UNIVERSITY OF CAPE TOWN

Department of Mechanical Engineering

RONDEBOSCH, CAPE TOWN
SOUTH AFRICA

2019

PROJECT No:
80

REDESIGN, MODIFY & TEST A SMALL TWO-STAGE GAS GUN

Viveshan Govender

GVNVIV009

To improve the design of protective equipment against improvised explosive devices (IEDs), it is important to have detailed knowledge of the way structures respond to projectile impact events. To do this, laboratory scale projectile launchers are required that are capable of safely launching large projectiles at high subsonic speeds and small projectile at supersonic speeds. To attain supersonic speeds, a driving gas at high initial pressure and temperature is required. 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. Recently, a small two-stage gas guns has been developed at the Blast Impact and Survivability Research Unit (BISRU) that is able to launch a small projectile at 400 m/s using 5 L of compressed air at a pressure of 1 bar. The aim of this project is to redesign, 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. The project will primarily focus on converting the current prototype to functional apparatus for routine testing and conducting extensive testing to map out the performance.

Words in Body:15000

SUPERVISOR:

Mr Trevor Cloete

I. Plagiarism Declaration

1. I know that plagiarism is wrong. Plagiarism is to use another's work and pretend that it is one's own.
2. Each significant contribution to, and quotation in, this assignment from the work(s) of other people has been attributed and has been cited and referenced.
3. This assignment is my own work.
4. I have not allowed and will not allow anyone to copy my work with the intention of passing it off as his or her own work.

Surname	Initials	Student Number	Signature
GOVENDER	V	GVNVIV009	

Date 08/10/2019

II. Abstract

This report aims to redesign a small two-stage gas gun that is capable of firing small projectiles at supersonic speeds and bigger projectiles at high subsonic speeds while making it more routine and user friendly.

The main goal of this project is to redesign the 2018 prototype with the aim of improving its usability and making it more routine by improving reload and piston replacement times.

Once the basic theory is reviewed numerical modelling of the gun will be created and used to check the parameters that affect the efficiency and performance of the gas gun. A basic concept is then generated.

III. Acknowledgements

Contents

List of Figures

List of Tables

1. Introduction

This project aims to redesign, modify and test the prototype two stage gas gun built in 2018. This two stage gas gun will be used for high velocity impact testing in the Blast Impact and Survivability Research Unit at the University of Cape Town. The main goal of this project is to improve the design in terms of usability to make it more user friendly and easier to operate on a routine basis while maintaining or improving it performance.

A Two-stage gas gun is a device that is used to launch a projectile at very high velocities with a smaller form factor design than a single stage gas gun. They are in this way more effective than single stage gas guns but are however less efficient. The gun has two chambers (stages) separated by a free piston, where the first chamber contains the driving gas and the second chamber contains a gas at atmospheric pressure. The driving gas in the first stage is used to drive the piston and compress the gas in the second chamber to a much higher instantaneous pressure and temperature. This gas is then used to drive the projectile down the barrel.

This project is an ongoing process an is being improved on each year with the hope of having a fully functional high velocity gas gun that can be used for testing and further research on the functioning of the intricate gas dynamics and operating principals of the gas gun.

The main consideration in redesigning the gun is to make it more user-friendly so that it can be effectively and efficiently used for routine testing and experimentation. The current design requires the gun to be fully disassembled to replace the piston cap and projectile, which is a cumbersome and time consuming process that needs to be conducted frequently. The goal is to design a gun that allows for the removal of the piston and projectile with minimal disassembly.

1.1 Project Limitations, Scope and Goals

1.1.1 Project Constraints and Limitations

One of these constraints has been changed since the start of the project, namely the overall length constraint. The location of the gas gun was decided to remain on the current I-beam, this reduced the limit on the overall gas gun length.

The following constraints and limitations must be considered throughout the design process.

- The is a overall length constraint on the gas gun and the space available on the current I-beam ($4m$) needs to be considered.

- The first stage(supply) pressure is limited to 10 bar ($1MPa$).
- The reservoir Volume is limited to 5 litres.
- Air is to be used in both stages (This is not and absolute constraint).
- Other gasses are an option provided that they are non volatile, non-toxic and fits within the budget.
- The reload process needs to be short (< 5 minutes) to ensure that repeated firing is possible with minimal effort and disassembly.

The gun needs to be safe to operate and assemble. All the relevant regulations(SANS)surrounding pressure vessels need to be adhered to . The pressure and volume in the first stage chamber are constrained to ensure that the vessel does not have to be certified - this will be verified in the report.

1.1.2 Scope and Goals

The scope of this project is to redesign the current two-stage gas gun such that it is more user-friendly. The gun needs to reach at least Mach 1 as well as have a short (< 5min) and easy reload process. The light trap that is currently being used to measure the projectile speed needs to be improved in terms of accuracy.

A long term goal of this project is to gather data from the gun to better understand gas dynamics.

2. Literature Review

The literature that will be reviewed below will mainly focus on gas gun designs so that the important aspects for the success of the gun can be determined and used in the design of this prototype. It will star with some basic background and history on 2 stage gas guns and then go into more detail. Literature on the working principals and theory behind single stage gas guns, and its limitations will be reviewed. The theory and principals applicable to 2 stage gas guns are then examined and the differences between single and two stage gas guns are discussed. Finally the detailed working principals and design of 2 stage gas guns are explored.

2.1 History of two-stage gas guns

Light gas guns operate in a similar way to conventional fire arms that use gun powder. The main difference is in the method of achieving the necessary pressure required to accelerate the projectile. Firearms use the combustion of gunpowder to accelerate the projectile and light gas guns use a compressed gas reservoir to achieve this.[5]

Common light gas guns include single stage gas guns, two stage gas guns and shock tunnel/shock tubes. Single stage gas guns are the simplest design. Single stage gas guns comprise of just one high pressure chamber that is used to accelerate the projectile down a barrel. Two stage gas guns are a more complex design that allows for higher pressures and therefore higher velocities than single stage gas guns. A two stage gas gun has an additional compression stage that allows the the final pressure to be much higher than that achieve in single stage guns. It achieves this pressure increase by combustion, heating, or free piston compression. Shock tubes are fundamentally the same as gas guns barring the projectile, they produce a gas blast wave on the target as opposed to launching a projectile at it.[5]

The first gas gun was designed and developed at the New Mexico school of mines in 1946 by Crozier and Hume. A. H. Jones first used the concept of two stage light gas gun for materials research at General Electric in the US. The gun used measured 30m in length and had a 25mm diameter launch tube and was used to conduct shock compression measurements of various metals.[6]

Around the mid nineteenth century, a great amount of research was conducted around the techniques involved in launching projectiles to high velocities (orders of Mach number).[7]

The US military conducted extensive research in the first few years after WWII in an attempt to simulate the hyper-velocity flight of various ballistic missile systems.[7]

In the 1950's interest around this topic peaked again, in particular from the US space program. They were concerned with the potential hazards and damage that could result from high velocity meteoroid impacts during space missions.[7]

2.2 Uses of two stage gas guns

Gas guns are typically used to to test material and composite properties for their suitability for armour applications. They can also be used, on a small scale, to simulate the impacts of small rocks on a moving vehicle, ice rocks on an aircraft in motion. Another prominent use is for the testing of spacecraft materials and components.

