The aim of this project is to design, modify and test a simple small prototype two-stage gas gun to launch a small projectile up to supersonic speeds using only compressed air at 10 bar.

Contents

List of Figures

List of Tables

Nomenclature

Symbol	Unit	Definition
P	Pa	Pressure
V	m^3	Volume
n	mol	Number of moles of gas
R	J/kg.K	Ideal Gas constant
T	K	Temperature
γ	-	Ratio of specific heats (C_p/C_v) – isentropic gas constant
m	kg	Mass
v	m/s	Velocity
E_k	J	Kinetic energy
a	m/s^2	Acceleration
A	m^2	Area
L	m	Length
W	J	Work done
x	m	Displacement
t	s	Time
F	N	Force

1 Introduction

This final year project entails designing, building and testing a small prototype two-stage gas gun that will be used in the Blast Impact and Survivability Research Unit (BISRU) at the University of Cape Town. A two-stage gas gun is a device that is used to fire small projectiles up to supersonic velocities by using two different gas chambers as well as a free piston and finally a small projectile. The gas in the first chamber, referred to as the first stage, is the input to the system and contains the driver gas. This gas is used to accelerate the free piston which moves along the section of the gun called the pump tube. As the piston moves along it compresses the gas in the second stage of the pump tube. This gas is compressed to a desired pressure and then used to accelerate a projectile in the last section of the gun called the launch tube or barrel [1]. This project has run several times previously and will hopefully continue to run in the future. Therefore, any design decisions, influential factors or important observations are clearly explained in order to aid future projects.

1.1 Project Scope and Goal

There are several design constraints associated with this particular project that outline the scope. There is a spatial constraint that limits the overall length of the gun to be at most 3 - 4 m in length as well as a functional constraint that only air can be used as the gas in both stages. Air was selected as it is readily available, non-toxic and inexpensive, making it safe to use by students as well as cost effective in terms of the final year project budget. The driver gas is limited to a pressure of 10 bar (1 000 kPa) which will be the input to the system and is used as the means to accelerate the piston. 10 bar pressure is used as BISRU has an available gas compressor rated for this pressure, as well as it being a commonly used value in industry. The gas in the second stage will be at atmospheric pressure initially and then rapidly increase to extremely high pressures during the firing process. The projectile shall accelerate without the use of a sabot to aid it and the piston (or a portion of it) is designed to be consumable and so will need to be replaced if the deformation prohibits it from functioning correctly. There have been three previous final year project attempts at designing a two-stage gas gun that is capable of firing projectiles at supersonic velocities .

However, these attempts were unsuccessful in reaching their desired goal mainly due to the design constraint that a re-usable piston had to be incorporated which in turn made the design too complex. Therefore, this project uses a simpler design in the hope that a successful outcome will be achieved and the insight will be used to gain knowledge on this subject that was lacking in previous attempts.

The scope of this project therefore includes designing the gas gun according to the above-mentioned constraints, measuring the projectile's velocity as it leaves the launch tube as well as to analyse and record data on each component after every fire. The following is not included in this project's scope but may be included in following years; the analysis and inclusion of pressure waves that occur during the projectile's acceleration, the combination of the previous final year student's code to aid in the analysis of the gun's operation as well as providing detailed analysis and measurement of the piston's and projectile's displacement and velocity during travel along their respective tubes.

The main goal of this project is to design a gas gun that can fire projectiles at rifle velocities which range from 400 – 700 m/s and any muzzle velocity above Mach 1 (the speed of sound in air - 343 m/s) will be deemed successful. Another goal is to gather data on how the gun performed as it is the hope that the gun will be used to further research in other areas such as human bone behaviour when impacted with low supersonic projectiles, as well as to test materials used for body armour and other protective gear. The long-term goal of a project such as this is to learn and understand more about complex gas dynamics that a system like this entails. As well as to eventually construct a fully functional small-scale gas gun capable of repeatedly firing supersonic projectiles which will be used to gather data in the above-mentioned fields. Even more so to hopefully lead to designing and building a large scale two-stage gas gun that can fire projectiles at extremely high hyper velocities. This project could even extend to allow for a better understanding of shock and pressure waves that result from this type of rapid increase in pressure and potentially also extend to the designing and building of shock tubes.

2 Literature Review

The literature that was reviewed was mainly focused on current and previous working gas gun models in order to identify several key aspects of each design that could be used to assist this prototype. The review firsts examines all applicable theory of gas laws, single stage models and finally two-stage designs. It then looks at the significant differences between single-stage and two-stage gas gun designs and then finally goes into detail of current two-stage working models.

2.1 Key Thermodynamic Theory

As gas is the means of operation in two-stage gas guns the relevant theory will be discussed in order to allow for a basic understanding of the principles used. The formulas shown below are the foundation of the theory used in the design and understanding of two-stage gas guns and will be referred to several times throughout this report.

The expansion and compression of the gas in both stages is assumed to be isentropic. This assumption is made in all the literature reviewed as in the first stage the velocity of the piston is much lower than the speed of sound in the propellant gas [2]. The assumptions and omissions used in the second stage will be explained in the following section. Thus, the pressures and temperatures can be determined using the below thermodynamic theory formulas [3] where a subscript of '0' represents the initial value. γ is the ratio of specific heats and is 1.4 for air.

$$PV = nRT \tag{1}$$

$$\frac{P_0}{P} = \left(\frac{V}{V_0}\right)^{\gamma} \tag{2}$$

$$\frac{P_0}{P} = \left(\frac{T_0}{T}\right)^{\frac{\gamma}{\gamma-1}} \tag{3}$$

The work-energy relationship is another key component that makes up the foundation of this subject and the equations used throughout are as follows [3];

$$F = P.A \tag{4}$$

$$E_k = \frac{1}{2}mv^2 \tag{5}$$

$$Work = F.x = \int P\,dV = A\int P\,dx \tag{6}$$

2.2 Basic Theory of Single-Stage Gas Guns

Two-stage gas gun designs are based off the simpler single-stage models, hence the theory concerning single-stage guns will be utilised to gain an understanding of how these types of devices operate. A single-stage gas gun makes use of pressurised gas in a reservoir to accelerate a projectile directly as can be seen in Figure 1 below.

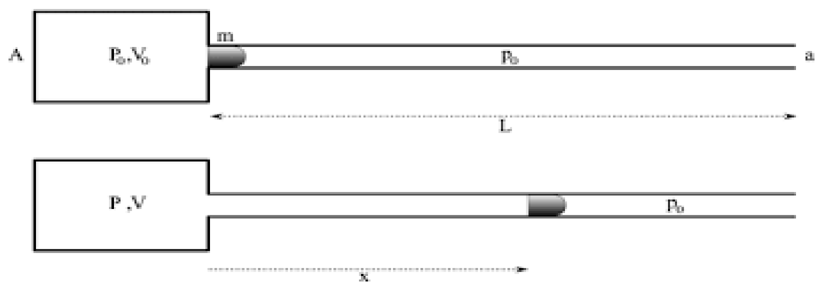


Figure 1: Single-Stage Gas Gun Design [4]

There are two modes of operation for single-stage gas guns, the first being that the reservoir is rapidly filled with a high-pressure gas and the projectile is accelerated simultaneously due to this sudden increase in pressure. The second mode is where the reservoir is pressurised beforehand, and a release valve is used to expose the projectile to the high-pressure gas causing it to accelerate. Both of these modes use the same working theory. The projectile's acceleration and velocity can be calculated using a Newtonian method shown below where a_p is the acceleration of the projectile, A and L are the area and length of the launch tube, m is the mass of the projectile and ΔP is the pressure difference between the front and the back of the projectile [5]. The work that is done on the projectile by the gas is equal to its kinetic energy (ignoring any losses), as the projectile starts from rest, which allows a formula for the projectile's velocity to be derived.

$$a_p = \frac{\Delta P.A}{m} \tag{7}$$

$$Work = \int P\,dV = A\int P\,dx = \frac{1}{2}mv^2 \tag{8}$$

$$\therefore v = \sqrt{\frac{2.\Delta P.A.L}{m}} \tag{9}$$

Equation 9 highlights the factors that must be manipulated in order to achieve the desired muzzle velocity. This can be done by decreasing the mass of the projectile, increasing the length of the launch tube (for a given cross sectional area) and finally by increasing the propelling pressure (base pressure) of the driving gas. However, as the projectile travels down the launch tube and the volume increases the base pressure will naturally decrease accordingly [6].

Using Equations 2, 6 and 8 as well as the assumption that all the energy that the gas has is transferred to the projectile by doing work on it, thus increasing its kinetic energy (again ignoring losses due to friction or heat). The following formula for the work done can then be derived;

$$Work = \int_{V_0}^{V} P_0.\left(\frac{V_0}{V}\right)^{\gamma}\,dV = \frac{1}{2}mv^2 \tag{10}$$

Evaluating to give a final answer of;

$$W = \frac{P_0V_0}{\gamma-1}\left[1-\left(\frac{V}{V_0}\right)^{1-\gamma}\right] = \frac{1}{2}mv^2 \tag{11}$$

Replacing the volume with the initial and final distance;

$$W = \frac{P_0V_0}{\gamma-1}\left[1 - \left(\frac{X}{X_0}\right)^{1-\gamma}\right] = \frac{1}{2}mv^2 \tag{12}$$

Re-arranging Equation 12 in terms of velocity;

$$v = \sqrt{\frac{2.P_0V_0}{(\gamma-1)m}}\sqrt{\left[1 - \left(\frac{X}{X_0}\right)^{1-\gamma}\right]} \tag{13}$$

Hence Equation 13 gives a clear indication that the initial volume, pressure and length as well as the final length are the main factors that influence the velocity.

2.2.1 Shortcomings of a Single-Stage Model

Now that the relevant factors have been identified the final achievable velocity can be determined to judge if a single-stage model is suitable for this application. If one were to use a single-stage gas gun under the specific constraints of this project (10 bar initial pressure, length of 3 m as well as a small diameter projectile of, for example, 10 mm and weighing roughly 10 g) as well as the overall goal of supersonic velocities (343 m/s), the achievable velocity using Equation 13 is hence;

$$\therefore v = \sqrt{\frac{2.(1000\ 000).\pi(0.005)^2.(3)}{0.01}} = 217 \text{ m/s}$$

Thus, demonstrating that to achieve supersonic velocities much higher pressures would need to be used. Adding to this, the velocity shown here is assuming a constant base pressure throughout the entire launch of the projectile and does not take into account any frictional or heat losses. Hence, it is mainly for this reason that a single-stage gas gun cannot be used in a project of this nature as it is unlikely to reach the main goal.

2.3 Single-Stage versus Two-Stage Gas Guns

As discussed above the design of a single-stage gas gun has short comings with respect to the goal of this particular project. It is illustrated here in Figure 2 the key difference between single and two-stage gas guns. Single-stage gas guns have a sole pressure reservoir that contains a pressurised gas that accelerates the projectile directly. A two-stage gas gun is based on the single-stage design with the addition of a free piston and a second reservoir of gas arranged as shown in Figure 2. The two types of guns are however two-stage gas guns use the piston to compress the second stage gas and it is this rapid compression that allows the second stage to reach high pressures and temperatures, thus allowing for the supersonic velocities desired [2]. This will be further discussed in the next section.

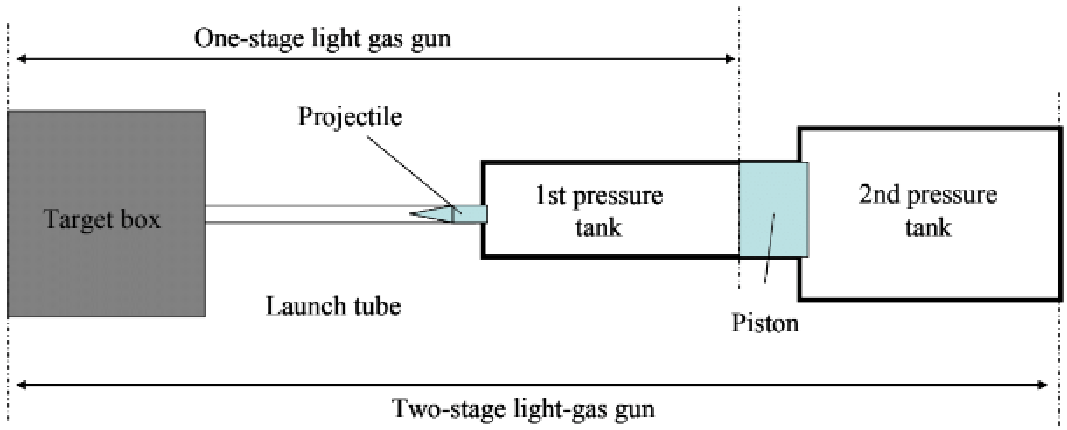


Figure 2: Single-stage vs Two-stage Gas Gun [2]

2.4 Theory of Two-Stage Gas Guns

As the single-stage gas gun theory has been evaluated, it can now be applied to two-stage models. A two-stage gas gun is a modified version of a single-stage gas gun that allows for higher muzzle velocities to be achieved by using a free piston to compress the gas in the second stage thus allowing for higher pressures to be reached. The theory used to design two-stage gas guns can be divided into two main sections, the pump tube and the launch and will be discussed separately below.

2.4.1 The Pump Tube

The main focus in a two-stage gas gun is the pump tube where both the first stage and second stage chambers are housed as can be seen in Figure 3 below.

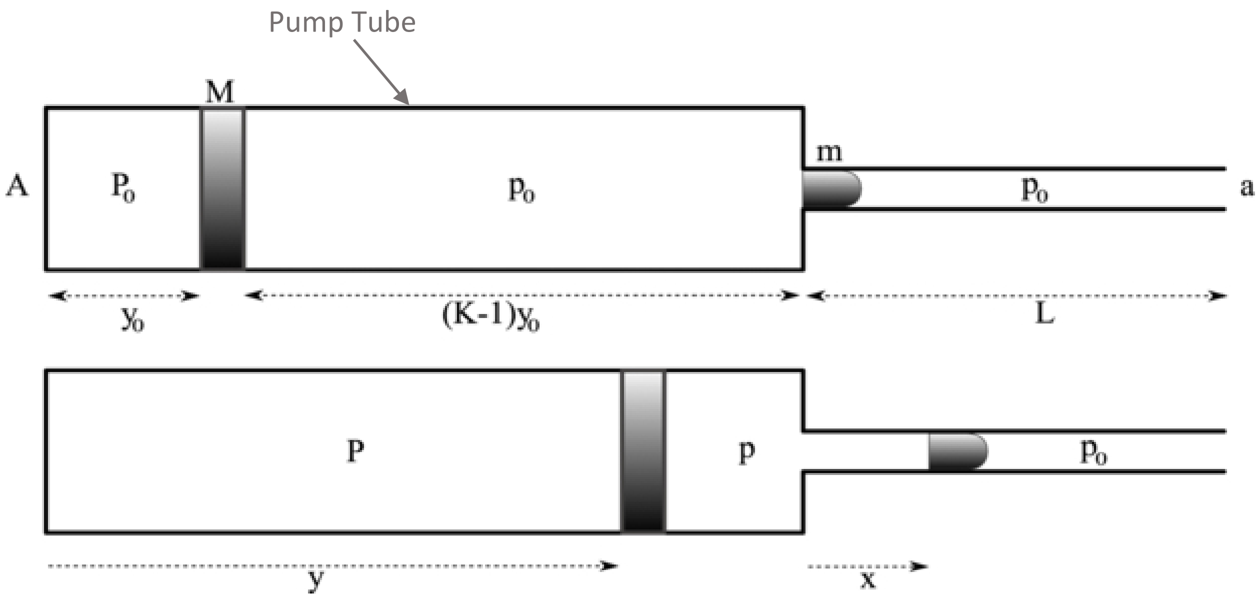


Figure 3: Basic Configuration of a Two-stage Gas Gun [4]

A first approximation approach is used to model the first and second stage gases as ideal, adiabatic and isentropic. Therefore, thermodynamics Equations 1, 2 and 3 can be applied in these sections using zero-dimensional expressions for mass and energy conversion [2]. Due to the assumption that the process is isentropic, heat transfer and friction losses are ignored in this basic first analysis. The acceleration of the piston is caused by the pressure imbalance between the two stages of the gun as the first stage is where the high-pressure gas is applied, and the second stage contains a low-pressure gas. By using a low initial gas pressure in the second stage (atmospheric pressure is used in this project) larger compression ratios can be achieved hence enabling higher pressure and temperature differences to be reached in the second stage [1]. This approach also uses the ideal scenario where all the kinetic energy of the piston is converted into work done on the second stage gas, again ignoring any losses. This method is appropriate for the initial design of this project as it allows for basic sizing to be done in order to give an indication if the desired muzzle velocities can be achieved while conforming to the given constraints.

The work-energy relationship also plays a vital role in the two-stage design and the different forms of energy can be analysed and used to determine the muzzle velocity of the projectile. The pump tube section is simply a conversion between work and kinetic energy between the gases in each stage and the free piston in between. The first stage gas does work on the piston and thus increasing its kinetic energy and moving it along the pump tube, this kinetic energy is then used to do work on the second stage gas thus increases its pressure and temperature which is finally used to accelerate the projectile in the launch tube [1].

2.4.2 The Launch Tube and Gas Dynamic Theory

The launch tube section of the gun is more complex as gas dynamics affect the projectile as it is accelerating due to the sudden pressure increase. As a results of this, there will be acoustic disturbances involved in this section.

When the projectile begins to move there is a rarefaction disturbance that is sent back at the speed of sound into the gas behind it causing an infinitesimal pressure drop in each layer of gas as can be seen in Figure 4. Although these disturbances are infinitesimally small, due to the fact that there is an extremely large number of them finite changes occur. There is a limiting case to this when the gas has expanded to a point where there can be no more pressure drop. Hence, there is no more force being exerted on the projectile and subsequently it is actually the speed of sound of the gas that will limit the muzzle velocity of the projectile as it is at this point (P = 0) where the projectile will reach its maximum velocity [6].

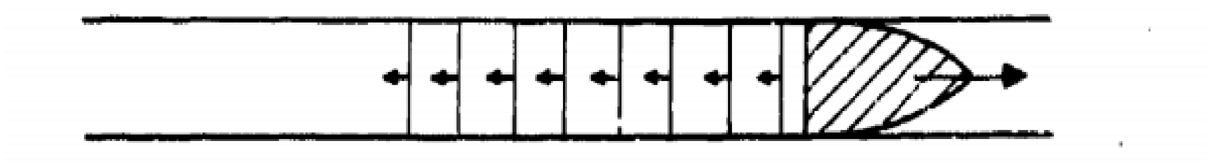


Figure 4: Rarefaction Disturbance Traveling Through the Gas [6]

This maximum velocity of the projectile can then be found using gas dynamic theory [4];

$$v_{max} = \frac{2}{\gamma-1}\sqrt{\gamma.R.T} \tag{14}$$

where $\sqrt{\gamma.R.T}$ is the speed of sound in the gas.