These guns are used extensively in the spacecraft design as the threat of impact of micrometeroids and man made orbital debris is massive. It is estimated that there is somewhere is the rage of $300kg$ of orbital debris measuring less than $1mm$ in diameter within a $2000km$ distance of the earth's surface. These particles travelling with velocities in excess of $10km/s$ relative to a travelling space craft.[5]

2.3 Governing Thermodynamic Theory

Since the driving mechanism in the gas gun is a pressurised gas (air). The pertinent theory of gasses under compression will be explored below to aid in the development of the theory and design on the two stage gas gun.

Two important assumptions will be made to narrow down and simlify the theory used to develop the gas gun theory. The first assumption is that the gas expansion is 1 dimensional. The second assumption that will be made is that the expansion and compression of the gas is adiabatic and reversible (isentropic). This essentially means that the friction and heat transfer effects within the gas are negligible. This assumption has been shown to be a good approximation and allow for a relatively simple solution to the problem [3].

2.3.1 Is the Isentropic Assumption Valid For a Gas Gun?

The isentropic assumption means that the process is reversible and adiabatic, i.e. the effects of friction and heat transfer are absent. For a process to be considered isentropic it needs the process to occur very slowly such that the gradients are infinitesimally small. This raise the question as to whether the assumption can be applied to a gas gun as the expansion of the gas occurs extremely rapidly (in the order of milliseconds). This rapid expansion will most definitely result in pressure, temperature and velocity gradients throughout the rapidly expanding gas.

All real processes are irreversible due to the existence of finite gradients. The irreversibilities associated with the process of rapid expansion are far smaller than those associated with that of rapid compression or expansion retardation. If one were to look at the various gradients in rapid expansion vs. compression, the expansion gradients will tend to decrease and the compression increase - resulting in turbulence and shock.

Therefore for the rapid expansion of gas in the gas gun from one equilibrium to another, most of the irreversibility occur in the deceleration part of the expansion. One therefore needs to consider to what extent is the process irreversible.

In [3] it was stated that the insentropic theory had good agreement with the experimental results at lower velocities ($< 12000 ft/s = 3657,6 m/s$). Since the gas gun being designed in this project will realistically reach speeds under Mach 1 this assumption will be valid.

2.3.2 Isentropic relationships

The isentropic property relationships are as follows

$$\frac{P_0}{P} = \left(\frac{V}{V_0}\right)^{\gamma} \tag{2.1}$$

$$\frac{P_0}{P} = \left(\frac{T_0}{T}\right)^{\frac{\gamma}{\gamma-1}} \tag{2.2}$$

$$\frac{P}{P_0} = \left(\frac{\rho}{\rho_0}\right)^{\gamma} \tag{2.3}$$

2.3.3 Work-Energy Relationship

The work energy relation ship forms the foundation of the analysis, the underlying equations are therefore shown here.

$$F = PA \tag{2.4}$$

$$W = F\mathrm{dx} = \int \mathrm{dV} \tag{2.5}$$

$$T = \frac{1}{2}mv^2 \tag{2.6}$$

2.4 Operating principals of single stage gas guns

2.4.1 Basic Principals

The purpose of a light gas gun is to accelerate a projectile to the required speed. This acceleration is produced by the pressure difference over the projectile and is dependent on the driving pressure P_0, the cross sectional area A and the projectile mass m. The acceleration can be determined from newtons second law as follows:

$$a = \frac{P_0 A}{m} \tag{2.7}$$

A realistic estimate of the muzzle velocity can be found by assuming that the gas reservoir is an infinitely long tube with the same diameter as the barrel. Doing this allows one to disregard reflection and refraction waves in the gas reservoir.[3][5]

Seigel [3] showed that the following relationship can be used to obtain a fairly realistic estimate of the projectile velocity. Where P_0 is the initial pressure γ is the ratio of specific heat capacities and a_0 is the speed of sound in the driving gas.

$$P = P_0 \left[1 - \frac{(\gamma-1)\,v}{2a_0}\right]^{\frac{2\gamma}{\gamma-1}} \tag{2.8}$$

2.4.2 Ideal Gas Assumption

A single stage gas gun operates by using pressurised gas to drive a projectile down a barrel. Figure 2.1 shows a schematic of a single stage gas gun, where P_0, V_0, A, a, m are the initial pressure, initial volume, reservoir cross sectional area, barrel cross sectional area and projectile mass respectively.[1]

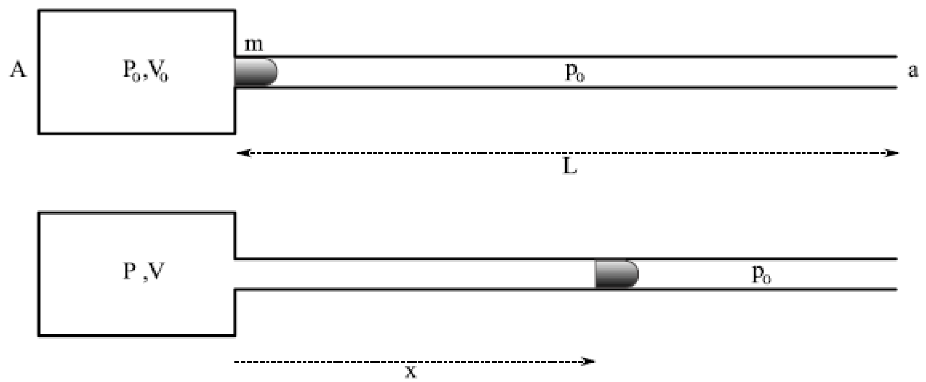


Figure 2.1: Single stage gas gun schematic[1]

A two stage gas gun operates by having a reservoir that is pressurised to a predetermined pressure for the required projectile velocity. This high pressure reservoir is separated from the barrel by either a diaphragm (typically in shock tubes) or a valve that is used to expose the high pressure to the projectile, accelerating it down the barrel.

In order to achieve significantly high velocities with a single stage gas gun a high pressure vessel and long barrels are required.