Hence, for the given constraint of using air at ambient temperature the maximum possible velocity of the projectile can be determined;

$$v_{max} = 1715 \text{ m/s}$$

As one can see the maximum achievable velocity is well above the goal velocity for this project and hence it can be deduced that Mach 1 is achievable using air as the medium for the second stage gas. However, it must be noted that to actually reach this velocity the barrel of the gun would have to be impractically long.

There are several means of mitigating the effect of complex gas dynamics however, for the purpose of this project detailed gas dynamics will not be included in the analysis or design as they are exceedingly complex. It can also be seen above that they are not the limiting factor in the design in terms of the maximum muzzle velocity and as a result are placed outside of the scope.

2.5 Current Two-Stage Gas Gun Designs

Current models of two-stage gas guns are discussed in the following section in order to utilize key aspects from working designs for this prototype. Majority of the two-stages gas guns currently in existence are large-scale and can span over 12 m in length on the launch tube alone and are capable of firing projectiles up to 9 km/s [3]. These designs analyse and vary several parameters that are applicable to this prototype project which will be discussed in detail below. They also have many design features that cannot be applied to this project, although they are still stated below in order to grasp a better understanding of all the internal workings of these devices.

The main parameters that current models design around are the lengths of the pump tube and barrel, initial pressure and temperature of both the first stage and second stage gases as well as the piston mass [7]. These were therefore also the focus of this prototype design as these parameters are within the scope of the project.

It can be seen in these designs that the initial second stage gas conditions have to be examined in detail as the initial pressure of the gas has a substantial influence on the muzzle velocity. It is explained in the literature that the lower the initial pressure of the second stage gas, the higher the pump rate/pressure gradient is [2]. This increase in pump rate will cause the projectile to accelerate earlier in the launch cycle, even before the piston has collided with the transition piece. The piston therefore continues to compress the gas which causes a higher average base pressure at the projectile, thus causing a high muzzle velocity. However there is a limit to this when the initial pressure is so low that there is an insufficient quantity of gas to maintain the base pressure for the entire launch of the projectile [2]. This is useful as the prototype will be using air at atmospheric pressure in the second stage and so a relatively low pressure is already incorporated into the design which is now shown to have a positive effect on the outcome.

The piston itself is an influential factor in the design and most working designs use a deformable piston, which is also employed in this project. Piston mass is an additional consideration as it influences the velocity at which the piston collides with the end of the pump tube and it should be sized in a way that allows for most - if not all – of the kinetic energy to be transferred from the piston to the second stage gas before it reaches the end of its stroke. The piston design revolves around its kinetic energy as it must have sufficient energy to compresses the gas to the desired point. If the piston is too light, it decelerates too quickly hence reducing the pump rate, while too heavy a piston requires unnecessary energy to accelerate and thus lowers the piston's velocity hence reducing the pump rate again [2]. The influence of piston mass (as well as projectile mass) will be illustrated in the numerical modelling section of this report as decreasing the projectile mass has also been proved to increase the muzzle velocity [7].

The length of the pump tube is a major factor when designing two-stage gas guns. There is an optimisation that needs to be done on the length, as it needs to be long enough such that the piston can complete its stroke, however making it too long is shown to reduce the muzzle velocity of the projectile [7]. Therefore, for a given pressure condition the pump tube length should be made as short as possible that will still allow the piston to complete its stroke and compress the second stage gas to the desired point. It is shown that the piston must be driven 'harder' – meaning a higher first stage gas pressure must be used - to achieve the same muzzle velocity for an increased pump tube volume [8]. Hence a smaller pump tube volume would be more ideal.

Another key section of the design is the connection between the pump tube and the launch tube. Current designs have a transition section between the two tubes that is used to stop the piston. These designs use a tapered transition section (a semi conical shape) which not only stops the piston form rebounding but also 'plugs' the end of the pump tube thus forcing all the second stage gas into the launch tube [9]. This is particularly useful for this project as piston rebound has been a design factor in previous projects as it creates back pressure which consequently slows down the projectile.

The angle of this conical section has also been shown to influence the pressure increase during the firing process. A larger angle used (closer to 60° compared to 12°) creates a smoother rise in pressure - which is useful if the projectile is fragile - due to a reduction in the shock focusing action of the cone. However, the actual base pressure at the projectile does not differ significantly with an increased cone angle [7]. The length of the conical section is also a factor as for higher energy shots it has been shown that the deformable plastic section of the piston can extend past the conical section and into the barrel and although this does not have a great effect on the outcome, it will complicate the dismantling process [8].

There are several design features that cannot be incorporated into this prototype design but are still noteworthy and must be discussed. Almost all working designs use a light gas such as helium or hydrogen in the second stage as it is easier to accelerate a gas with a lower molecular weight – therefore more energy available to accelerate the projectile. As well as the speed of sound in these gases are higher than that of air (as discussed previously the medium affects the final velocity) and thus having a lighter gas allows for a higher muzzle velocity to be achieved [2]. They also employ gun powder to accelerate the piston in the first stage in combination with pressurised gas and the powder burn rate is shown to also have an effect on the final velocity of the projectile. This explosion rapidly accelerates the piston which leads to higher pump rates in the second stage gas [7]. The first stage gas is also heated to higher initial temperatures which is shown to increase the velocity gain, for a given pressure loss, as it allows for higher final temperatures to be reached [2].

Adding to this there are several designs used in order to separate the second stage gas from the projectile. One common technique uses a diaphragm/valve at the entrance to the launch tube that bursts/opens at a specific pressure allowing the projectile to accelerate down the launch tube only when a high enough pressure has been reached [8]. However, in this project the projectile is free to move as the pressure builds up as when the pressure spikes it causes the projectile to accelerate rapidly and consequently no diaphragm is needed [2], this will be shown in the numerical model in the following chapter. Many designs also evacuate the launch tube in order to minimise drag effects and increase projectile velocity as well as use sabots in order to aid in the acceleration [9].

Therefore, following the review of relevant literature and the examination of detailed working designs, all the influential design parameters applicable to this project can be included in the design. Basic calculations can now be done based on the equations mentioned in this chapter and can be used to guide the design into isolating certain parameters that are crucial in controlling the muzzle velocity. Comparing the method undergone to that used in already successful models is a useful way to ensure that the most pertinent parameters are being optimised to full effect.

3 Basic Sizing

The overall approach taken in order to complete the basic sizing of the prototype will now be discussed. First the relevant pressure vessel law is consulted as the maximum volume of the reservoir needs to be determined before any other calculations can be performed. Subsequently the maximum theoretical limits are calculated to check that the goal velocity is possible under these design constraints.

3.1 Pressure Vessel Theory

As we are dealing with pressurised gas, the relevant pressure vessel law needs to be consulted. South Africa follows the standards found in SANS 347 and classifies pressure vessels as housings that are designed and manufactured to contain a fluid under a pressure greater than or equal to 50 kPa (0.5 bar). The gas used in this project in the first stage is air at a pressure 10 bar (1 000 kPa) hence the following graph (Figure 5) can be used to determine the maximum volume of the reservoir of gas used as air is classified as a non-dangerous gas. The design needs to remain in the Sound Engineering Practice (SEP) portion of the graph, which is to the left, to warrant safe operation. Using Figure 5, it can be read off that a volume of 5 litres (0.005 m^3) or less will be the allowable maximum initial volume of the first stage [11].

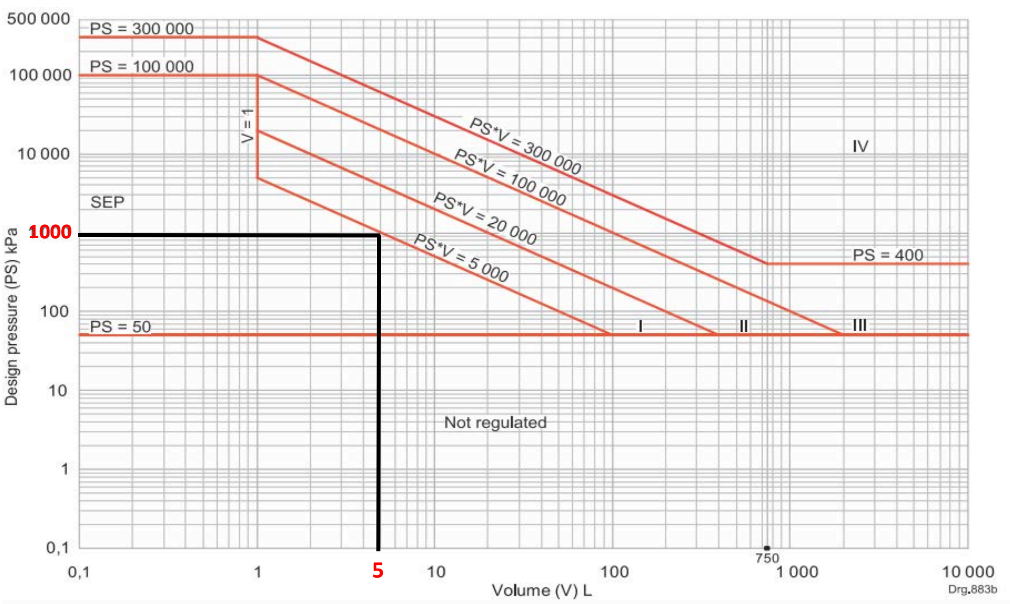


Figure 5: Pressure Volume Relationship for a Non-Dangerous Gas [11]

Due to the fact that the firing procedure of gas guns is inherently an exceptionally fast process the remaining sections of the gun (pump tube and launch tube) do not need to conform to these standards as the pressure formed in them will not be contained for a significant length of time (only milliseconds). Any longer and the gun is designed to leak as a default method of relieving the pressure ensuring no static pressure can be held hence safety is guaranteed to the highest possible degree. Thus, the volumes of these sections are not limited by these standards.

3.2 Maximum Theoretical Limits

The maximum limits for work and velocity are calculated now in order to determine if the specific design constraints allow for a desirable result. The maximum work comes from Equation 11;

$$W_{max} = \frac{P_0 . V_0}{\gamma - 1} = 12.5 \text{ kJ} \tag{15}$$

Using this maximum amount of work and assuming no losses throughout the entire process (as discussed previously) the muzzle velocity of the projectile can be calculated using different projectile masses.

$$\therefore v_{muzzle} = \sqrt[2]{\frac{2W_{max}}{m_{projectile}}} \tag{16}$$

It was seen from this equation that the maximum mass of the projectile was 150 g in order to allow for a muzzle velocity above Mach 1. This was deemed acceptable as most working gas guns use projectiles weighing less than 10 g [10]. Since the maximum velocity using gas dynamic theory has already been calculated using Equation 14 and shown to be far above the aim of 343 m/s, it can be deduced that theoretically a two-stage gas gun under these specific design constraints has sufficient energy to fire a supersonic projectile.

Now that maximum values have been determined and seen to be above the goal, more realistic values have to be calculated. This is done first analytically using Equation 12 and the work-length relationship as well as using numerical modelling to included factors such as mass.

3.3 Analytical Approach

Using a purely work and energy approach the final muzzle velocity of the projectile can be calculated. This method uses a step by step procedure to calculate the different pressures, temperature, work and velocity at each stage in the gun using different length ratios ($\frac{X_0}{L}$ and $\frac{X_f}{L}$). These length ratios therefore gave an indication of how long the pump tube needed to be in order to achieve the desired muzzle velocity. Equation 2, 3 and 12 were at the root of this method and were adapted in several different ways in order to isolate the terms needed, they are given below again for reference purposes.

$$\frac{P_0}{P} = \left(\frac{V}{V_0}\right)^{\gamma} \tag{2}$$

$$\frac{P_0}{P} = \left(\frac{T_0}{T}\right)^{\frac{\gamma}{\gamma-1}} \tag{3}$$

$$W = \frac{P_0 V_0}{\gamma - 1}\left[1 - \left(\frac{X}{X_0}\right)^{1-\gamma}\right] = \frac{1}{2}mv^2 \tag{12}$$

The above method gave the highest maximum velocity using an initial pressure of 10 bar to be 741 m/s, with a final pressure of 30 bar in the second stage gas. It also gave the final temperature in the second stage to be 797 K. These values are encouraging and consolidate the fact that the goal of supersonic projectiles is reachable.

3.4 Numerical Modelling

A numerical model was developed in order to highlight which factors had the most influence over the final muzzle velocity, as well as to be used as a means to judge if the specific values chosen gave a suitable outcome. The Central Difference Method was used, and a Newtonian approach was adopted [12].

$$x_{n+1} = \frac{F}{m}\Delta t^2 + 2x_n - x_{n-1} \tag{17}$$

The equations of motion for both masses are;

$$m_1.\ddot{x}_1 = P_1.A_1 - P_2.A_2 \tag{18}$$

$$m_2.\ddot{x}_2 = P_2.A_2 - P_{atm}.A_2 \tag{19}$$

This allowed the acceleration of both the piston and the projectile to be calculated using the force exerted on them by the respective pressure as well as their mass. This acceleration was then integrated using the Central Difference Method to determine the velocity and displacement of each mass. The pressures at each displacement were calculated using an adaption of Equation 2. A note must be made that this model neglected retarding forces such as friction in both the pump and launch tube as well as energy lost as heat transfer. Therefore, this numerical model should result in an overestimation of the muzzle velocity.

3.4.1 Influential Input Identification

The Central Difference Method formed the basis of the numerical model and using this approach and the equations of motion numerous inputs were shown to be influential on the overall design. These inputs included; lengths and areas of the pump tube and barrel, masses of the piston and projectile, the total volume of the reservoir and the initial pressures in each stage.

The inputs that had fixed values due to project constraints were added first such as the maximum reservoir volume, the initial pressures as well as the ratio of specific heats. Values of inputs of certain components that were being re-used were also added in such as the pump tube, barrel and piston. The other inputs were given rough values (indicated in the Table 1) and then one input was varied at a time to see which gave the best result in terms of final muzzle velocity as shown in Table 2.

Table 1: Initial Rough Values of Inputs

Input	Value
Pump Tube Length	0.8 m
Barrel Length	2.9 m
Diameter of Pump Tube	0.05 m
Diameter of Barrel	0.01 m
Mass of Piston	524 g
Mass of Projectile	4 g
Length of Piston	0.2 m
Length of Projectile	0.03 m

Table 2: Effect of Inputs on Muzzle Velocity

Input Varied	Initial	Final	Result on Velocity (m/s)
Pump Tube Length	0.5 m	1 m	+ 232
Barrel Length	2 m	4 m	+ 87
Diameter of Pump Tube	0.05 m	0.08 m	- 34
Diameter of Barrel	0.01 m	0.02 m	- 157
Mass of Piston	800 g	300 g	+ 74
Mass of Projectile	3 g	1 g	+ 215
Length of Piston	0.170 m	0.250 m	- 38

As one can see from the table above the inputs that were the most influential were the length of the pump tube, the diameter of the barrel and the mass of the projectile.

Therefore, proceeding with the design there are several optimisations that can be done; the pump tube length should be maximised, the barrel diameter minimised as well as the projectile being made of a light metal and being as small as possible.

Another factor that was noteworthy was the mass of the piston. From the literature reviewed it was shown that the mass of the piston does play a significant role in the design as if the piston is too heavy it takes unnecessary energy to accelerate it however if it is too light it decelerates too quickly and hence does not compress the gas adequately [2]. This observation can also be seen in the code, illustrated below in Figure 6. However, the code does differ from literature as decreasing the piston mass actually increase the muzzle velocity without an apparent limit.

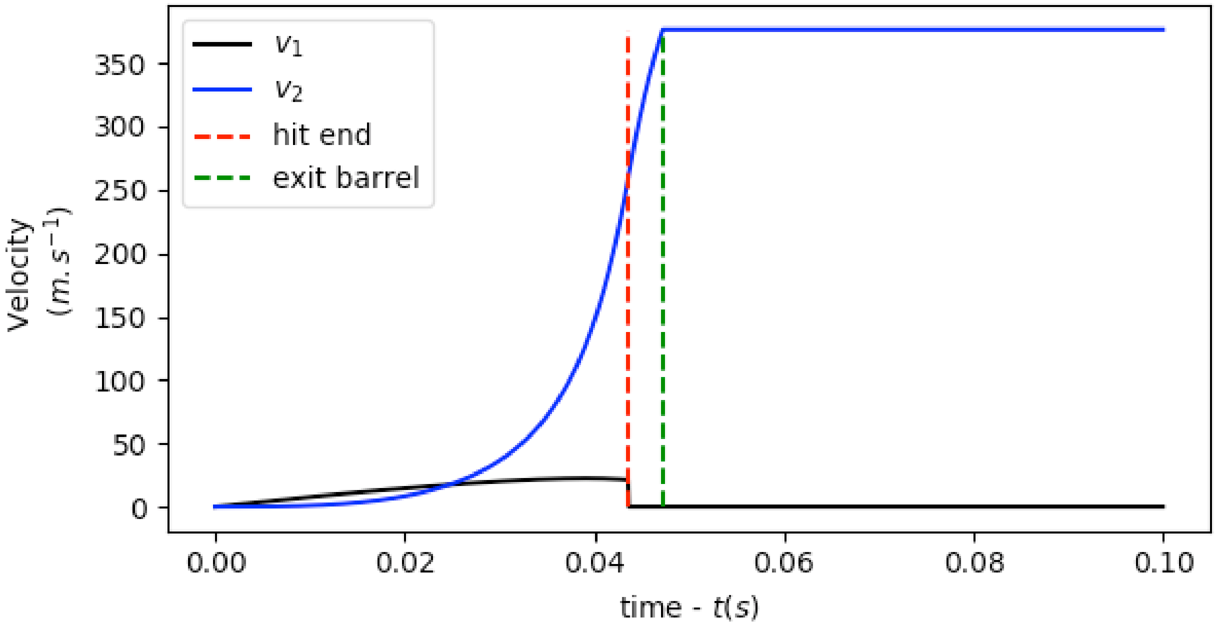


Figure 6:Velocity Graph of Heavy (2.5 kg) Piston

In Figure 6 the piston had a mass of 2.5 kg and from this it can be seen that it took much longer for the piston to complete its stroke (almost double when compared to a piston mass of 500 g). As well as the piston does not decelerate before hitting the end of the pump tube hence more damage would result from this collision as the piston would have more momentum and be traveling at a higher velocity. The piston is a reusable part from a previous project and so the mass was fixed at 425 g.