Knowing that pressure is not constant with expansion due to an increase in volume and assuming that the process is isentropic expansion of an ideal gas properties, an expression for the projectile velocity can be determined as follows.[3]

The pressure-volume and pressure temperature relationships are as follows, where P_0, V_0, T_0 are the initial pressure volume and temperature respectively.

$$\frac{P_0}{P} = \left(\frac{V}{V_0}\right)^{\gamma} = \left(\frac{T_0}{T}\right)^{\frac{\gamma}{\gamma-1}} \tag{2.9}$$

The work done on the projectile can be found by integrating the pressure over the volume.

$$W = \int_{V_0}^{V(x)} \frac{P_0 V_0^{\gamma}}{V(x)^{\gamma}} \mathrm{d}V(x) = \frac{P_0 V_0}{\gamma - 1}\left[1 - \left(\frac{V(x)}{V_0}\right)^{1-\gamma}\right] \tag{2.10}$$

If we assume no losses and that the pressure remains the same everywhere (i.e. the projectile velocity is less than the speed of sound in the gas), then all the work is converted to kinetic energy and a theoretical expression for the projectile velocity can now be found.

$$\frac{P_0 V_0}{\gamma - 1}\left[1 - \left(\frac{V(x)}{V_0}\right)^{1-\gamma}\right] = \frac{1}{2}mv^2 \tag{2.11}$$

$$v=\sqrt{\frac{2P_0V_0}{m\left(\gamma-1\right)}\left[1-\left(\frac{V\left(x\right)}{V_0}\right)^{1-\gamma}\right]} \tag{2.12}$$

If we make the assumption of a constant diameter gas gun the velocity can be expressed follows, where x is the projectile position along the barrel and x_0 is the equivalent initial length of the barrel such that it has the same initial volume V_0 and diameter as the barrel.

$$v=\sqrt{\frac{2P_0V_0}{m\left(\gamma-1\right)}\left[1-\left(\frac{x}{x_0}\right)^{1-\gamma}\right]} \tag{2.13}$$

A plot of this velocity against barrel length is shown on Figure 3.1 on page 13 in the Theory section.

2.4.3 Gas Dynamics Assumption

Considering the effects of gas dynamics the maximum attainable exit velocity for the projectile is only a function of the specific heat ratio, ideal gas constant and temperature. It is independent of the initial pressure and volume, which means that one cannot simply keep increasing the driving pressure to reach higher velocities. The governing equations are given below [2].

$$c=\sqrt{\gamma RT} \tag{2.14}$$

$$v_{max}=\frac{2}{\gamma-1}\sqrt{\gamma RT} \tag{2.15}$$

The ideal gas assumption over estimates the performance characteristics and once can infinitely obtain higher velocities if the initial base pressure is increased. The gas dynamics approach has a maximum attainable velocity based on the gas properties and is lower than the ideal gas outputs - it is therefore the limiting case.

The following was derived in [2] to show a relationship between barrel length and projectile exit velocity considering the effects of gas dynamics.

$$L=\frac{v_{max}^2}{\dot{v}_{max}}\frac{\gamma-1}{2}\left[\frac{2}{\gamma+1}\left[\left[1-\frac{v}{v_{max}}\right]^{-\frac{\gamma+1}{\gamma-1}}-1\right]-\left[1-\frac{v}{v_{max}}\right]^{-\frac{\gamma+1}{\gamma-1}\frac{2}{\gamma+1}}\right] \tag{2.16}$$

where,

$$v_{max}=\frac{2}{\gamma-1}\sqrt{\gamma RT}$$
$$\dot{v}_{max}=a_{max}=\frac{P_{net}}{m_{projectile}}$$
$$v=\text{Exit Velocity}$$
$$L=\text{Barrel length}$$

Figure 2.2 shows the attainable velocity for a given barrel length. It was also shown in this paper that beyond a barrel length of $5m$ the results in terms of velocity had diminishing returns. This also shows that the barrel length for nitrogen at 25bar and a barrel diameter of 12mm requires a barrel length greater than $5m$ to reach the speed of sound for a $10g$ projectile.[2]

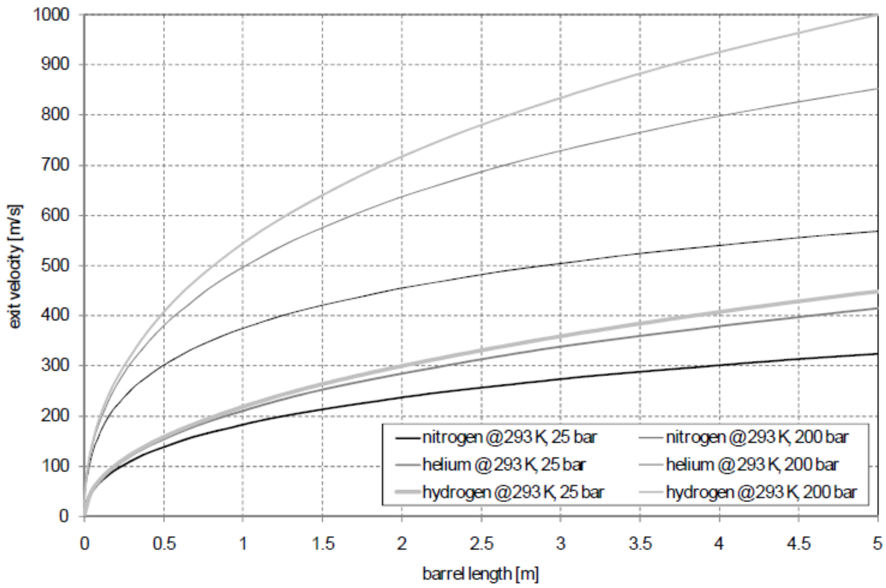


Figure 2.2: Exit velocity for an ideal constant diameter gas gun with a 12 mm bore and 10 g projectile [2]

It is therefore beneficial to explore 2 stage gas guns when space is a constraint and high static pressures are not an option. Two stage gas guns allow for high Temperature and Pressure gasses, in a shorter space, both of which are paramount to achieving high velocities.

2.5 Operating principals of two-stage gas gun

It is necessary to explore two stage gas guns as the barrel lengths and initial pressures required in single stage gas gun are are not feasible.

Two stage gas guns are based on the operating principle developed for the single stage model earlier. The two stage gas gun comprises of a reservoir which supplies pressure to the first stage, and a second stage is separated from the first stage by a free piston. The idea is that the pressure in the reservoir is used to accelerate the free piston by doing work on it, to allow it to compress the gas in the second stage from an ambient pressure to a much higher pressure. This pressure in the second stage is then used to drive the projectile down the barrel (From this point the gun behaves as a single stage model.

Two stage gas guns are more efficient than single stage guns as the second stage allows for a significantly higher transfer of compressed gas energy to the projectile for the same initial pressure as a single stage gas gun.[1]

The effectiveness of energy transfer to the piston is determined by the volume of the pump tube. Therefore a large pump tube volume is beneficial as the work done by the expanding gas is the pressure integrated over volume. The dynamics of two stage gas guns, and interplay between the barrel length and projectile inertia result in the piston energy being rapidly transferred to the projectile. It was also shown in a paper by Mark Denny [1] that single stage gas guns convert approximately 9% of the compressed gas energy to projectile kinetic energy whereas 2 stage gas guns convert about 47% of the initial gas energy.[1]

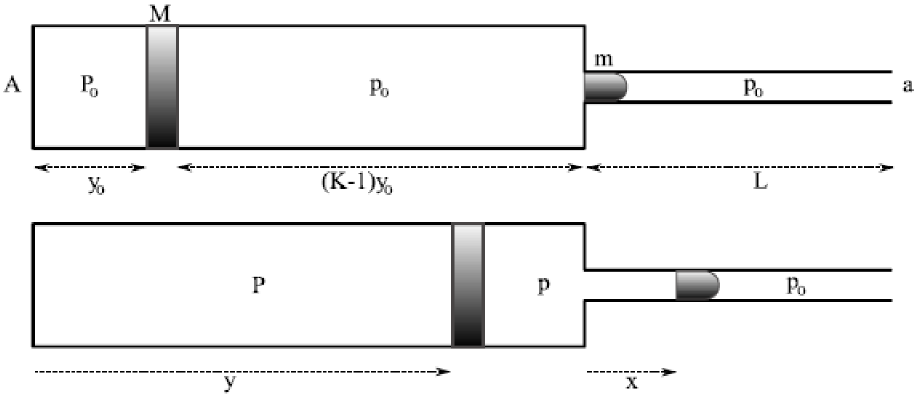


Figure 2.3: Two stage gas gun schematic [1]

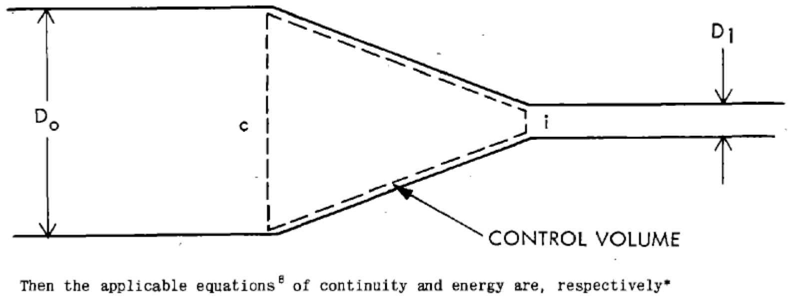


Figure 2.4: Control Volume transition piece [3]

The thermodynamic properties in the first stage of the gas gun can be calculated from the zero dimensional(the pressure equilibrates instantaneosly) expressions for mass and energy if the assumption of ideal gas and adiabatic expansion are assumed [8]. The equation of motion can be determined for the piston by applying newtons second law to it where the force is caused by the pressure imbalance between the two stages. By using a low pressure in the second stage (generally atmospheric pressure) very high compression ratios can be achieved which results in very high final pressures and temperatures. This allows for much higher projectile velocities. The final pressure in second stage is found on the basis that the kinetic energy of the piston is ideally converted to work in the second stage under the ideal gas assumption[8].

An analytical solution for the projectile velocity can be found by assuming the compression in the first stage is isentropic and the piston reaches the end of its stroke before the projectile moves. A control volume in the transition piece (Figure 2.4) can be taken to apply the energy conversion to the projectile [3]. This is sufficinet for a first order approximation, however, in reality this is better aproximated by an 1D model [8].

2.5.1 Pressure Disturbances

As the projectile moves within the barrel a rarefaction disturbance is transmitted into the gas at the speed of sound in the opposite direction of the projectile. If one were to consider an infinitesimal layer of gas behind the projectile at every instant in time, there exists an infinitesimal rarefaction disturbance in this layer resulting in an infinitesimal pressure drop in the layer of gas behind it. As the projectile moves along the barrel it leaves a low pressure region directly behind the projectile which the layer of gas directly behind fills and drops in pressure. As the projectile moves along the barrel all these infinitesimal pressure drops add up and have a finite effect, the figure below shows this. A qualitative analysis shows that the faster the layer of gas behind the projectile moves to fill the evacuated space behind the projectile the lower the effect of rarefaction will be. This indicates that a driving gas with low inertia and therefore low mass will be beneficial. It should also be noted that this effect is more noticeable at higher velocities.[3]

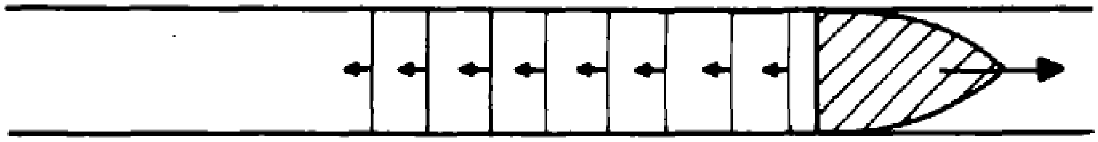


Figure 2.5: Rarefaction Pressure disturbances [3]

2.5.2 Pressure build up ahead of the projectile

The pressure build up in front of the projectile is another factor that will affect the projectile velocity.[5]

The expression for this pressure was derived in The Theory of High Speed Guns, the final expression of which is given below. [3]

$$\frac{P_t}{P_1} \approx 1 + \left(\frac{v}{a_1}\right)^2 \frac{\gamma_1(\gamma_1+1)}{4} + \frac{\gamma_1 v}{a_1}\left[1 + \left(\frac{\gamma_1+1}{4}\right)^2 \left(\frac{v}{a_1}\right)^2\right]^{\frac{1}{2}} \tag{2.17}$$

P_t is the pressure that builds up ahead of the projectile, P_1 is the initial pressure ahead of the projectile, γ_1 is the ratio of specific heat capcities and a_1 is the speed of sound.

2.6 Optimisation

Decreasing the molecular mass of the driving gas has been shown to increase the muzzle velocity. The rationale behind this is that the gas and projectile needs to be accelerated. If the molecular mass is decreased then the speed of sound increases and one can attain a higher muzzle velocity.[5]

Using a gas with a lower specific heat ratio and higher specific gas constant results in higher final velocities as the gas has more energy per kg. The table below gives the properties of some gasses, it can be seen that hydrogen would be an ideal option however as it gas constant is significantly higher than other similar gasses. However due to the volatility of this gas it will be ruled out as an option in most cases.

Table 2.1: Add caption

Gas	$R(Jkg^{-1}K^{-1}$	γ	$M_g(g)$	δ
Air	287	1.4	3.84	0.5
CO_2	189	1.3	5.84	0.76
H_2	4124	1.4	0.27	0.035

2.7 Existing Two-Stage Gas Gun Designs

There are many existing two stage gas guns designs, most of which are large scale testing apparatus housed in labs at various institutions all over the world. Most of these gas guns are used for ultra high velocity impact testing and are as a result very complex in design and large in size. Many of these guns use a combustion in the initial stage to drive the piston. These guns are generally capable of firing small projectiles in the region of $1km/s$ all the way up to $10km/s$.