Another factor that is of interest is the barrel length. If the barrel is too short, it does not allow the projectile to reach its maximum velocity before it exists. Hence ideally the barrel should be made to an optimum length just as the projectile reaches its peak velocity. The barrel that will be used is 2.9 m long and the resultant velocities can be seen in Figure 7. This shows that the projectile does not reach its peak velocity before exiting hence the barrel is not at the optimum length.

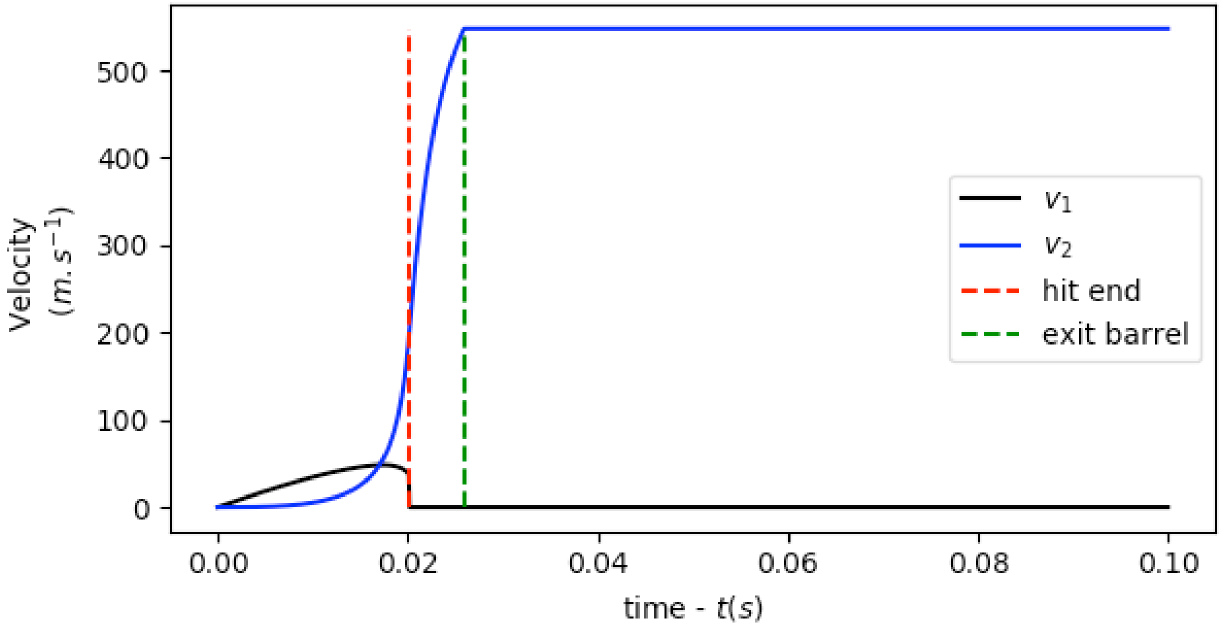


Figure 7: Velocity Graph of a 2.9 m Long Barrel

For the projectile to reach its peak velocity the barrel would need to be 12 m in length as shown in Figure 8. This length is impractical although would result in a 100 m/s increase in velocity.

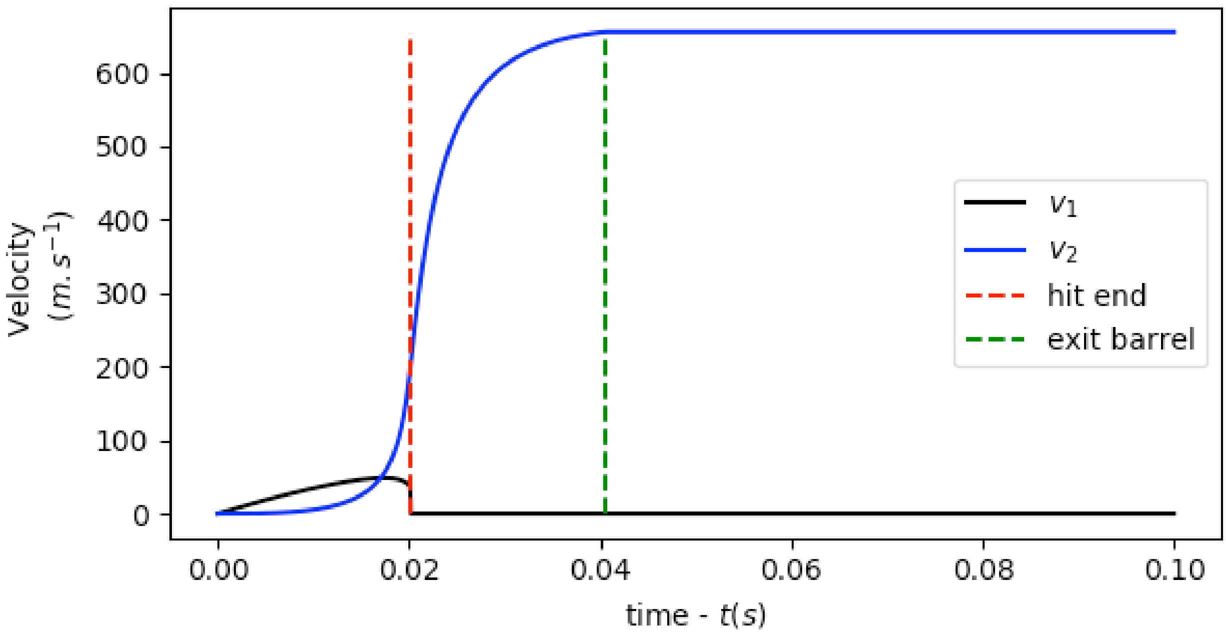


Figure 8: Velocity Graph of a 12 m Long Barrel

It can be seen from the simulations that after the length increases above 8 m the increase in velocity is less than 10 m/s for each meter and hence would not be worth the extra length. Therefore, numerically speaking the optimum length of barrel is 8 m although this is still an extremely long barrel to practically use.

3.4.2 Final Numerical Model After Completed Sizing

Now that key inputs were identified, combinations were examined in order to choose the most sufficient outcome. During this process the design phase had begun hence geometries of certain components that were being used from previous projects were included into the code to give a better approximation of how the gun would actually perform (the details of each component is to follow in the design chapter). The remaining inputs were varied to allow for the desired muzzle velocity to be reached and the final numerical model of the final design is shown below. Five graphs were plotted to see the displacement, velocity, pressure, temperature and volume of both the projectile and piston as well as both stages of the gun during the entire firing process.

The displacement graph of both the piston and the projectile is shown below.

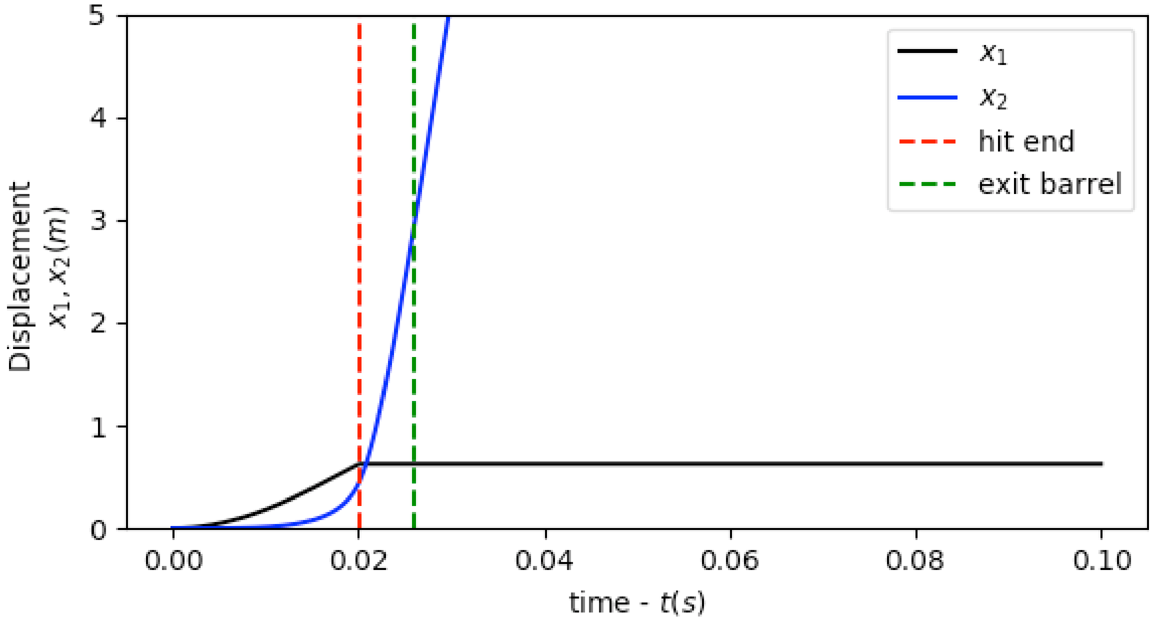


Figure 9: Final Displacement Graph of Piston and Projectile

As one can see the piston's displacement increases fairly constantly until it reaches the end of the pump tube where it becomes lodged in the transition piece. This is expected as the piston should have enough mass to keep accelerating for its entire stroke. Additionally, it is crucial to add that the projectile does not move a significant amount before the pressure spike as shown in Figure 10.

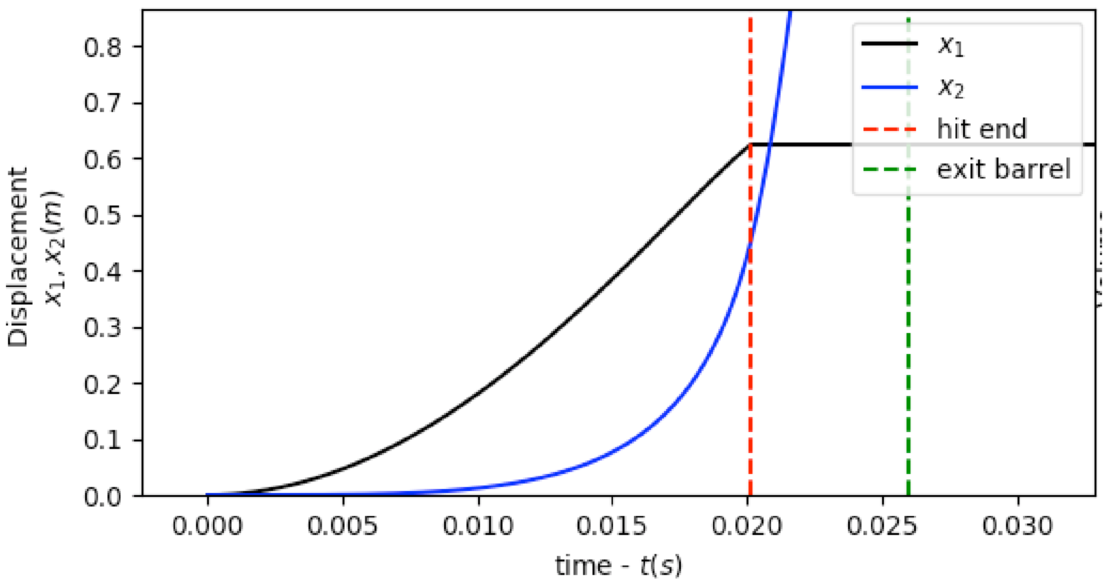


Figure 10: Closer View of Piston and Projectile Displacement

The projectile moves only a small amount, less than 15 cm before the pressure spike which occurs at roughly 0.018 s. Hence it can be reasoned that for this prototype project there is no need to have a diaphragm or control valve as it would not have great effect on the results. This is useful as a diaphragm would have to be designed to burst at a specific pressure as well as it would need to be replaced after every fire which would add to the assembly and dismantling process.

In terms of velocity, as discussed previously, it can be noted that the projectile does not reach its peak velocity before leaving the barrel thus ideally the barrel should be made longer. The projectile's velocity as expected suddenly increases rapidly during the pressure spike and reaches 547 m/s at its maximum, shown in Figure 11. It is to be noted that this model does not include the effects such as drag that occurs during the projectile's launch down the barrel.

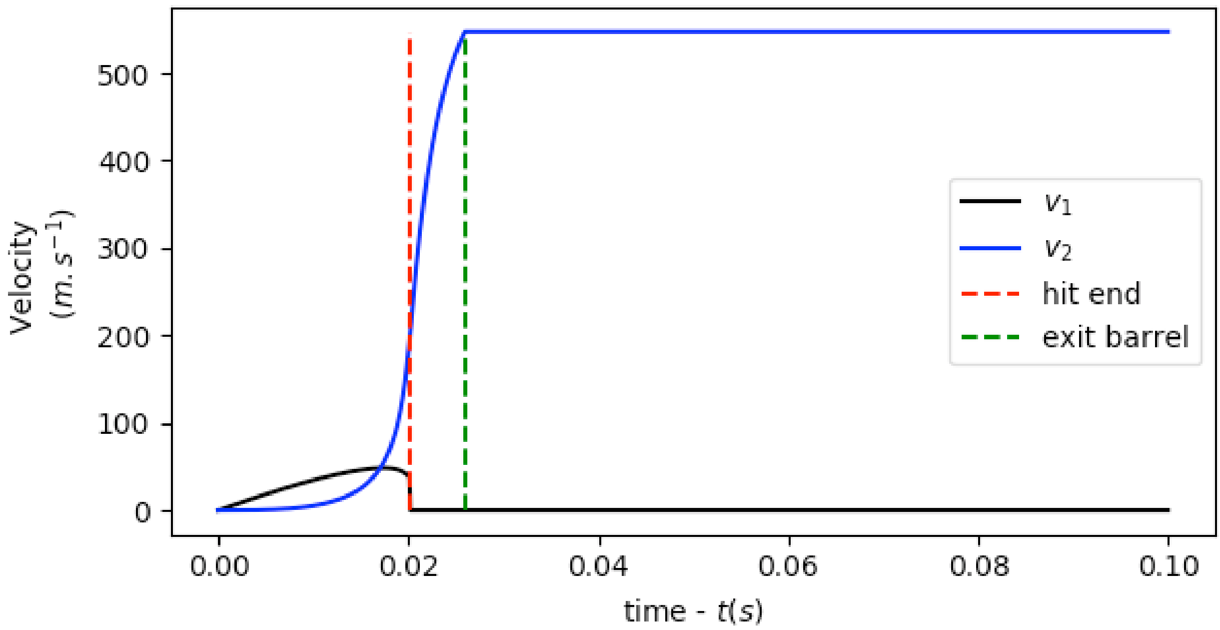


Figure 11: Final Velocity Graph Showing Both the Piston and Projectile

Referring to the piston it can also be seen that it reaches its maximum velocity before hitting the end of the pump tube and actually begins to decelerate before the collision which is advantageous as it will lessen the effect of the impact and damage to the end of the tube and transition piece. This also indicates that more energy is transferred to the projectile as the piston is decreasing in kinetic energy. Ideally it would be more advantageous to design the piston so that its comes to a complete stop before hitting the pump tube thus eliminating the potential damaged entirely and allowing all of its kinetic energy to be transferred to the projectile.

Turning to pressure, it can be seen below that the pressure of the first stage gas decreases from 10 bar to 8 bar while the piston is completing its stroke and settles when the piston comes to a stop. The second stage gas pressure peaks/spikes when the piston collides with the end of the pump tube which is an expected result. It then falls swiftly as the projectile accelerates down the launch tube and finally drops to atmospheric pressure when the projectile leaves the launch tube. As one can see the peak pressure is 42 bar, which allows for a satisfactory final velocity. This value also approximates the analytical model's predictions.

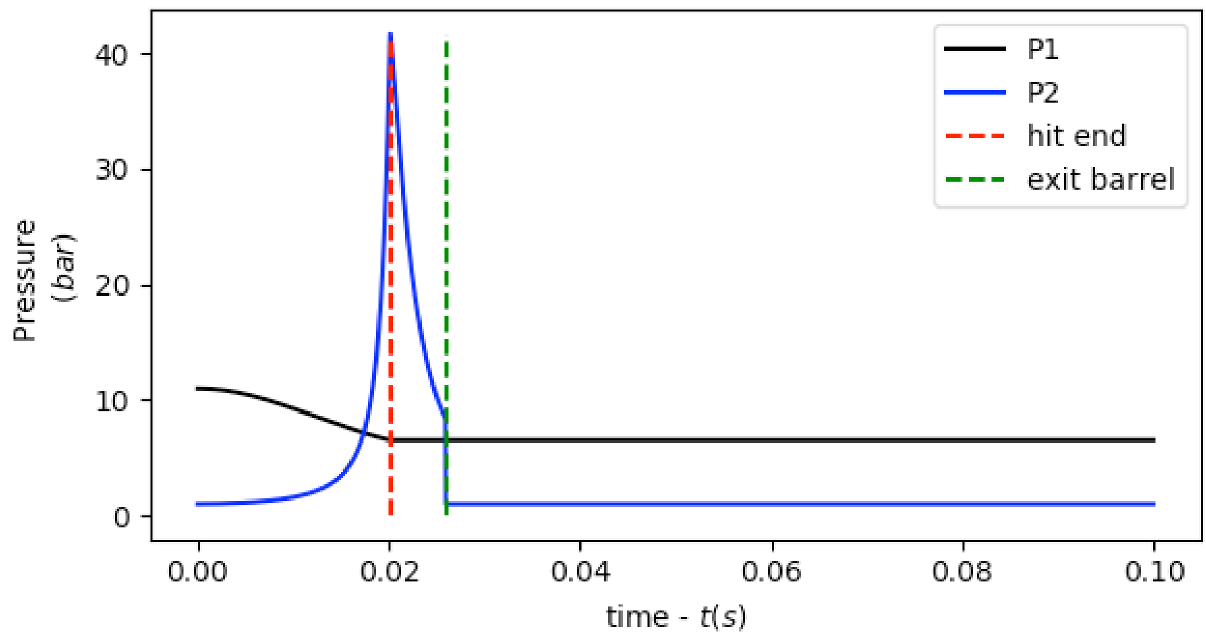


Figure 12: Final Pressure Graph Showing Both Gas Stages

The temperature of the second stage gas is shown below in Figure 13. The temperature follows the same rough path of the pressure and spikes during the collision of the piston and pump tube. This is again an expected result based on thermodynamic theory and the equations mentioned in Chapter 2. The peak temperature is 875 K which is fairly close to the analytical model's value of 797 K which is a positive outcome as it solidifies the fact that both models are predicating the same values.

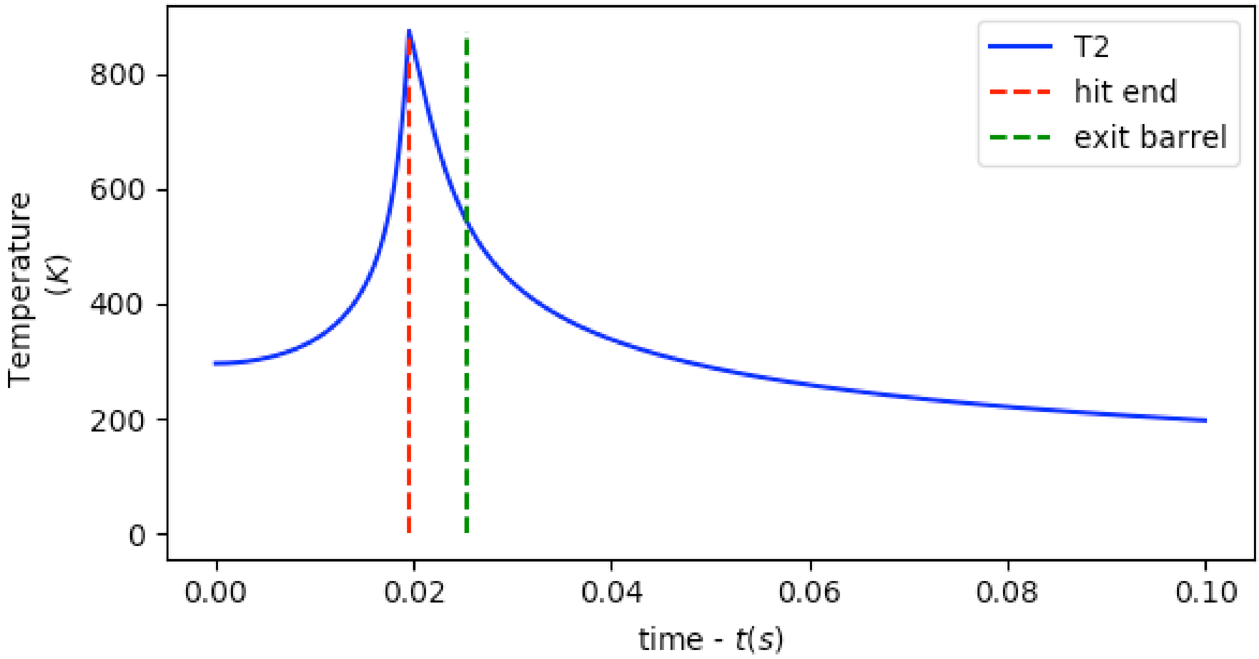


Figure 13: Temperature of Second Stage Gas During Firing Process

Now with reference to the volume of each stage shown below in Figure 14, the first stage is seen to increase along with the piston's movement until it reaches the end of its stroke and stops. This volume of the first stage gas starts at the volume of the reservoir. The second stage volume decreases until the piston collides with the end of the pump tube however, does not go to zero as there is still the volume of gas in the conical section of the pump tube. It then increases again as the projectile travels down the barrel. The minimum volume in the second stage is 0.00009 m^3. These are both expected and obvious results which encourages the fact that the simulation takes relevant parameters into account. This model does not take into account any effects that occur after the projectile has left the barrel and is the reason why the second stage volume increases continually.

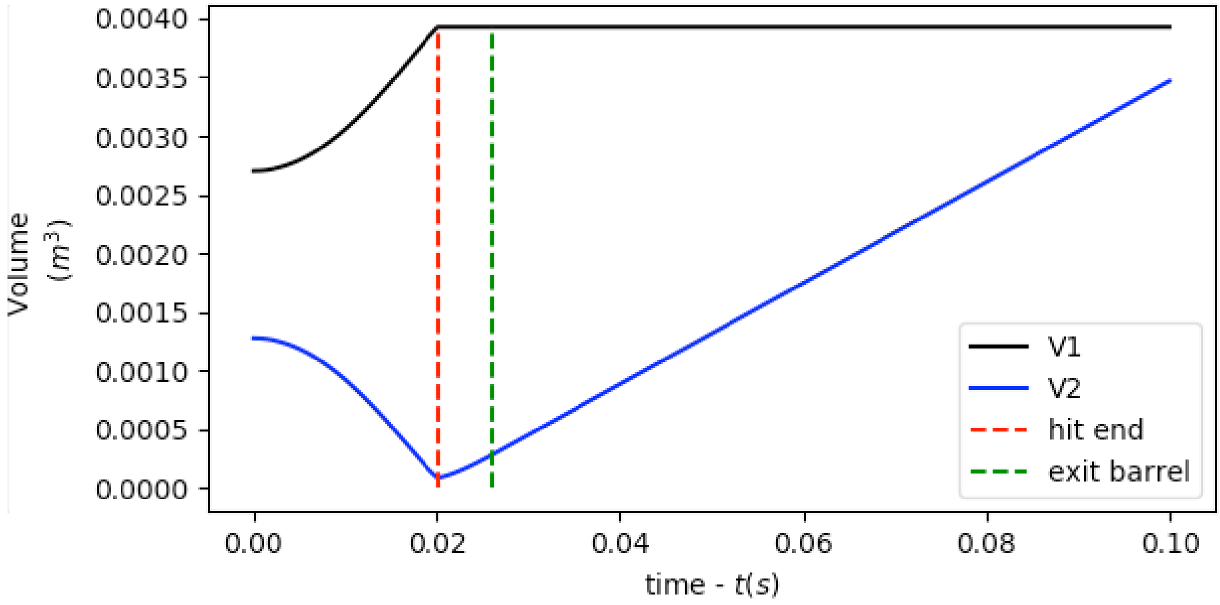


Figure 14: Final Volume Showing Both Stages

Referring to the design as a whole it would be ideal to size components so that the projectile leaves the barrel before the piston hits the end of the pump tube as this would again lessen the damage of the collision and allow the projectile to use all the available energy transferred from the piston. Nevertheless, due to certain component choices this was not possible for this prototype.

With reference to the overall goal of the project of firing a projectile at supersonic velocities this model is encouraging as even though forces such as friction have not been included the maximum muzzle velocity is 547 m/s which is 204 m/s above the target. Therefore, it can be deduced that theoretically the final design should produce a satisfactory outcome.

4 Concept Designs

In order to begin the design process, the constraints imposed onto the project as well as the information gathered in the literature review were used to create an overall concept design of the gun. It was known from the project description that the total size of the gun had to be roughly 3 - 4 m in length as well as the initial reservoir volume had to be 0.005 m^3 or less in order to remain in the SEP sector according to SANS 347. Most components are re-used from previous years and so not many would be re-designed. Only the components that have various conceptual options that needed to be reviewed in order for the most suitable version to be selected are discussed in this section, the rest are detailed in the final design chapter.

4.1 Pump Tube and Reservoir Positioning

From literature it was known that the first stage gas chamber (situated inside the pump tube) is connected to a separate reservoir which holds the high-pressure gas until firing and so this connection and mounting between the two components needed to be considered. Two mounting options were assessed; longitudinal mounting and concentric mounting. In both options the reservoir is a cylinder as it is easier to machine and can be purchased in standard sizes.

4.1.1 Longitudinal Mounting

Longitudinal mounting involves the reservoir to be positioned in line behind the pump tube. They would then be connected via pneumatic tubing, this is shown below in Figure 15. The advantage of this design is that each part is separate and hence can be accessed individually allowing for ease of assembly and a quick re-loading procedure of the piston into the pump tube. This also allows for a smaller reservoir as it is a stand-alone part. However, this configuration forces the design to be much longer as the parts are axially positioned as well as there is no fail-safe design as the pump tube is exposed directly to the operators. Another disadvantage of this design is that it requires a separate pneumatic control circuit between the two cylinders.

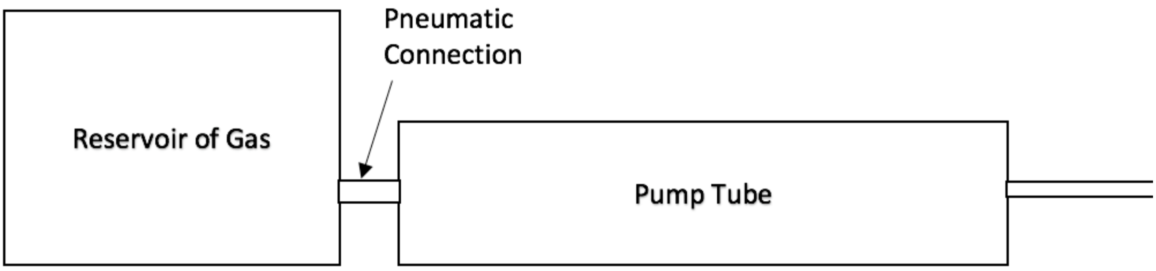


Figure 15: Image Showing Longitudinal Mounting of the Reservoir and Pump Tube

4.1.2 Concentric Mounting

Concentric mounting involves the entire pump tube assembly to be placed inside of the reservoir. The rough concept is shown in Figure 16. The pump tube would need to be sealed off from the reservoir during the pressurisation process and two flanges would need to be used in order to connect, position and seal the two tubes. This design is advantageous as it saves space and length as well as it is by nature a fail-safe design. If the pump tube were to fail the pressurised air would be released into the reservoir thus ensuring that there is no danger to the operator. The disadvantage to this design is that it adds a level of complexity to accessing and assembling the pump tube, piston etc. and sealing the two tubes from each other as well as any leaks are more difficult to isolate.

This concept was selected mainly because it was deemed safer and more space conscious. Safety is an extremely important factor in this project and so takes top priority.

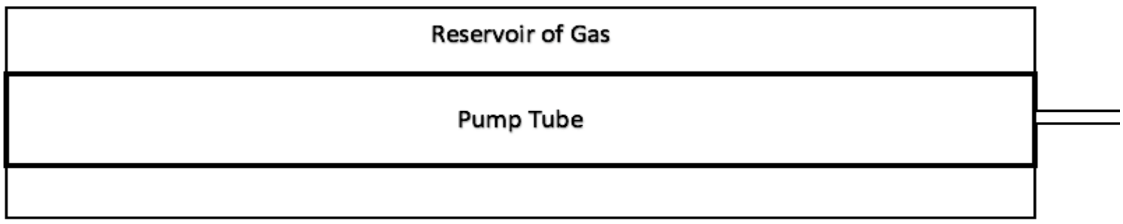


Figure 16: Concentric Mounting of the Reservoir and Pump Tube

4.2 The Transition Section

Since the piston (or the front section of it) is designed to be consumable there needs to be a transition piece to the gun between the pump tube and the flange that the piston will collide with, thus ensuring the rest of the gun remains undamaged. This section is also used to ensure that the piston does not rebound after the initial collision. This piece has the option of either being at a 90-degree angle to the piston or it can be tapered into a conical section.

4.2.1 Flat Transition Piece

A flat transition piece would consist of a flat face and a centre hole that the piston would collide with head on. Thus, in this mode the piston is likely to rebound and so needs an additional method of preventing that motion. A magnet could be used in conjunction with a metal piston cap, however this adds an additional component as well as a level of complexity as magnets have different behaviours under high temperatures and will need to be replaced after every firing of the gun. Although it would be easier to remove the piston from this design as it will not become lodged in the transition piece.

4.2.2 Tapered Transition Piece

The tapered section would consist of a face that is angled inward creating a cone effect that the piston would collide into, illustrated in Figure 17. This allows for a simple way of rapidly stopping the piston at the end of its stroke as it will become ‘plugged’ in the piece and prevent any backflow of gas. Most gas gun designs have a tapered transition section for this exact reason [7]. However, this does create an issue of removing the used piston as it will be more difficult to remove the piston from the tapered section if it has become deformed into it. This design also ensures that all the air from the pump tube will be forced into the barrel thus propelling the projectile to greater velocities. This concept was selected as it allows both requirements - of stopping the piston at the end of its stroke as well as protecting the rest of the assembly - to be met simultaneously.

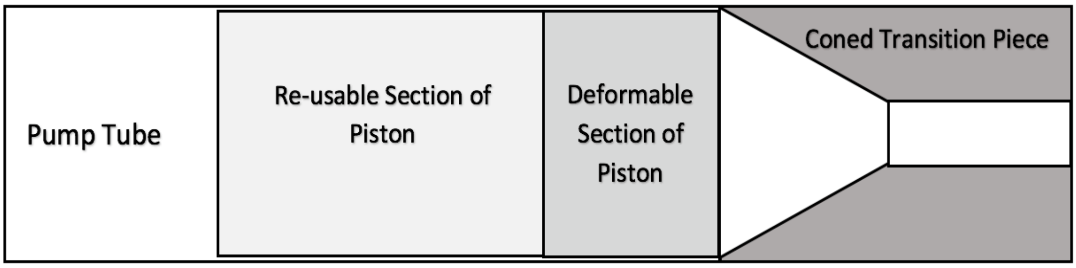


Figure 17: Illustration of Tapered Transition Section

5 Final Design

Now that conceptual designs have been made and various design options reviewed the detailed design phase could begin. Specific design decisions needed to be made to ensure that the all components worked well together and allowed the gun to reach its overall performance goals while still conforming to the design constraints. The final design attempts to construct components that are easy to machine, have the fewest possible number of parts, allow for easy assembly and dismantling, use standardised sizes, are low cost as well as have an inherent safety design. The project budget was a major factor in designing components and material selection and re-use of previous components played a large role in making many design decisions. As mentioned previously most components are re-used from various previous projects and the reasons for this will be discussed in detail in the individual component section. Individual component designs as well as the decisions behind these designs are also discussed below.

5.1 Overall Design

The final design is shown below in Figure 18 and 19.

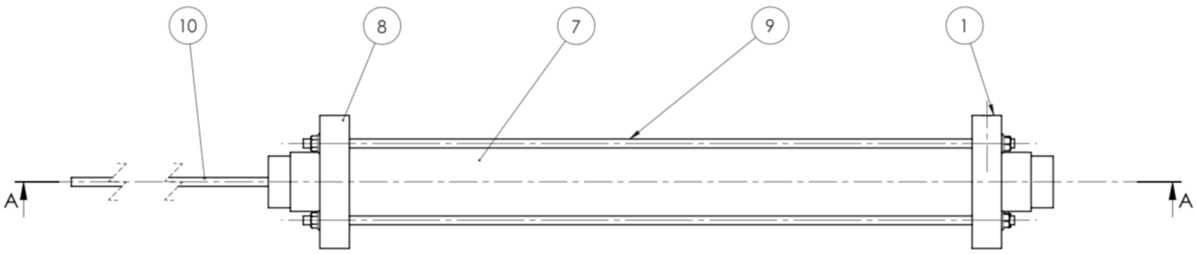


Figure 18: The Overall Assembly Schematic

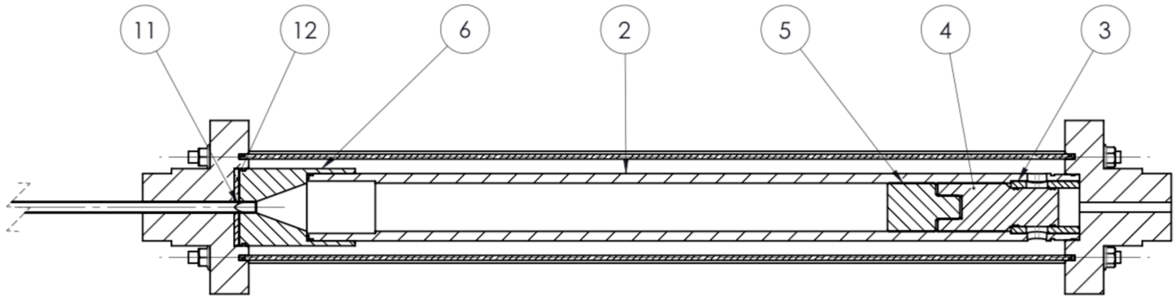


Figure 19: Section View of Overall Schematic Showing All Components

The design consists of a pump tube and reservoir that are concentrically mounted with the reservoir surrounding the pump tube connected by two flanges on either side of the tubes. The entire assembly is connected and tightened together using four tie rods with corresponding nuts and washers placed through the flanges. The pump tube is connected to a transition piece between the tube and the second flange. The piston and cap are placed inside the pump tube in the start position near the first flange, on the right of Figure 19. The barrel is threaded into the transition piece and positioned through the second flange. The overall length of the gun is 3. 865 m. In order to fire the gun, pressurised air is supplied directly to the pump tube via the first flange that causes the piston to move past the slots in the pump tube allowing the pressurised air from the reservoir to flood into the tube. External O-rings are used on all respective parts where sealing is necessary. External O-rings were used as they are cheaper than gaskets and do not come off the part as easily as internal ones. In the case of certain components, two slightly different versions are made in order to gather more data and compare results.

5.2 Component Design

5.2.1 The Pump Tube

In order to save costs and machining time the 2015 pump tube has been re-used for this project. The piece has had to have slight adaptions to fit the new flanges, such as shaving off the thread on the one side as this design uses tie rods to secure the assembly and not threaded sections. As well as the diameter of a section of the tube has been filled to a 50 mm in an attempt to use the whole length of the tube for the piston's stroke, this can be seen to increase the overall performance of the gun as shown in the simulations previously. The inside of the pump tube was also polished as a smooth surface finish is required to minimise friction.

Figure 20: Mild Steel Pump Tube Before Use

This design uses the method of the piston acting as the seal in the start position and using several slots along the circumference of the pump tube which allows for a sudden flow of pressurised air to enter the pump tube from the reservoir when the piston is forced past the slots (these can be seen below in Figure 21). An additional pump tube insert (also re-used from 2015) is placed inside the tube to position the piston and allow for the sealing mentioned above. This insert gives the added benefit of reducing friction during the piston's stroke as the external O-rings are placed on the small diameter section of the piston that fits into the insert, this will be discussed further in the piston design section.

Figure 21: Pump Tube End Demonstrating the Gas Slots

5.2.2 The Piston

The pistons from the 2015 project are going to be re-used in order to save costs as there are two already available and undamaged that fit the existing pump tube and insert. Only one will be used unless major damage occurs. The full steel one is chosen (the top one in Figure 22) as it is hollowed out thus reducing weight (final mass of 425 g) and making it lighter than the other, which from simulations is shown to be advantageous. This piston design is advantageous as it is long enough to ensure that it does not rock during its stroke which would have a negative effect on the muzzle velocity. The piston also has a smaller end section that fits into the pump tube insert at the front of the pump tube, this is where the external O-rings are placed thus sealing the pump tube before firing and therefore allowing the piston to slide without sealing (and with less friction) during its stoke along the pump tube.