Most of the designs of the existing two-stage gas guns that currently exist have concentrated mainly on the pump tube length and volume as well as the barrel length, initial pressures and temperatures of the gasses in both stages as the variables for optimisation purposes. The deformable piston cap material and weight was also a key consideration in performance optimisation.

Many of the designs use an in-line mounting of the stages, i.e the reservoir and pump tube are mounted longitudinally (not concentrically). The reason for this is that they use a combustion reaction to drive the free piston as opposed to a pressurised gas, so this gives better access to the various components. Typically space is not of great concern with these designs as they have dedicated laboratories. Another typical design of these gas guns is a tapered piece between the pump tube and barrel, where the deformable piston gets lodged into after a shot. Due to the very high initial pressures these pieces typically deform into the entire tapered piece and in some instance become lodged into the barrel.

Many of these gas guns also make use of a diaphragm between the second stage and the barrel. This is done to ensure that the correct pressure is reached in the second stage before it is exposed to the projectile. This results in higher compression ratios as the projectile remains stationary until the correct pressure is reached.

3. Theory

3.1 Single stage Gas gun Performance

A graph for barrel length versus projectile velocity can be plotted to demonstrate the performance of two stage gas guns. This plot is shown below using two different theories, The ideal gas assumption and the gas dynamics assumption.

The graph below is for a 5g projectile accelerated down a 10mm diameter barrel by an initial pressure of 10 bar.

The equations used to plot these graphs are explained in the literature review and fully derived in the appendix. They will be shown bellow for convenience.

Ideal Gas

$$v = \sqrt{\frac{2P_0V_0}{m\left(\gamma - 1\right)}\left[1 - \left(\frac{V}{V_0}\right)^{1-\gamma}\right]}$$

Gas Dynamics

$$L = \frac{v_{max}^2}{\dot{v}_{max}}\frac{\gamma - 1}{2}\left[\frac{2}{\gamma + 1}\left[\left[1 - \frac{v}{v_{max}}\right]^{-\frac{\gamma+1}{\gamma-1}} - 1\right] - \left[1 - \frac{v}{v_{max}}\right]^{-\frac{\gamma+1}{\gamma-1}\frac{2}{\gamma+1}}\right]$$

It can be seen that the gas dynamics approach is the limiting case for the velocity and it can be seen that one needs a barrel length in excess of $7m$ to achieve supersonic speeds. This is clearly not feasible, therefore two stage gas guns will be explored.

3.2 Barrel length of single stage gas gun vs 2 stage gas gun

The following plot of barrel length versus velocity of a two stage gas gun under the same two theories as mentioned above is shown here as comparison to the single stage. The theory and solution method will be developed in the next section under Analytical Solution.

3.3 Effect of gas mass on velocity

The effects of the mass of the gas behind the projectile can be determined as follows.

A linear velocity profile is assumed for the gas accelerating behind the projectile. The velocity of a layer of gas a distance from the breach can be related to the projectile velocity as follows.

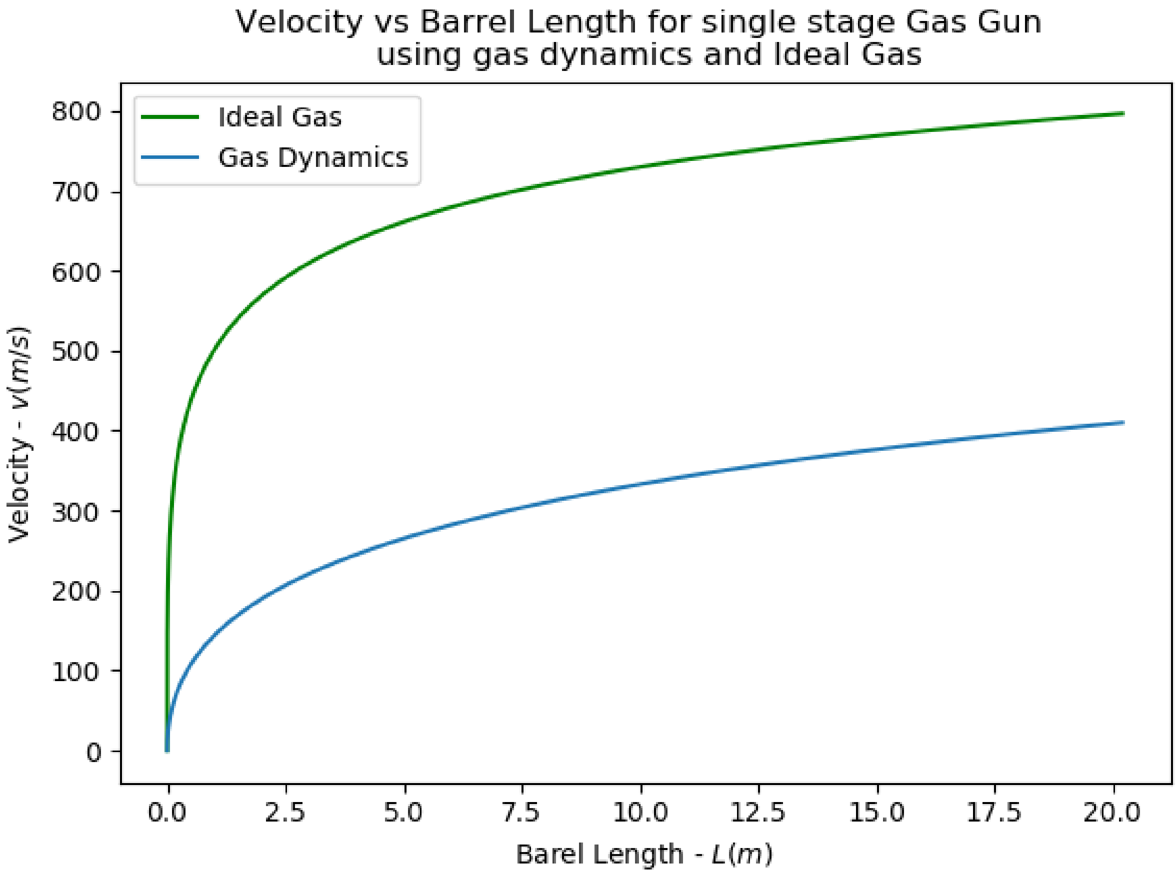


Figure 3.1: Ideal Gas vs Gas Dynamics Barrel Length Of Single stage gas gun

$$v_x = v\frac{x}{x_p}$$

The kinetic Energy for both the gas and projectile can then be expressed as follows

$$T = \frac{1}{2}mv_p^2 + \int_{\mathrm{V}} \frac{1}{2}\mathrm{d}mv^2$$

Looking at the energy term for the mass:

$$\int_{\mathrm{V}} \frac{1}{2}\mathrm{d}mv^2 = \int_{\mathrm{V}} \frac{1}{2}\rho A\mathrm{dx}(v\frac{x}{x_p})^2 = \frac{1}{2}\rho A\int_0^{x_p}(\frac{v}{x_p})^2x^2\mathrm{dx} = \frac{1}{2}(\frac{1}{3}m_g)v^2$$

This shows that the overall affect of the mass of the gas is a contribution of 1/3 its total mass.

3.4 Room for growth in SEP

As can be seen from the second stage compression in the SEP region of the SANS pressure vessels graph, there is alot of room to move to higher pressures while still remaining in SEP. The problem is that the initial volume cannot increase without lowering its pressure to remain in SEP.

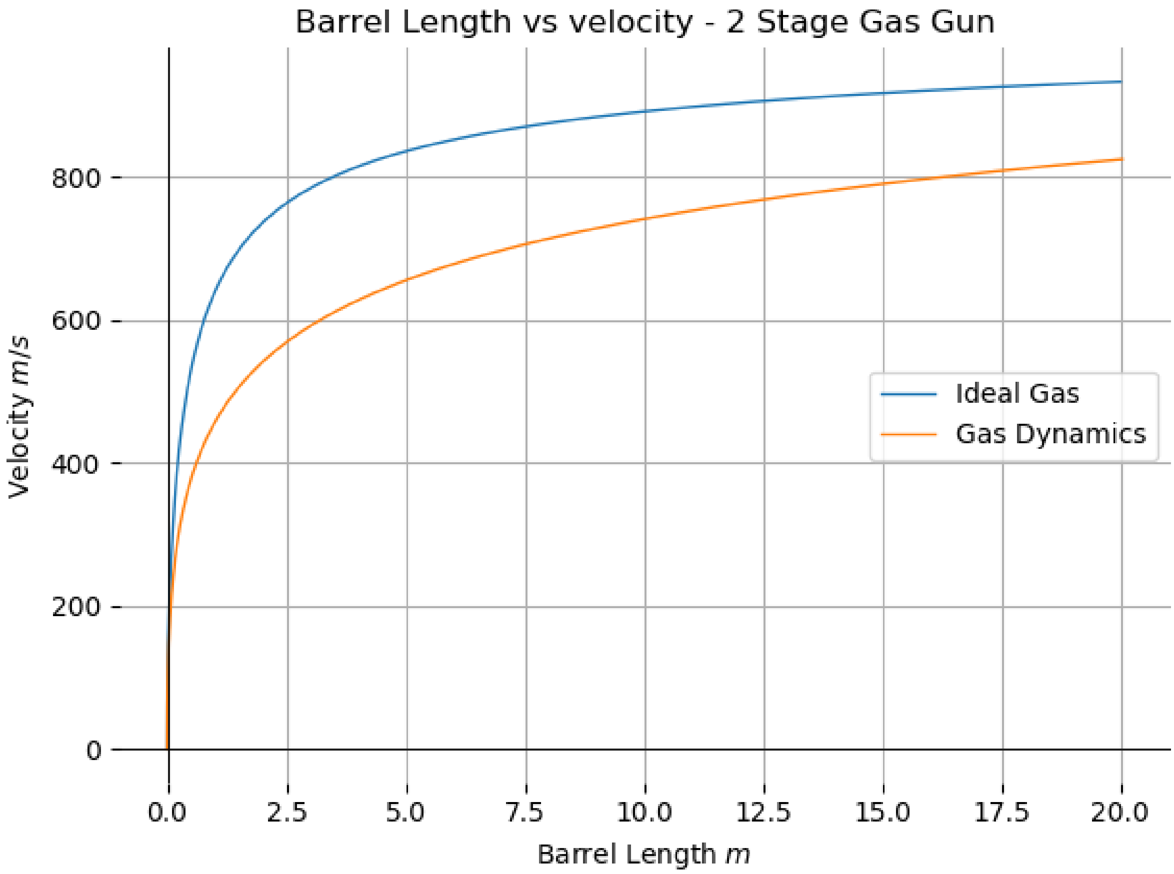


Figure 3.2: Ideal Gas vs Gas Dynamics Barrel Length Of Two stage gas gun

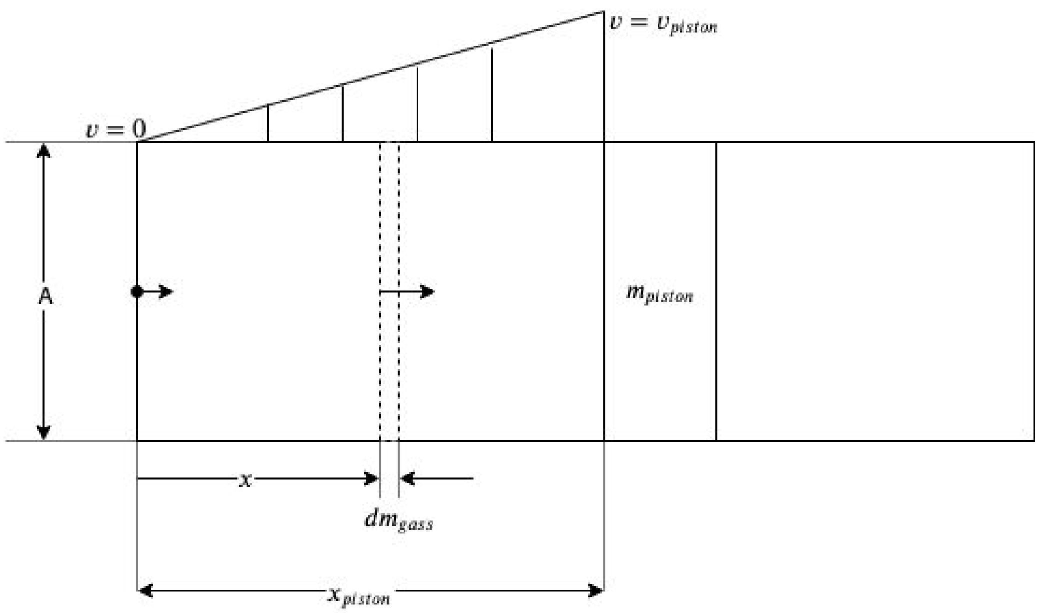


Figure 3.3: Gas mass vs Projectile mass Diagram

A potential solution to this is to have multiple pump tubes that feed into one final compressed volume. This will allow for a combined compression effort resulting in higher compression ratios which will result in a higher pressure and Temperature gas diving the projectile down the barrel. This is however a significantly more complex design and one should perfect the current design before moving on to such a design.