Figure 22: Re-Usable Pistons Section Before Use

An additional front piece called the piston cap will be connected to the front face of the piston. This piece is designed to be consumable in the firing process. The piston cap is made out of a soft plastic, high density polyethylene (mass of 100 g) and a second material polyethylene (mass of 95 g), which will collide with the transition piece and plastically deform thus preserving the rest of the piston. This piston cap design has also been used in current gas guns where consumable pistons are required [9]. After each firing the piston cap will need to be examined and potentially replaced.

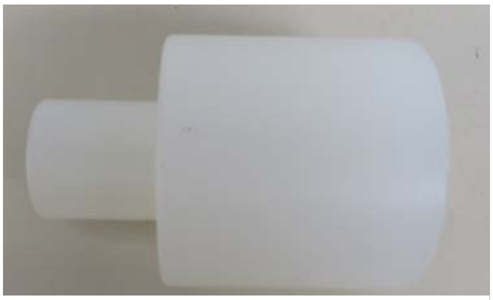


Figure 23: HDPE Piston Cap Before Use

5.2.3 The Transition Piece

Similar to most two-stage gas gun designs a tapered transition piece at the end of the pump tube is used to stop the piston at the end of its stroke. This design has a conical section where the piston will deform which leads into a small hole where the barrel will be connect and the gas will flow through. This has advantages such as ensuring the piston does not rebound after the initial collision which would cause back pressure issues and will not damage the pump tube itself as the transition piece, if damaged, can be replaced more easily and cheaply. There is also an added buffer of a soft material (rubber in this case) between the transition piece and the second flange to guarantee that the flange does not become damaged due to the piston's impact.

The transition piece will fit over the end of the pump tube in order to use the full tube length and the conical section will start at the interface between the pump tube end and cone base. The transition piece also acts as the connection to the barrel as the barrel is threaded into the end of this piece. This allows the projectile to be placed as close to the pump tube as possible ensuring there is no dead space between the two.

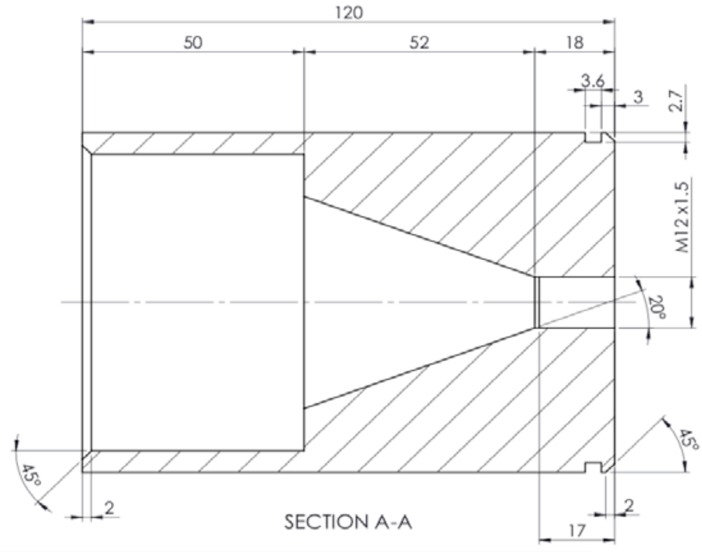


Figure 24: Section View of Transition Piece Demonstrating Conical Section

Figure 25: Top View of the Transition Piece Before Use

5.2.4 The Reservoir

In order for the reservoir to conform to SANS 347 standards the total volume of pressurised air needs to be 5 L or less. This is calculated by taking the total volume of the reservoir and subtracting the volume of materials inside of it such as the pump tube, transition piece and piston. This allows for the entire length of the pump tube to be utilised while still remaining in the SEP sector. The reservoir is a simple cylinder that will be fitted onto the flanges encompassing the entire pump tube assembly. The cylinder is designed to be thick enough to withhold the pressure of 10 bar that will be the input to the system.

The diameter of the reservoir was mainly determined by its length as the length of the piston's stroke needed to be maximised. However, since the pump tube was being re-used, the length was also designed to fit this existing part as well as include the length of the transition piece. Therefore, the diameter was chosen to match these lengths and still be less than 5 L, however the volume occupied by the internal components needed to be factored in and so the diameter could be larger than originally thought due to these components inside the reservoir. The calculation is shown below;

$$Area = \frac{0.005 + V_{pump\ tube} + V_{piston} + V_{transition\ piece}}{Length\ of\ Pump\ Tube\ and\ Transition\ Piece} \quad (20)$$

$$\therefore Max\ Diameter = 138 \text{ mm}$$

However, this part is not made to order and so a standard size needed to be chosen. The outer dimeter of the flanges depended on the reservoir outer diameter and so needed to be factored in as a smaller outer diameter would lead to a lighter and cheaper flange which is a significant benefit. A reservoir with an outer diameter of 101.6 mm and an inner diameter of 95.24 mm was chosen in the end as this was a difficult part to source as well as was the largest size the supplier had in stock.

The final volume of the reservoir using the acquired cylinder is thus;

why piston?

$$V_{res} = Length * \pi \left(\frac{D_{inner}}{2}\right)^2 - V_{pump\ tube} - V_{piston} - V_{transition\ piece} \quad (21)$$

$$V_{res} = 0.0042\ m^3$$

Hence the volume of the entire reservoir still remained in SEP and so is safe to use.

The volume of 10 bar air that was to flow into the pump tube from the reservoir was thus;

$$V_{10bar} = V_{res} - V_{total\ pump\ tube} - V_{total\ transition\ piece} \quad (22)$$

$$V_{10bar} = 0.0027\ m^3$$

Which even though is much smaller than 5 L, the simulations showed that this was not a significant issue as it only decreased the muzzle velocity by 10 m/s which resulted in a final muzzle velocity of 547 m/s which is still higher than required. In this type of design, it proved difficult to maximise the useful reservoir volume while still ensuring that the total volume of the reservoir remained in SEP for a pressure of 10 bar.

Now that the volume had been calculated the cylinder needed to be examined in terms of failure criteria. The cylinder must obviously be designed to not yield or fracture while containing the required 10 bar pressure. The following formulas were used to determine if the current cylinder met these requirements;

$$\sigma 1 = \frac{P.D}{2t} \tag{23}$$

$$\sigma 2 = \frac{P.D}{4t} \tag{24}$$

$$\sigma 3 = 0 \; if \;\; \frac{t}{D} \leq \frac{1}{20} \tag{25}$$

$$(\sigma 1 - \sigma 2)^2 + \; (\sigma 1 - \sigma 3)^2 + \; (\sigma 2 - \sigma 3)^2 \leq \; 2{\sigma_y}^2 \tag{26}$$

$\sigma_y = 276\ Mpa$ for aluminium

t = 3.18 mm

D = 101.6 mm

Using the above values, Equation 26 becomes;

$$382.8 < 152\ 352$$

Hence the reservoir should not fail under these conditions.

Figure 26: Aluminium Reservoir Before Use

5.2.5 The Flanges

The flanges will be the means of connecting the pump tube assembly to the reservoir as well as sealing the entire assembly. The design has slots where both tubes will fit and will be sealed using O-rings on each perspective part to ensure that no leaks occur. This design uses tie rods and nuts to tighten the gun together allowing for ease of assembly. However, since this is a prototype project the entire assembly will be dismantled to see how each part is fairing after each fire.

The tie rods were used as an alternative to a threaded section as to screw each large and heavy component on is time consuming and difficult. The tie rods give an easier alternative though it still will not be a swift process, but it will be relatively easy to perform. This also allows for easier to machine components and keeps the overall design much simpler.

The first flange will have two connections to the pressurised air inputs, one directly to the pump tube and the back face of the piston that will fire the gun (forcing the piston past the beginning of the slots thus breaking the seal the piston is forming and allowing the reservoir gas to fill the tube) and another one to pressurise the reservoir itself. The second flange acts as the means of aligning the barrel to the rest of the gun as it will slide through the centre hole and thread into the transition piece.

Figure 28: Top View of First Flange

Figure 27: Top View of Second Flange

Both flanges have to be thick enough to ensure that no strength is compromised during the impact of the piston against the transition piece. Calculations were performed to judge if, at the thinnest part of the flange, shearing would occur and a safety factor of 34 was determined, thus the flanges are thick enough to withstand these forces.

The flanges also have to fit onto the mounts already available in BISRU, which requires a mounting section as well as a shoulder which positions them and allows for space to tighten the nuts onto the threaded rods. This can be seen in Figure 29 below.

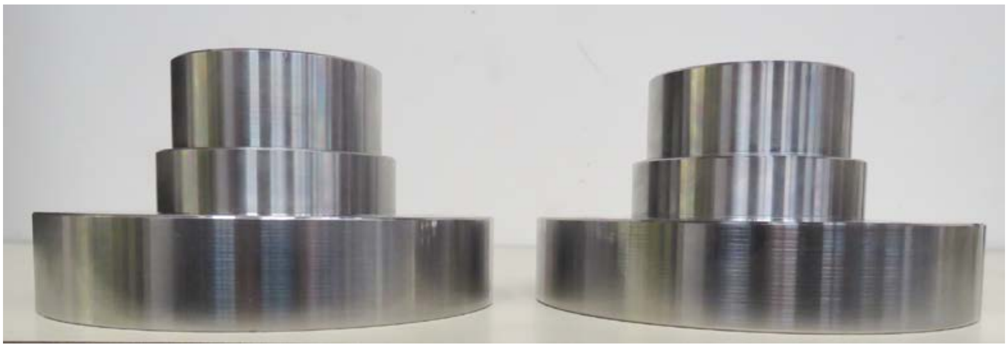


Figure 29: Side View of Both Flanges

5.2.6 The Barrel

The launch tube/barrel is being re-used from a previous project and is a simple cylinder of length 2.9 m. It is more beneficial to use a previous barrel as it saves budget costs. The current barrel has a threaded section at one end where it will screw into the transition piece. This connection needs to be sealed to ensure no high-pressure gas escapes during the firing process and thus uses the concept of a labyrinth seal. A labyrinth seal is a mechanical seal that provides a long and winding path that the gas flows through, in this case it is the threaded section that the barrel and transition piece are connected via. This allows for a very slow leakage/flow rate which is ideal for a process of this nature as the high-pressure gas is only contained in this section of the gun for a few milliseconds. Therefore the seal works well as there is not enough time for the gas to leak out through the threaded section acting as the labyrinth seal.

The projectile is to be placed against this threaded section in the start position hence eliminating any 'dead space' between the end of the pump tube and the back face of the projectile. The barrel also has fluting near the exit which allows for the light trap to be placed over in order to measure the velocity of the projectile as it about to leave the barrel.

Figure 30: Threaded End of Barrel

Figure 31: Fluting on the Barrel End where Light Trap will be Placed

5.2.7 The Projectile

The projectile is based on an ogive shape which is a common shape for bullets in many guns, this includes a cylindrical section with a round tapered end that leads into a point. Ideally the projectile should be as light as possible as, from the simulations shown previously, it allows for a higher muzzle velocity. However, having the diameter too small will cause the flow of gas to choke and not allow for enough air to apply a force on the projectile. Two different projectiles are used, one is the standard shape and the second has a hollowed out back in an attempt to decrease the weight further. Two different weights are used to allow for more data to be collected and for comparisons to be made. The solid projectile has a mass of 3.58 g whereas the hollow one has a mass of 2.48 g.

Figure 33: Both Types of Projectile Before Use

Figure 32: Image Illustrating the Two Different Types of Projectiles Used

5.2.8 The Tie Rods

The entire assembly is held together using four tie rods. This is done as it is easy to assemble and dismantle, are cheap and do not require machining time or specific tolerances. This design uses 4 x M12 threaded rods which ensure that the forces will not break the assembly or cause it to leak. Additionally, if a rod were to fail they are easy and cheap to replace. The minimum amount of tie rods necessary is used as it will be quicker to assemble and dismantle however, strength could not be compromised and so four were chosen as each one can withstand at least 10 kN of force which is more than enough for this process.

5.3 Material Selection

Almost all of the metal parts are made out mild steel as the project is a prototype and hence cost is a large factor in the design. Mild steel is a cheap option and allows for good strength properties which is key in a project where high pressures and impact forces are a factor. Components such as the pump tube and flanges are bulky, and hence using steel makes them extremely heavy and thus aluminium would be a more suitable choice as they would be much lighter and would not rust. Unfortunately, aluminium did not fit into the project budget. The reservoir, however, is made out of aluminium as it reduces the weight of the overall assembly substantially and this will allow for it to be re-used in future projects.

Polyethylene and high-density polyethylene (HDPE) are used as the piston cap materials as most two-stage gas gun use either of these materials as they are soft and easily deformable [9]. However, an error was made with ordering the materials and the caps that were meant to be made from polyethylene were supposedly made from polypropylene instead. However, this was not a major issue as the HDPE piston caps were simply made the focus of the testing. Two different materials are used in order to collect more data and to compare the softer plastic, HDPE, to a slightly more brittle plastic, polypropylene. Adding to this, HDPE is the cheaper option and so having several caps made from this material reduced the overall cost of this part.

A soft rubber is used to further protect the second flange from the impact of the piston and will be placed between the transition piece and the flange. Rubber was chosen as it was readily available from the workshop as well as being soft and durable which allows for sufficient ‘cushioning’ between the two pieces.

The piston used is made out of steel and hollowed out as this reduces the weight which, illustrated in the numerical modelling, gives a better performance. The projectiles are made from aluminium as this reduction in weight, compared to making them out of mild steel, leads to a substantial increase in the muzzle velocity thus the mass was minimised.

5.4 Pneumatic Circuit Design

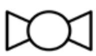
Due to the fact that the gas gun is operated by applying pressurised air to the reservoir and pump tube at specific times, a pneumatic circuit needed to be designed that allowed for easy and safe operation as well as being cost effective. Several pneumatic circuits were reviewed in order to choose the cheapest and safest configuration.

As cost is, again, a large factor in projects of this nature all components used in the design either needed to be already available or inexpensive to purchase. Ball valves were used as the means of on/off operation as they are simple to use as well as cannot be turned accidentally due to their lock feature. Adding to this they were available in the BISRU laboratory thus adding no additional cost to the project which is the main reason for their use in the design as the procurement of valves (not only ball valves) was discovered to be an exceptionally expensive task. A 3-way ball valve would have been preferable as it would allow for one valve to control both the pressurisation of the reservoir and the actual firing of the gun however this did not fit into the budget for this project. However, using two 2-way ball valves was safer as the controls are now separate and will be clearly labelled.

Fittings needed to be purchased as well as tubing. A 6 mm outer diameter tube was used in almost all of the connections as the flow rate and time taken to pressurise the tube is not critical and using 6 mm tubing and fittings allowed for a decreased flow rate which added another safety feature as the pressure would therefore be increased slowly.

Figure 34 below gives the final pneumatic circuit used as well as Table 3 gives the symbols used and Table 4 shows the quantity of parts used.

Table 3: Key of Pneumatic Symbols

Symbol	**Description**
	2-way Ball Valve
	Pressure Source
	Pressure Gauge
	Working Line

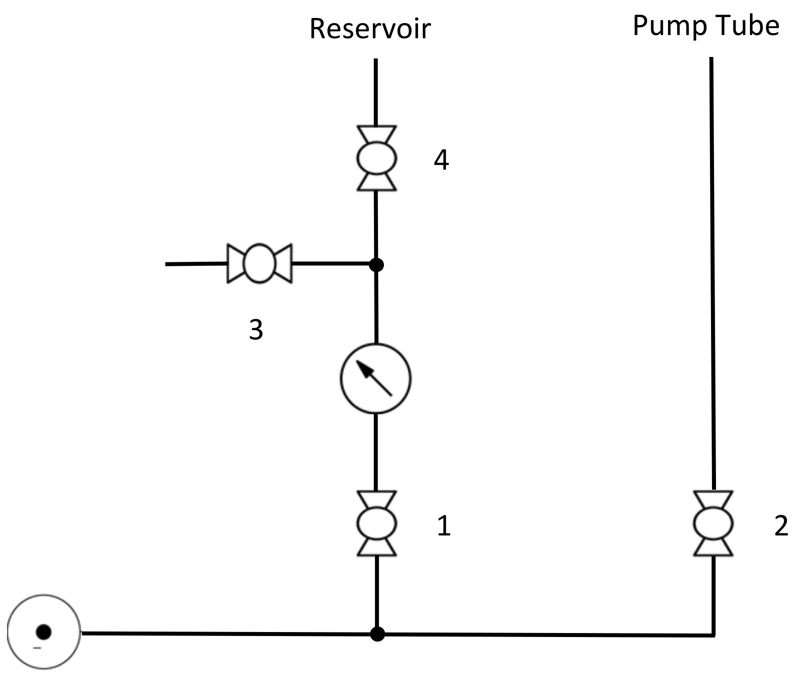


Figure 34: Pneumatic Circuit Used

Table 4: Pneumatic Inventory List

Component	Quantity
Fittings (6 mm, ¼" thread)	12
Fitting (8 mm, ¼" thread)	2
Fitting (10 mm, ¼" thread)	2
3-way Fitting (¼" thread)	3
Tubing (6 mm)	7
Tubing (8 mm)	1
Tubing (10 mm)	1
2-way Ball Valve (¼" thread)	4
Pressure Gauge	1

In the circuit above the pressure source is supplying 10 bar of pressurised air to the system. Two ball vales (referred to as the control valves) are used to turn the connection to the pump tube and reservoir on and off separately. The pressure gauge is connected directly to the reservoir but separated from the pressure source by a valve in order to read the reservoir pressure only. The gauge was needed to measure the correct pressure as well as testing would not begin at 10 bar but would rather be slowly incremented to 10 bar as a maximum value. Another ball valve was used as a relief valve - with the one side connected to atmosphere - to ensure that the reservoir was not over pressurised. Finally, a forth ball valve was used between the pressure gauge and the reservoir as the pressure gauge needed to be protected against any sudden pressure changes that would occur during the firing of the gun.

The operation would be as follows; the two reservoir control valves (1 and 4) would be opened and the reservoir would be pressurised to the desired point and the control valve (1) would be shut off to ensure the correct reading for the reservoir was captured, the relief valve (3) would only be used if the pressure needed to be lowered, once the correct pressure was reached the second control valve (4) would be closed to guarantee that the pressure gauge is not exposed to fluctuating pressures, finally the pump tube control valve (2) would be opened to fire the gun by supplying pressurised air to the pump tube pushing the piston past the inlet slots and allowing the pressurised air in the reservoir to flow into the pump tube. The actual pneumatic circuit used is shown in Figure 35.

Figure 35: Real Life Pneumatic Circuit

5.5 Velocity Measurement

As a muzzle velocity above Mach 1 was the overall goal of this project a means of measuring the velocity of the projectile as it leaves the barrel was needed. A light trap has been used in previous projects and gave a simple way of measuring this velocity. It consists of two infra-red LEDs and two corresponding phototransistors that are lined up with the fluting at the end of the barrel and are connected to a control circuit. As the projectile moves passed the light trap it blocks the light for a small amount of time and this can be read on an oscilloscope and the velocity can be calculated from this reading. The housing of the light trap for the device previously used was not the correct size for this design and so a new housing had to be manufactured that fit the 12 mm OD barrel being used in this project. Figure 36 below is the circuit diagram of the control circuit.

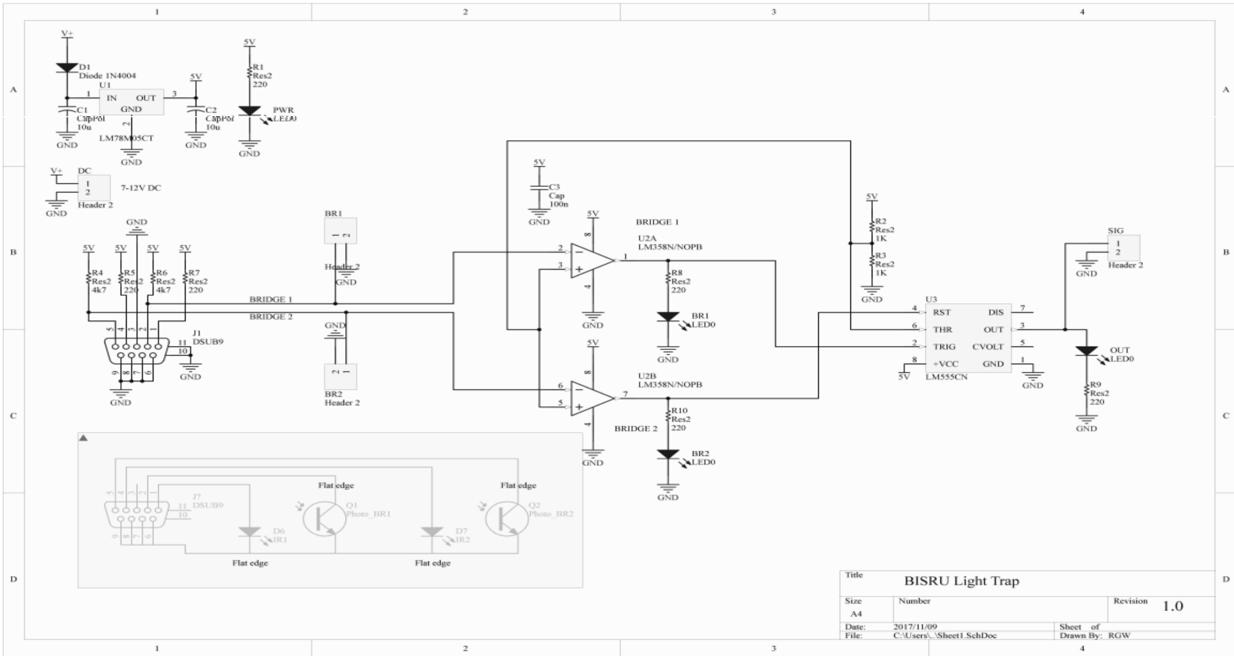


Figure 36: Light Trap Circuit Diagram

5.6 Catch Box

A catch box will be used to stop the projectile once it leaves the launch tube. This catch box will be filled with wax billets that will stop the projectile which can be seen in the figure below.

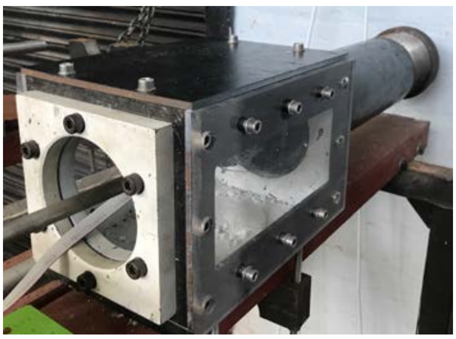


Figure 37: The Catch Box

Figure 38: Wax Billet for Catch Box Before Use

5.7 Budget Report

As mentioned above the financial restriction on the project was a main factor in deciding on final designs. Below is a table illustrating the final budget report as well as potential prices for alternative material, sizes or different supplier's prices.

Table 5: Final Budget Report

Part	Final Price	Excluded Costs	Alternative Price
Flanges	R 630,00		R 2 300,00 (Al)
Pump Tube	-		
Piston	-		R 130,00
Piston Cap HDPE 5x	R 140,00		
Piston Cap PE 5x	R 240,00		
Transition Piece	R 190,00		
Reservoir	-	R 292,00	R 490,00
Tie Rods	R 112,00		
Barrel	-		
Barrel Mount	-		
Projectiles	-		
Flange Protection	-		
Pump Tube Filler	-	R 49,00	
O-rings	R 17,00		
Light Trap Housing	-		
Pneumatics	R 177,00		
Total	**R 1 506,00**		
Saved		**R 2772,00**	

As one can see from the above table there are not many components that needed to be purchased and yet the budget was still reached, coming in at just over R1 500. This is mainly due to the fact that the components are large in size as the gun assembly is over 4 m in length as well as 0.2 x 0.2 m wide and high. The highest cost was for the flange material as well as the pneumatic fittings. Ideally, the flanges should have been made out of aluminium which would have decreased the weight of each flange by 6 kg, however the price would have quadrupled. The reservoir was not included in the design budget as a previous reservoir that was planned on being re-used had been taken by another project and so the cost of a new one was compensated. Only two suppliers were found for the reservoir, and the cheapest option was chosen. There are components that do not have prices as they are either being re-used, or the workshop used scrap parts to make them. Hence the motivation to re-use as many parts as possible is clearly reasonable, otherwise the cost would have been far over the budget.

6 Testing

6.1 Safety Considerations

As the testing process will involve a projectile potentially firing at supersonic velocities and high-pressures gas there are certain safety concerns that need to be addressed. A catchment box containing candle wax is used to stop the projectile as it leaves the barrel which guarantees the safety of all those involved as the projectile will never be in free flight. The fact that only air is used as the gas in both stages ensures that if a pneumatic pipe were to come lose there will be no consequence other than the pipe colliding with a person. This is addressed by making sure all persons involved wear safety googles at all times as well as ear protection each time the gun is fired, as this is an extremely loud activity.

Before the gas gun could be used it was pressure tested inside the blast chamber at BISRU to ensure that the reservoir could hold 1.25 times the pressure required as per the risk assessment requirement. This was done by using a gas canister and pressure regulator and connecting it to the reservoir via a suitable pipe that went under the door of the chamber while the door remained slightly ajar. This high pressure of 12.5 bar was placed inside the reservoir to ensure that it does not yield or fracture during operation, shown in Figure 39 as required by the risk assessment document. This test was performed and was successful and the assembly seemed to not leak. This method was used as an alternative to water pressure testing as the water could damage certain components and cause the steel parts (of which there are many) to rust prematurely.

Figure 39: Pressure Gauge Showing Value During Pressure Test

6.2 Testing Procedure

Now that the reservoir had been successfully pressure tested the actual tests could commence. The original aim was that 10 shots would be performed in order to ensure the reliability of the results. The testing procedure was as follows; first the gun was assembled and the piston was set in the start position, then the wax billets were inserted into the catch box and the light trap and oscilloscope were both tested and adjusted correctly, the reservoir was then pressurised to the desired pressure using the pressure gauge, starting at 4 bar and incrementing up on to a final pressure of 10 bar. This was done in order to prolong the life of the gun and to allow for data to be collected in case the gun broke while using high pressures such as 10 bar. Next the pressure to the supply was cut off – ensuring that the correct reservoir pressure was read off the pressure gauge, the projectile was then loaded, and a siren was let off before a shot was fired and ear protection was applied, finally the trigger ball valve was turned on and the gun was fired. After each shot the gas gun had to be dismantled and each part examined, and any observations recorded. Two different materials were used for the piston cap, HDPE and PP, as well as two different projectiles, a solid and a hollowed out one. Testing occurred over three days and 13 shots were fired, the results are discussed in the following chapter.

The velocity was measured using the light trap mentioned in a previous chapter that was connected to an oscilloscope. The oscilloscope would show two pulses, one as the projectile passed through the first LED – phototransistor pair and a second as it passed through the next pair. The time between these pulses could then be recorded and the velocity found as the distance between the LED – phototransistor pairs was known to be 40 mm. The light trap and housing can be seen in position in the figure below.

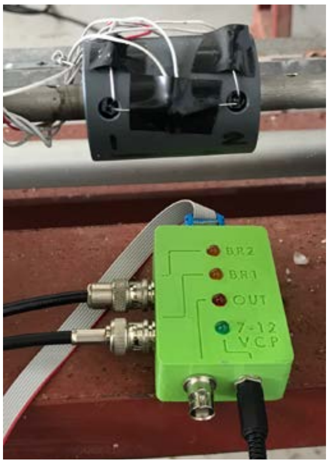


Figure 40: Housing of Light Trap and Circuit

However, there was a setback leading up to the testing process that delayed the processes. A setback occurred while pressuring the reservoir, the fitting to the wall connection as well as other connections were leaking and so all needed to be tightened further. While the wall fitting was being tightened a section of the copper pipe that carries the pressurised air from the main compressor came loose and snapped off of the wall falling to the ground as can be seen in Figure 41. No one was injured, however it needed to be reported as a near miss incident as it had the potential to be dangerous. The exact cause of this event is unknown, but it can be speculated that the pipe connections were faulty or not connected securely enough and so came loose when under the force of the pressurised gas as well as the tightening of the end fitting. This caused a delayed as the pipe now needed to be replaced and so an alternative means of supplying the gas needed to be found. A nitrogen gas canister was used as the alternative and could be easily fitted to the existing pneumatic circuit. Using nitrogen instead of air did not alter the process or results in any way as it also a non-toxic gas in these amounts.

Figure 41: The Piece of Copper Pipe That Broke Off

Now that pressurised gas could be supplied the leak test could continue. While pressuring the reservoir the piston cap was noticed to have come loose from the piston and moved along the pump tube indicating that the seal created by the piston using two O-rings was inadequate. This was easily fixed as two additional O-rings - that had been previously removed to allow for an easier sliding fit between the pump tube and piston - were added back on either side of the pump tube slots. This movement could have caused premature firing which would potentially be dangerous as well as distort the results and so is why it is noted here.

7 Results

The following table shows the results captured of all the tests conducted showing the pressure and the velocity according to which piston cap and projectile type was used over the three days of testing.

Table 6: Testing Results Showing the Pressure Used and Velocity of Each Shot

Day	Material	Projectile Type	Pressure (bar)	Distance (m)	Time (us)	Velocity (m/s)
Day 1	HDPE	Solid	4	0.04	230	173.91
	HDPE	Solid	6	0.04	160	250.00
	HDPE	Hollow	6	0.04	140	285.71
	PP	Solid	6	0.04	156	256.41
	HDPE	Hollow	8	0.04	162	303.03
	HDPE	Hollow	9	0.04	82	487.80**
	HDPE	Hollow	9	0.04	108	370.37
Day 2	PP	Solid	9	0.04	160	250.00
	HDPE	Hollow	10	0.04	76	526.32**
	HDPE	Hollow	10	0.04	90	444.44*
Day 3	HDPE	Hollow	4	0.04	168	238.00
	HDPE	Hollow	7	0.04	136	294.12
	HDPE	Solid	9	0.04	102	392.16**
	HPDE	Solid	10	0.04	148	270.27
	PP	Solid	10	0.04	96	416.67*

The velocity was determined using the time between the pulses that were read off the oscilloscope. Most shots gave a clear readable image on the oscilloscope as shown below in Figure 42.

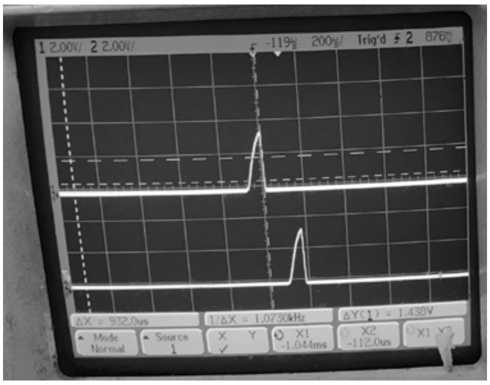


Figure 42: Normal Reading of Pulses on Oscilloscope

However, there were several shots (indicated by the asterisk next to their velocity) that gave a slightly irregular oscilloscope reading as shown in Figure 44. This type of reading made it slightly more difficult to precisely determine the time of the start of the pulse and so the accuracy of these readings is slightly less than the readings shown in Figure 42. The three shots indicated by a double asterisk gave the reading shown below in Figure 43. These readings were exceedingly difficult to accurately determine the time of the pulses and so their reliability is very low, they are therefore excluded from any analysis.

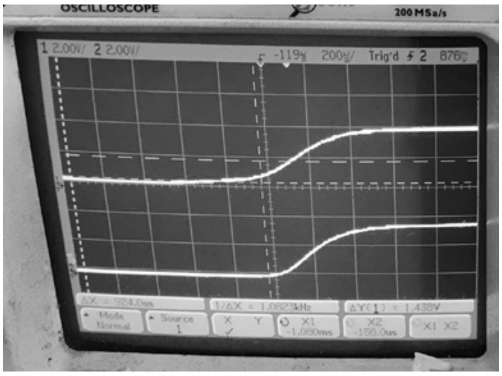


Figure 43: Extremely Abnormal Reading of Pulses on Oscilloscope

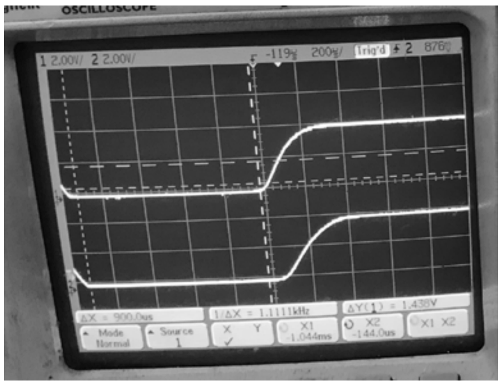


Figure 44: Slightly Abnormal Reading of Pulses on Oscilloscope

4 shots were fired where the velocity was not recorded due to an oscilloscope or light trap error. In addition to this, there was one miss-fire, as an O-ring on the piston had broken and so the pump tube did not seal causing premature firing. However, the projectile had not been loaded yet and so there was no consequence besides having to reset the piston and replace the O-ring.

8 Discussion

After examining the results several trends were identified according to the final muzzle velocity. These trends were based on several parameters that were variable in each test such as the type of projectile used, the material of piston cap and the number of times the piston cap had been used.

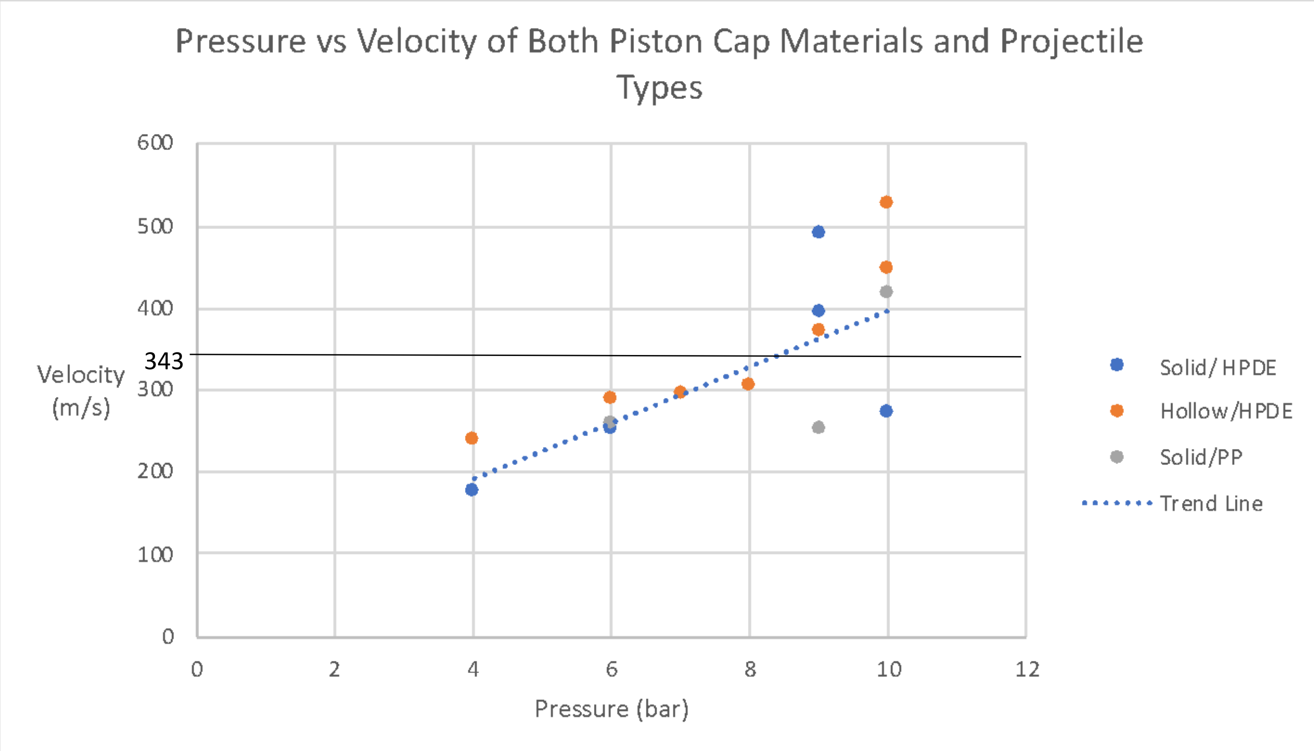


Figure 45: Graph Showing All Recorded Results

Figure 45 is a graph illustrating all the results recorded and separating them into piston cap material as well as projectile type. An expected trend has emerged that with an increase in pressure there is also an increase in muzzle velocity. The trend seen here appears to be linear with a gradient of 33. However, an exponential curve was expected with an asymptote at the peak velocity achievable. The fact that the results do not taper off indicates that the peak velocity has not been reached and that higher pressures would still result in higher velocities. However, due to the imposed constraint of the maximum pressure being 10 bar this point of maximum could not be identified. There a number of results that were above the speed of sound (343 m/s) and these occurred with pressures from 9 bar and above.