4. Initial Sizing

4.1 Pressure Vessel Theory

This project involves the use of a pressure vessel, therefore all the necessary standards and regulations surrounding pressure vessels need to be considered. A pressure vessel is defined as a housing/container that holds a fluid or gas at a static pressure of greater than or equal to 50 kPa. This project will follow the SANS 347 pressure vessel standards[4]. The maximum static pressure held in the reservoir for this project is 10 bar ($1000KPa$), the following graph can be used to determine the maximum volume for the reservoir such that it remain in the Sound Engineering Practice (SEP) region of the graph. For the given pressure of 10 bar($1000KPa$) the maximum allowable volume to remain in the SEP region is $5l$.

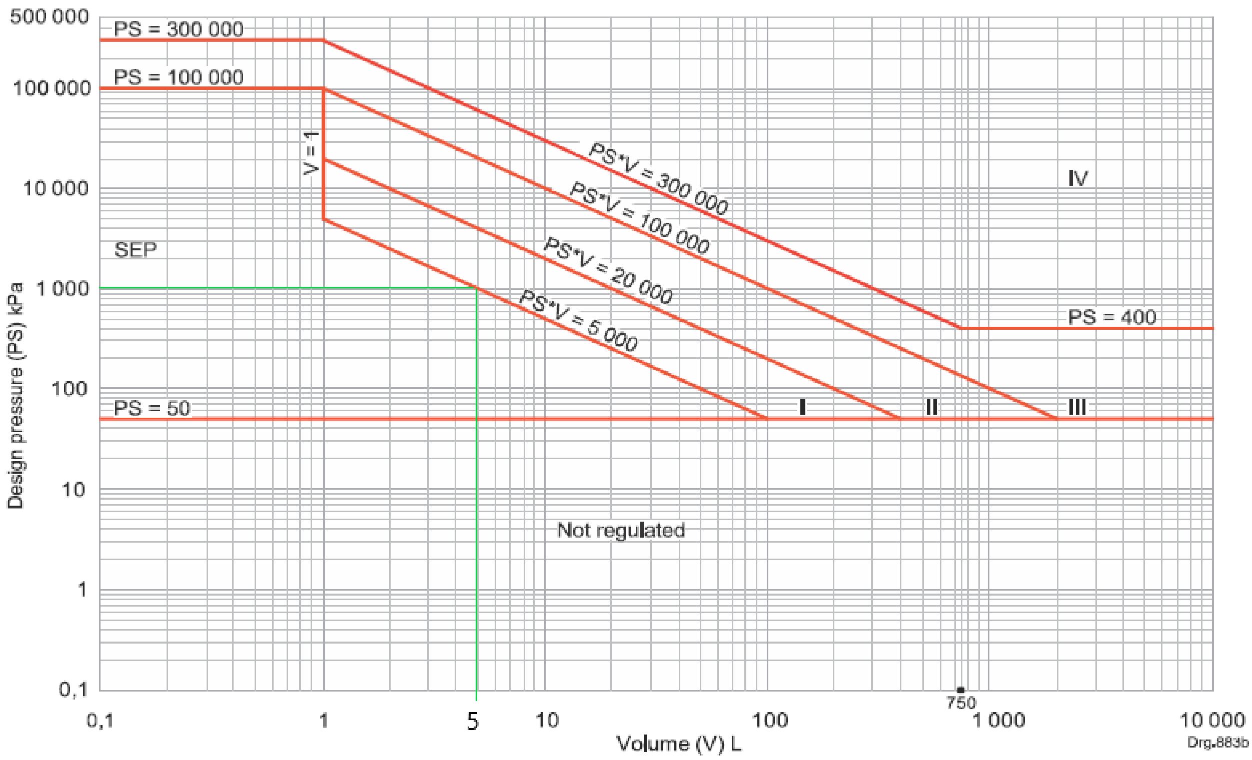


Figure 4.1: Graph for pressure vessels — Non-dangerous gas [4]

The high pressure region of the gas gun will most likely be less than $1l$, and one can see that the maximum allowable pressure to remain in SEP at this volume is 100 bar ($1000MPa$). It will be shown later in the report that this region does in fact remain in the SEP section through a numerical and analytical model. These models do no replicate the exact behaviour, but will over estimate the values are therefore sufficient to use to show the maximum pressure as the real pressure will be lower. The vessel strength will be calculated to ensure that the wall thickness is enough to support the pressure. The design will also be fail safe in nature as it will be designed to leak if the pressure is held for too long - ensuring that static pressure cannot be stored in this section.

4.2 Upper Limits for initial conditions

The maximum limits for the work done by the gas on the piston and the velocity obtained using a pressure work relationship can be conducted to determine if the initial conditions of $10bar$ and $5l$ are sufficient.

$$W_{max} = \frac{P_0 V_0}{\gamma - 1} = \frac{(1000000)(0.005)}{1.4 - 1} = 12500J$$

The maximum obtainable velocity is given by the following relationship, this however requires the pressure of the compressed gas in the transition piece to get the projectile velocity. One can calculate the maximum velocity obtained if the pressure were 10 bar in the section (it will however be higher than this).

$$v_{max} = \sqrt{\frac{2P_0 V_0}{m\,(\gamma - 1)}} = \sqrt{\frac{2(1000000)(0.005)}{0.003\,(1.4 - 1)}} = 2886.75m/s$$

The gas dynamics theory can give a limit on the maximum obtainable velocity that is independent of initial volume and pressure as follows. This is the limiting case as it gives a lower velocity.

$$v_{max} = \frac{2}{\gamma - 1}\sqrt{\gamma RT} = \frac{2}{1.4 - 1}\sqrt{1.4(287)(273.15 + 23)} = 1724.77m/s$$

Both these maximum velocities are far above the required Mach 1 velocity, however in a single stage gas gun the barrel length required to reach this maximum is in excess of $20m$, this can be seen in Figure **??** on page **??**. Therefore as can be seen in Figure **??** on page **??** a two stage gas gun under the gas dynamics theory can reach velocities above Mach 1 with a reasonable barrel length.

An analytical and numerical model based on the ideal gas assumption will be developed in the next section to obtain a rough estimate of the performance of the 2 two stage gas gun.

4.3 Analytical Model

4.3.1 Analytical Model Overview

The analytical model uses a purely work energy relationship as its approach. It ignores effects of friction and assumes that the projectile remains stationary until the desired pressure is reached(as it needs to be 0D approach to be done analytically).