As is observable from the basic trend line there are several outliers that need to be discussed. The two data points at 9 and 10 bar that are around 500 m/s were both readings that were extremely irregular and hence made the time between pulses very difficult to determine accurately. Based on this and the fact that they do not fit the trend line, they can be excluded from the analysis as outliers. There are an additional two data points also at 9 and 10 bar that are below 300 m/s, these points gave clear results on the oscilloscope, however this large difference in velocity must therefore be due to other factors such as the number of times the piston cap was used – in both cases a new piston cap was used. This relationship will be discussed further on in this section.

8.1 Oscilloscope Irregularities

The issue of oscilloscope irregularity plays a large role in the measurements of the velocities and hence some readings marked with an asterisk are slightly inaccurate and others marked with a double asterisk are extremely inaccurate as mentioned earlier. Due to this, a non-numerical observation can be made as the shot that corresponded to 370 m/s muzzle velocity was the highest velocity recorded that gave a clear and accurate oscilloscope reading, all shots corresponding to higher velocities gave more abnormal readings. The following can therefore be said, the light trap cannot handle velocities above this speed of 370 m/s and thus the less clear the reading the higher the velocity must have been, although it could not be read accurately from the oscilloscope. Hence all irregular readings were supersonic.

8.2 Projectile Type Effect

From this initial depiction of the data an observation can be made that the type of projectile used, hollow or solid, has a substantial influence on the muzzle velocity. This is illustrated in the figure below.

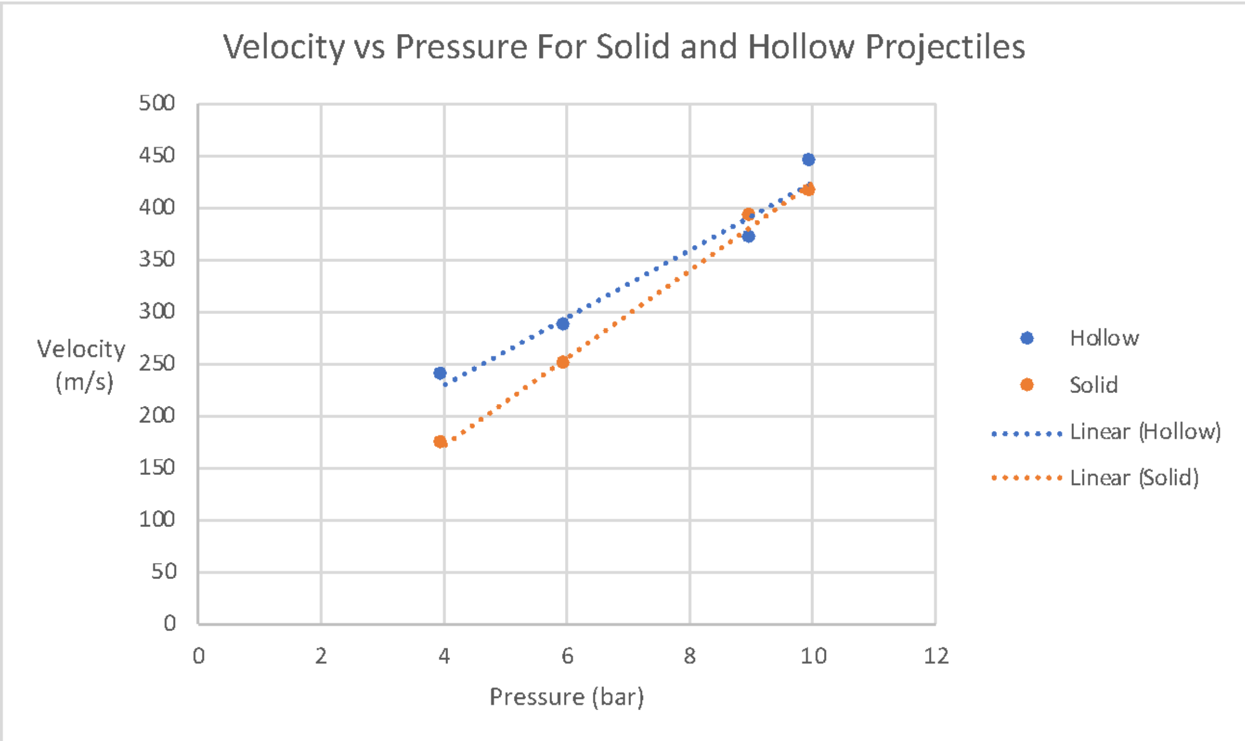


Figure 46: Graph Showing the Effect of Projectile Type on Velocity

It can be seen that for a given pressure the hollow projectile gave a higher velocity in almost all cases. The solid projectiles were averagely 42 m/s slower than the hollow projectiles. At lower pressures the difference in velocity is more pronounced compared to the higher-pressure shots. This could indicate that the higher-pressure shots are beginning to reach an asymptote corresponding to the highest achievable velocity.

There is one data point at 9 bar where the use of the solid projectile is seen to result in a higher velocity which could be due to other factors such as the number of times the piston cap had been used or the fact that the reading was slightly more abnormal than the hollow version, which would lead to inaccurate measurements. However, regarding the other results, a stable trend has arisen and it can be deduced that the lighter projectile results in a higher velocity, which concurs with the numerical prediction.

As the hollow projectile was seen to give higher velocity Figure 47 demonstrates the trend of only hollow projectiles, using HDPE as the piston cap, and their corresponding muzzle velocities.

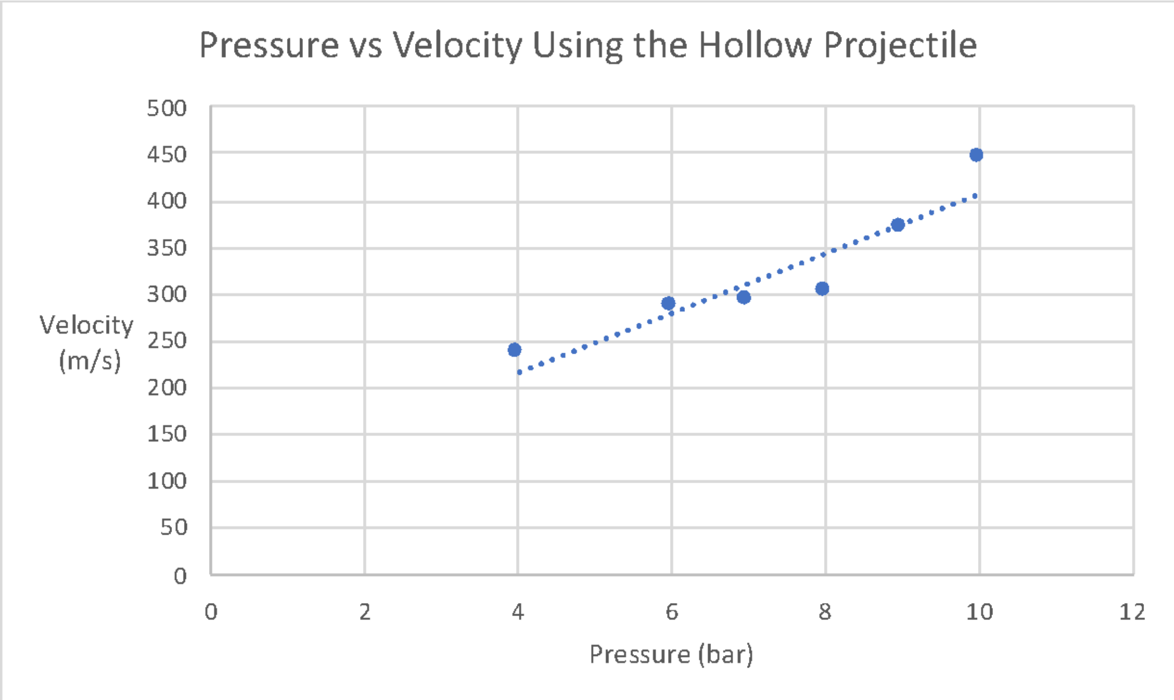


Figure 47: Graph Showing the Velocities of Hollow Projectiles

Upon examining the graph, there is a slight plateau between 6 – 9 bar which is unexpected however, this could be due to a number of other factors such as the number of times the piston cap was used. Of all the results this combination of hollow projectile and HDPE piston cap gave the highest velocity. Again, the clear trend of increasing the pressure results in an increase in overall muzzle velocity is illustrated in this figure with the maximum velocity being 444.44 m/s at 10 bar.

8.3 Comparison Between Simulations and Recorded Results

The next analysis that needs to be performed is the comparison between the numerical simulation values and the recorded values as the gas gun was sized based on this numerical model. From Figure 48 below, the numerical simulation velocities are seen to be much higher (averagely 174 m/s higher) than the recorded values. The difference in values mainly comes down to the neglect of retarding factors such as friction and heat transfer. From the trend lines it can be seen that the velocities increase at roughly the same rate in both cases, with the numerical values slightly flatter with a gradient of 27 compared to the recorded value's gradient of 31. This is encouraging as it gives validity to the accuracy of the numerical model.

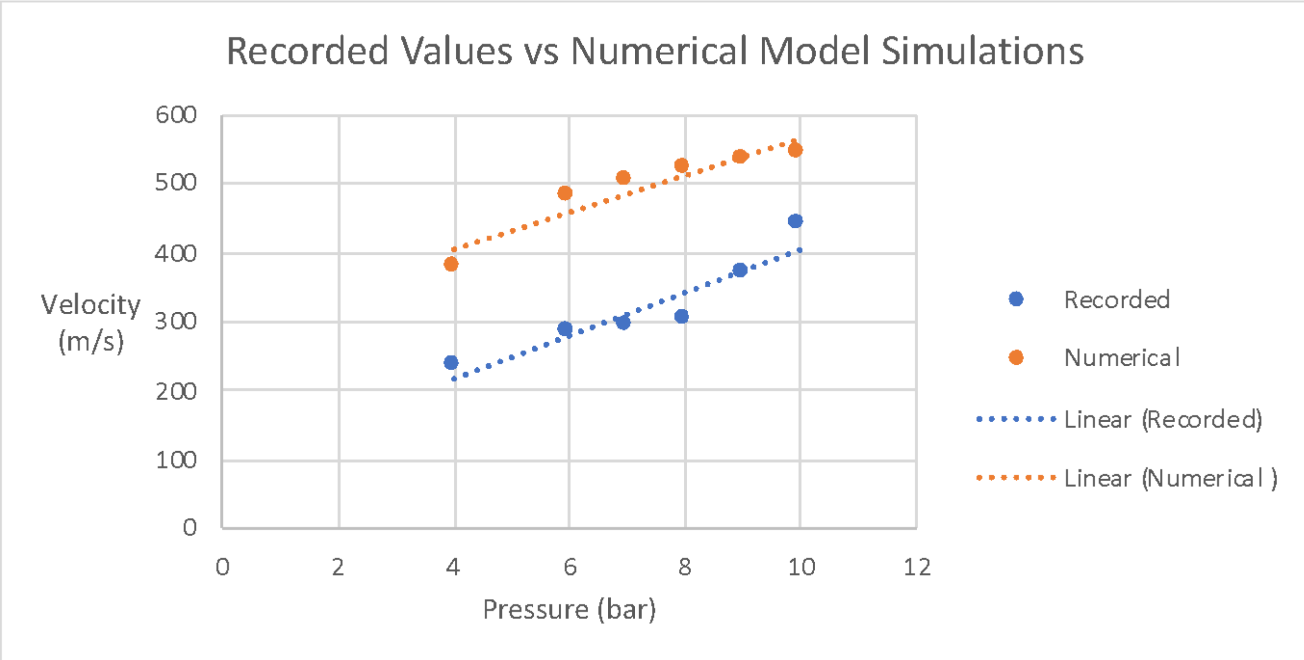


Figure 48: Graph Showing Recorded Results and Simulation Results

8.4 Piston Cap Effects

It was the intention that the piston cap would have to be replaced after each shot however, after examining the caps it was seen that minimal deformation occurred and hence the caps could be re-used several times. HDPE was mainly used for the piston cap as the other cap - which was intended to be made of polyethylene - was actually polypropylene (according to a plastic supplier) which is a harder plastic compared to HDPE and hence the focus was placed on the HDPE caps as it was the softer material and the certainty of this material was more reliable.

Furthermore, the piston caps are a factor that need special consideration, taking into account the material they are made of as well as the number of times they were used –

which influenced their degree of deformation. As the volume of the conical section of the transition piece is known, the final volume of the pressurised gas can be calculated using the volume that the piston cap had been deformed after each shot. In retrospect, a measurement of each piston cap should have been performed before and after every single shot. Unfortunately, this was not performed from the start and only on the third day of testing were the piston caps geometries documented before and after shots. In future it would be wise to document this throughout the entire testing in order to gather more data on the final volume of the second stage gas.

Below is a table showing the recorded results of the degree of deformation of the piston caps after the corresponding amount of uses. This is then used to calculate the final volume of the second stage gas assuming that the projectile had not moved up until this point. This assumption is not accurate as it is known that the projectile will move before its rapid acceleration however there was not an available means in place to measure this movement. The pressure of the final shot (where the cap is used multiple times) as well as the corresponding velocity is also shown. All the piston caps' original radii were 50 mm as well as the total volume of the conical section of the transition piece is 5.33×10^{-5} m^3.

Table 7: Table Showing Piston Cap Deformation

Piston Cap Material	Number of Uses	Pressure Used (bar)	Deformation radius (mm)	Deformation Depth (mm)	Deformation Volume (m^3)	Final Volume of Second Stage (m^3)	Velocity (m/s)
HDPE	1	8	48	4	7.544×10^{-6}	5.470×10^{-5}	238.09
HDPE	1	10	46	9	1.630×10^{-5}	3.700×10^{-5}	270.27
PP	1	10	47	6	1.109×10^{-5}	4.221×10^{-5}	416.67*
HDPE	5	10	44	12	2.085×10^{-5}	4.139×10^{-5}	444.44*
HDPE	7	9	43	13	2.212×10^{-5}	3.118×10^{-5}	392.16**

From the table, it can be seen that with the increased amount of use, there is a decrease in final volume of the second stage. This is expected as the cap will deform further into the conical section each time it is used. It can be seen from the table that a smaller final volume of second stage gas results in a higher velocity, which is again an expected observation.

There is an outlier with the shot corresponding to one use and 10 bar pressure. This shot results in a lower velocity for a fairly small final volume which is an interesting result and cannot be theoretically explained hence there must have been another factor influencing this shot.

As there is such limited data on the relationship between piston cap deformation and muzzle velocity, deductions cannot be conclusively drawn. However, from the data available, it can be said that the more deformed/coned the piston cap is, the higher the muzzle velocity for a given pressure. This can be observed from examining two sets of results in particular in the table below where the velocities were recorded. All shots used a solid projectile.

Table 8: Table Showing the Comparison Between Used and New Piston Caps

Piston Cap Material	Pressure (bar)	Piston Cap Quality	Velocity (m/s)
HDPE	9	Coned/Deformed	392.16
HDPE	10	New	270.27
PP	9	New	250
PP	10	Coned/Deformed	416.67

For the HDPE material, it can be seen that using a new piston cap even at a higher pressure gave a much lower muzzle velocity when compared to the highly deformed piston cap used at 9 bar. With regards to the PP (polypropylene) piston cap, it can be seen that using a new piston cap also resulted in a much lower muzzle velocity although this was at a slightly lower pressure. Thus, from this data it can be inferred that the use of a coned piston cap results in a higher muzzle velocity, which is an expected result. Nonetheless, as there is such limited data this will need to be followed up in the next project to either prove or reject this deduction.

By examining the piston caps, further observations were made. An HDPE piston cap after seven shots can be seen in the figures below.

Figure 50: HDPE Piston Cap Front Used Multiple Times

Figure 49: HDPE Piston Cap Showing Coning Used Multiple Times

Small black dots can be seen on the piston's front face and the surface has become rough, these markings are only around the edges and do not continue all the way to the centre (shown in Figure 50). It can be deduced that they are from the compression of this area and not from the high temperatures in the tube as they are not uniform across the entire face. From Figure 49 it can be seen that the front end is deformed into a slight conical shape and from the measurements recorded the higher pressures resulted in a large deformation whereas the lower pressures barely deformed the front. The figures below (Figure 51 and 52) show the deformation of the HDPE piston cap after 1 shot at 4 bar pressure. The front end is barely chamfered, and one can see a sliver of plastic has detached. Besides this slight coning there is no other deformation or change in appearance.

Figure 51: HDPE Piston Cap Front Face Used Once

Figure 52: HDPE Piston Cap Used Once

While dismantling the gun, the HDPE pistons slid back down to the start position only under the force of gravity. This indicates that the HDPE did not swell under the high temperatures and pressures, thus did not add more friction between its surface and the pump tube during re-use. The PP piston caps however did not slide back into place, some after only one use, therefore indicating that this material did swell under these conditions. Hence re-using this cap would have led to an increase in friction between its surface and the pump tube consequently leading to slower piston velocities.

Below is an image of the transition piece after the final shot where the coned HDPE piston cap was used. One can see the residue of plastic on the conical section inside the piece. This residue appears slightly burnt. Adding to this, after these high velocity shots there was a faint ‘burnt’ aroma coming out of the pump tube and barrel. Therefore, both of these observations indicate the high temperatures that are known to be present.

Figure 53: Transition Piece After Multiples Uses

8.5 Projectile After Use and Penetration of Wax Billets

The projectiles themselves were also examined after each shot and were not deformed in anyway and could be re-used without significant effect. They did have slight scrape marks which would indicate friction between their surface and the barrel due to small particles or general contact between the surfaces.

Figure 54: Used Solid Projectile

Another way of measuring the velocity could have been to measure how deep the projectile penetrated the wax billet. However, the hollow projectiles did not penetrate straight into the wax but rather veered sideways as soon as they entered and hence depth readings could not be used to infer velocity. Below are the images of the projectiles in the wax billets. One can see that the two solid projectiles (the left and centre image, Figure 56 and 57) go fairly straight whereas the hollow projectile curves in the wax (right image, Figure 55).

Figure 57: Low Velocity Solid Projectile in Wax Billet

Figure 56: High Velocity Solid Projectile in Wax Billet

Figure 55: Low Velocity Hollow Projectile in Wax Billet

8.6 Single Stage Model Comparison

As mentioned in the literature review the use of single stage gas gun would not be sufficient in terms of achieving the desired supersonic velocity. For the now known mass of projectile being used the muzzle velocity is as shown from Equation 9;

$$v = \sqrt{\frac{2 * 10^6 * \frac{\pi}{4}(0.01)^2 * 2.9}{0.00248}}$$

$$v = 428.58\, m/s$$

This velocity is supersonic however this is neglecting any fraction or heat transfer as well as this equation assumes a constant base pressure throughout the entire launch of the projectile, which is far from reality. This maximum theoretical velocity is lower than the achieved maximum of 444 m/s using the two-stage gas gun. Hence it cannot be assumed that a single stage gas gun could in reality achieve supersonic velocities whereas with this project is has now been proven.

8.7 Assembly Process

In terms of the assembly and dismantling, the whole process was fairly easy and could be dismantled and assembled again within 5 minutes, however the process required two people. The reloading of the wax billets and removing the used projectile was the most time-consuming process. The tie rods were a good method of tightening and ensuring sealing as well as they made assembly easy. It should be noted that if the tie rods were not tightened sufficiently the whole assembly would leak. It would be ideal to design a method of reloading the piston without having to dismantle the entire gun however it is sufficient for the next project.

9 Conclusion and Recommendations

9.1 Conclusion

As a whole, the project was a success as the main goal of firing projectiles at supersonic velocities was achieved. The project also completed the project brief of designing, building and testing the prototype. However, the constraint of using air as the gas in both stages was not conformed to, as nitrogen was used as the first stage gas due to a mechanical failure in the laboratory. This was deemed acceptable in order for testing to proceed and did not affect the results in a significant manner. All other project restrictions were adhered to.

An added benefit of this project is that gas gun is still intact and operational and can be re-used in the following year as the project continues through the next iteration. The project remained within the scope that was originally outlined and fell just within the budget. The project completed an entire design cycle where a problem was proposed and evaluated, a potential solution was determined and was tested and proved to be correct. The project produced a working two-stage gas gun using only air (or nitrogen in this case) that could be used to fire repeated supersonic projectiles bringing the larger scale goal of testing protective materials much closer to being achieved.

9.2 Recommendations

Since this project is just one of the iterative steps in a longer process, it will run again a number of times in order to collect more data on two-stage gas guns and hopefully lead to a fully functional small scale two-stage gas gun that can be used in BISRU. Therefore, several recommendations can be made in order to help future students improve on the current design;

- Since the gun is still functional an easier way of reloading the piston needs to be designed. A hatch can potentially be made on the first flange that can screw in and out, along with the pump tube insert, allowing a much faster way to reload and remove the piston.

- A new light trap should be made that can measure higher velocities than the current one in order to eliminate the oscilloscope uncertainties.
- The holes for the tie rods can possibly be positioned so that they extend over the edge of the flanges, this will make assembly and disassembly much faster and easier. This can be done as there are no radial forces being exerted on the rods. Or the holes can be made slightly bigger to allow for easier removal and insertion of the rods as they often became caught.
- The flanges should be re-made out of aluminium to reduce weight and make assembly, maintenance etc. much easier. Additionally, the flange thickness could be reduced as it was slightly over designed.
- A method of reading the pressure inside the pump tube could be introduced to allow for more data to be collected and to gain a better understanding of what is happening inside the gun assembly during firing.
- A method of tracking the projectile's movement and velocity during the entire process could be introduced in order to gain more data on the actual final volume of the second stage gas.
- The piston cap could potentially be made of wax as it much cheaper than the plastics used however this would require a method of cleaning the gas gun after firing. Another alternative would be to use polyurethane which is a rubber material which would deform much better than the current piston caps.
- More barrel mounts should be made in order to ensure the barrel is exactly straight which would aid the projectile's motion.
- The barrel could be evacuated in order to reduce drag on the projectile during launch as currently it has loose sliding fit.
- A tighter fit between the projectile and the barrel could be designed in order to reduce losses.
- The piston should be remade out of aluminium to decrease its mass which showed from the simulations to give a higher muzzle velocity.

- A longer pump tube can be used in order to increase the overall performance of the gun as was seen in the numerical analysis. Adding to this it would be better to make a new pump tube as the current one is over designed and so much thicker than needed and hence incredibly heavy which added to assembling time and effort.

10 References

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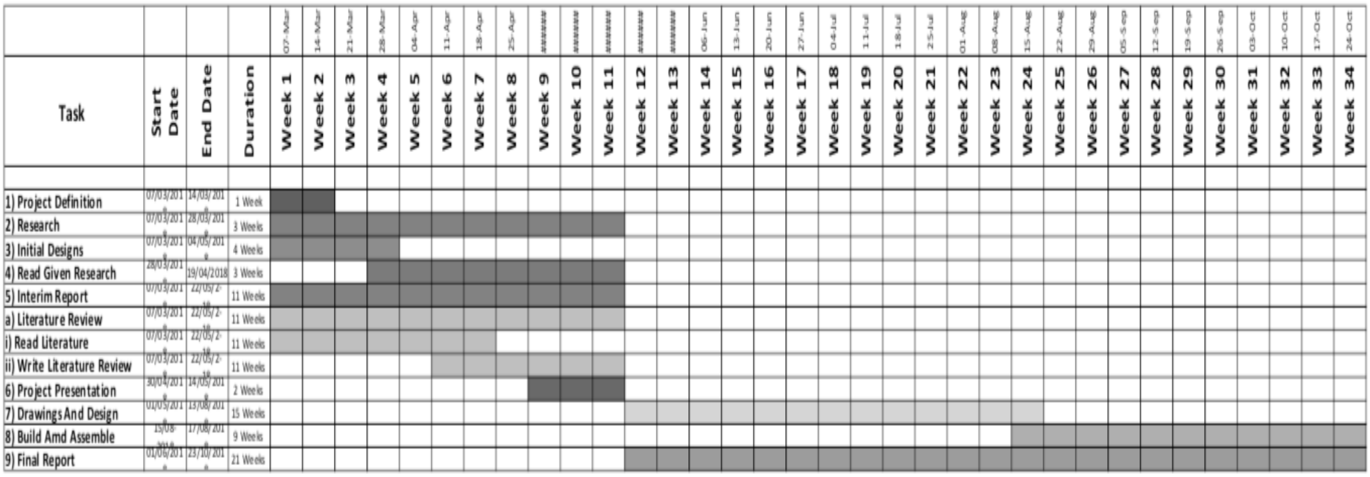
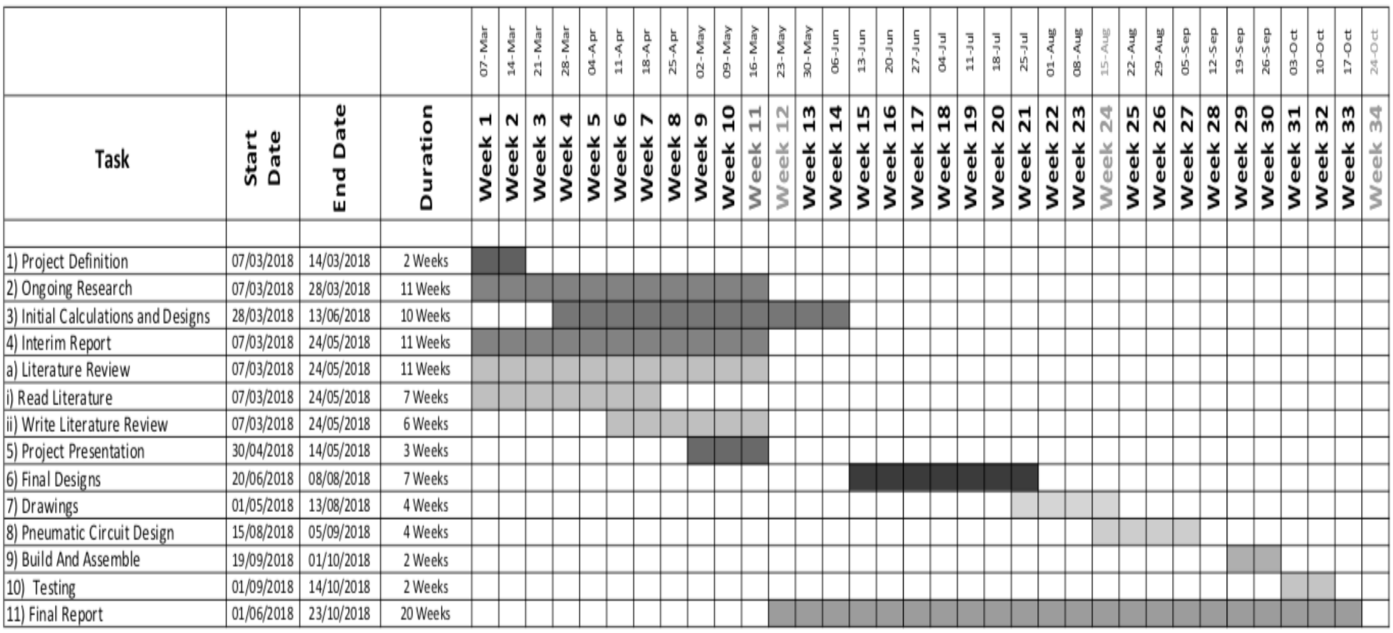
11 Appendices

11.1 Gantt Charts

11.1.1 Initial Gantt Chart



11.1.2 Final Gantt Chart



11.2 Numerical Model – Code

```
import numpy as np
import matplotlib.pyplot as plt

#define system
gamma = 1.4
rho_pist = 8750.0                               # density for piston
rho_def = 970.0                 # density for deformable part of piston polymer
rho_proj = 2700.0                               # density for projectile Al
L10 = 0.001                                     # initial length Section 1
Lpiston1 = 0.125                                # length of piston
Ldef = 0.05                     # length of deformable part of piston
Lprojectile = 0.022                             # length of projectile
d1 = 0.05                                       # diameter of Section 1
d2 = 0.01                                       # diameter of Section 2
P0 = 1100000.0                  # initial pressure in first stage and reservoir
L = 0.8                                         # length of pump tube
Lb = 2.9                                        # length of barrel
Vresevior = 0.005               # volume of the reservoir excluding pump tube

n_steps = 5000                  # number of time steps taken throughout
end_time = 0.1                                  # end time
time = np.linspace(0,end_time,n_steps)          # time vector
delta_t = time[1] - time[0]                     # time step size 0-indexed

#empty vectors to store solution
x1 = np.zeros(n_steps+1)
v1 = np.zeros(n_steps+1)
a1 = np.zeros(n_steps+1)

x2 = np.zeros(n_steps+1)
v2 = np.zeros(n_steps+1)
a2 = np.zeros(n_steps+1)

P1vec = np.zeros(n_steps+1)
P2vec = np.zeros(n_steps+1)
V1vec = np.zeros(n_steps+1)
V2vec = np.zeros(n_steps+1)
T2vec = np.zeros(n_steps+1)

A1 = np.pi*(d1**2)/4                             # area of inside pump tube
A2 = np.pi*(d2**2)/4                             # area of inside barrel

Vpiston = A1 * Lpiston1            # volume of steel section of piston
Vdef = A1 * Ldef                   # volume of deformable section of piston
V0 = A1 * L10 + Vresevior          #initial starting volume - including reservoir

#m1 = Vpiston*rho_pist + Vdef*rho_def            # mass of entire piston
#m2 = A2*Lprojectile*rho_proj     # mass of projectile - assuming it is a cylinder

m1 = 0.52484                                     # weighed value of piston
#m1 = 0.300
m2 = 0.00248                       # weighed value of projectile - hollow
#m2 = 0.00358                      # weighed value of projectile - solid
#m2 = 0.001

x1max = L - Lpiston1 - Ldef - L10    # max length of the piston stroke - end to end
Vtotal = A1*L + A2*Lb              # total volume of p.t and barrel

#initial conditions
x1[1] = 0.0
v1[1] = 0.0
a1[1] = P0*A1/m1                                 # from equation of motion
```

```python
x1[0] = x1[1] - delta_t*v1[1]+a1[1]*(delta_t**2)/2
v1[0] = v1[1] - delta_t*a1[1]

x2[1] = 0.0
v2[1] = 0.0
a2[1] = 0.0                                          # from equation of motion
x2[0] = x2[1] - delta_t*v2[1]+a2[1]*(delta_t**2)/2
v2[0] = v2[1] - delta_t*a2[1]

P20 = 100000.0
T20 = 296.0
V20 = A1*L - A1*L10 - Vpiston - Vdef + 5.33*(10**-5)    # initial volume of the
second stage including conical section

# collision and exit
exit_barrel = False
hit_chamber_end = False

#loop over all timesteps
for n in range(1,n_steps):
    V1 = V0 + A1*x1[n]
    V2 = V20 - A1*x1[n] + A2*x2[n]
    P1 = P0*(V0/V1)**gamma
    P2 = P20*(V20/V2)**gamma
    T2 = T20/((P20/P2)**((gamma-1)/gamma))
    if x2[n] >= Lb:
        if exit_barrel == False:
            exit_barrel_time = time[n]
        exit_barrel = True
        P2 = P20

    x1[n+1] = 2*x1[n] - x1[n-1] + (delta_t**2)/m1*(P1*A1-P2*A1)
    if x1[n+1] >= x1max:
        if hit_chamber_end == False:
            hit_chamber_end_time = time[n]
        hit_chamber_end = True
        x1[n+1] = x1max

    # making the piston stop in the final position (can't rebound)
    if hit_chamber_end == True:
         x1[n + 1] = x1max

    # central difference equations of motion
    v1[n] = (x1[n+1] - x1[n-1])/(2*delta_t)
    a1[n] = (x1[n+1] - 2*x1[n] + x1[n-1])/(delta_t**2)

    x2[n+1] = 2*x2[n] - x2[n-1] + (delta_t**2)/m2*(P2*A2-P20*A2)
    v2[n] = (x2[n+1] - x2[n-1])/(2*delta_t)
    a2[n] = (x2[n+1] - 2*x2[n] + x2[n-1])/(delta_t**2)

    # making the pressure in bar
    P1vec[n] = P1/100000
    P2vec[n] = P2/100000

    V1vec[n] = V1
    V2vec[n] = V2
    T2vec[n] = T2

x1 = x1[1:]
v1 = v1[1:]
a1 = a1[1:]

x2 = x2[1:]
v2 = v2[1:]
a2 = a2[1:]
```

```python
P2vec = P2vec[1:]
P1vec = P1vec[1:]
V2vec = V2vec[1:]
V1vec = V1vec[1:]
T2vec = T2vec[1:]

print(max(v2))
print(max(P2vec))
print(np.size(x1))
print(min(v2))
print(max(T2vec))

# plotting the graphs
plt.figure(0)
plt.subplot(221) #(number of rows, number of columns, number of this plot)
plt.plot(time, x1, 'k', time, x2, 'b')

plt.xlabel('time - $t (s)$')
plt.ylabel('Displacement \n $x_1, x_2 (m)$')
if hit_chamber_end == True:
    plt.plot([hit_chamber_end_time,hit_chamber_end_time] , [ min(min(x1),min(x2)),
max(max(x1),max(x2))], '--r')
if exit_barrel == True:
    plt.plot([exit_barrel_time,exit_barrel_time] , [ min(min(x1),min(x2)),
max(max(x1),max(x2))], '--g')
plt.legend(['$x_1$','$x_2$', 'hit end', 'exit barrel'], loc=1)
axes = plt.gca()
axes.set_ylim([0,5])


plt.subplot(223)
plt.plot(time[:-1], v1[:-1], 'k', time[:-1], v2[:-1], 'b')
if hit_chamber_end == True:
    plt.plot([hit_chamber_end_time,hit_chamber_end_time] , [ min(min(v1),min(v2)),
max(max(v1),max(v2))], '--r')
if exit_barrel == True:
    plt.plot([exit_barrel_time,exit_barrel_time] , [ min(min(v1),min(v2)),
max(max(v1),max(v2))], '--g')
plt.xlabel('time - $t (s)$')
plt.ylabel('Velocity \n $\ (m.s^{-1})$')
plt.legend(['$v_1$','$v_2$', 'hit end', 'exit barrel'], loc=0)

# plt.subplot(413)
# plt.plot(time[:-1], a1[:-1], 'k', time[:-1], a2[:-1], 'b')
# plt.xlabel('time - $t (s)$')
# plt.ylabel('Acceleration \n $\ddot{x}_1 (m.s^{-2})$')

plt.subplot(222) #(number of rows, number of columns, number of this plot)
plt.plot(time[:-1], V1vec[:-1], 'k', time[:-1], V2vec[:-1], 'b')
plt.xlabel('time - $t (s)$')
plt.ylabel('Volume \n $\ (m^{3})$')
if hit_chamber_end == True:
    plt.plot([hit_chamber_end_time,hit_chamber_end_time] , [
min(min(V1vec),min(V2vec)), max(max(V1vec),max(V2vec))], '--r')
if exit_barrel == True:
    plt.plot([exit_barrel_time,exit_barrel_time] , [ min(min(V1vec),min(V2vec)),
max(max(V1vec),max(V2vec))], '--g')

plt.legend(['V1','V2', 'hit end', 'exit barrel'], loc=4)


#plt.subplot(224)
#plt.plot(time[:-1], P1vec[:-1], 'k', time[:-1], P2vec[:-1], 'b')
#if hit_chamber_end == True:
#    plt.plot([hit_chamber_end_time,hit_chamber_end_time] , [
min(min(P1vec),min(P2vec)), max(max(P1vec),max(P2vec))], '--r')
```

```
#if exit_barrel == True:
#    plt.plot([exit_barrel_time,exit_barrel_time] , [ min(min(P1vec),min(P2vec)),
max(max(P1vec),max(P2vec))], '--g')
#plt.xlabel('time - $t (s)$')
#plt.ylabel('Pressure \n $\ (bar)$')
#plt.legend(['P1','P2', 'hit end', 'exit barrel'], loc = 1)

plt.subplot(224)
plt.plot(time[:-1], T2vec[:-1], 'b')
if hit_chamber_end == True:
    plt.plot([hit_chamber_end_time,hit_chamber_end_time] , [ min(T2vec),
max(T2vec)], '--r')
if exit_barrel == True:
    plt.plot([exit_barrel_time,exit_barrel_time] , [ min(T2vec) , max(T2vec)], '--
g')
plt.xlabel('time - $t (s)$')
plt.ylabel('Temperature \n $\ (K)$')
plt.legend(['T2', 'hit end', 'exit barrel'], loc = 1)


plt.show()
```

11.3 Technical Drawings

11.4 Risk, Safety, Ethics and Impacts Forms