The model works by equating the work done by the high pressure gas on the piston to the work done by the gas in front of the piston. This can be done as the compression and expansion is assumed to be isentropic, therefore there is no energy loss to the external environment. The pump tube and reservoir are assumed to be of the same diameter.

$$W_1 = \frac{P_0 V_0}{\gamma - 1}\left[1 - \left(\frac{V}{V_0}\right)^{1-\gamma}\right] = \frac{P_0 A_0 L_0}{\gamma - 1}\left[1 - \left(\frac{A_0(L_0 + x)}{A_0 L_0}\right)^{1-\gamma}\right] \tag{4.1}$$

$$W_2 = \frac{P_{atm} V_0}{\gamma - 1}\left[1 - \left(\frac{V}{V_0}\right)^{1-\gamma}\right] = \frac{P_{atm} A_0 L_{20}}{\gamma - 1}\left[1 - \left(\frac{A_0(L_{20} + x)}{A_0 L_{20}}\right)^{1-\gamma}\right] \tag{4.2}$$

Equating the work done infront of and behind the piston

$$\frac{P_0 A_0 L_0}{\gamma - 1}\left[1 - \left(\frac{A_0(L_0 + x)}{A_0 L_0}\right)^{1-\gamma}\right] = \frac{P_{atm} A_0 L_{20}}{\gamma - 1}\left[1 - \left(\frac{A_0(L_{20} + x)}{A_0 L_{20}}\right)^{1-\gamma}\right] \tag{4.3}$$

$$P_0 L_0\left[1 - \left(\frac{(L_0 + x)}{L_0}\right)^{1-\gamma}\right] = P_{atm} L_{20}\left[1 - \left(\frac{(L_{20} + x)}{L_{20}}\right)^{1-\gamma}\right] \tag{4.4}$$

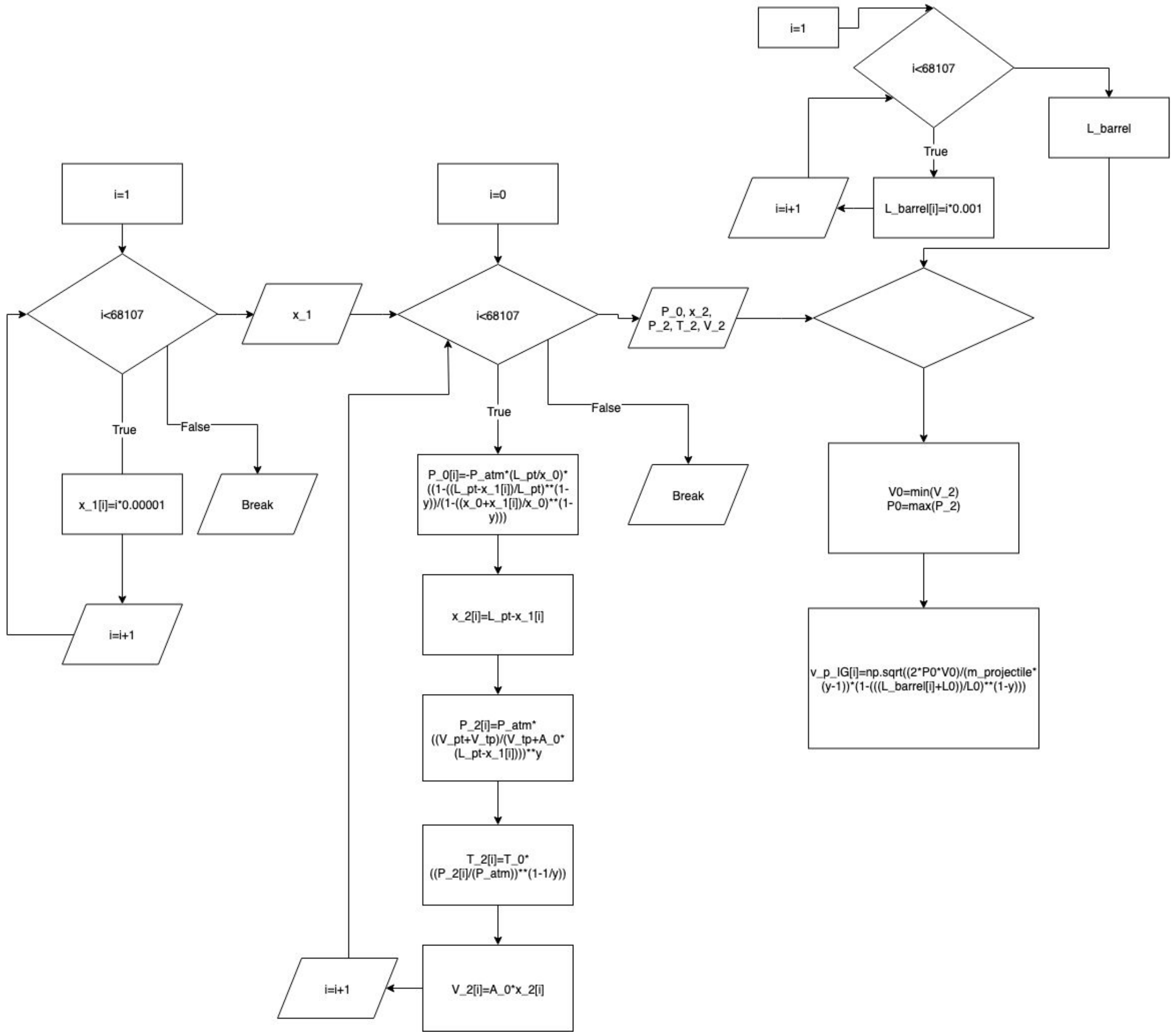
$$P_0 = -P_{atm}\frac{L_{pt}}{x_0}\frac{1 - \left(\frac{L_{pt} - x}{L_p t}\right)^{1-\gamma}}{1 - \left(\frac{x_0 + x}{x_0}\right)^{1-\gamma}} \tag{4.5}$$

Where P_0 is the reservoir pressure and x_0 is the hypothetical initial length assuming that the gun is constant diameter.

The piston position was varied until the desired initial pressure was reached. This final piston position allows us to determine what the final volume in the second stage is, this can then be used to determine what the final temperature and pressure is using the isentropic compression equations.

Once the final pressure was known the rest of the process was treated as a single stage gas gun with the initial pressure and temperature being the final temperatures previously determined. The gas dynamics equation that relates velocity to barrel length can also now be used.

4.3.2 Analytical Model Flow Chart



4.3.3 Analytical Model Outputs

4.4 Numerical Model

4.4.1 Numerical Model Overview

$$m_{piston}\ddot{x}_{piston} = P_1 A_{pump-tube} - P_2 A_{pump-tube} \tag{4.6}$$

$$m_{projectile}\ddot{x}_{projectile} = P_2 A_{barrel} - P_{atm} A_{barrel} \tag{4.7}$$

$$P_1 = P_0 \left(\frac{V_0}{V_0 + A_{pump-tube} x_{piston}} \right)^{\gamma} \tag{4.8}$$

$$P_2 = P_{atm} \left(\frac{V_{20}}{V_{20} + A_{barrel} x_{projectile} - A_{pump-tube} x_{piston}} \right)^{\gamma} \tag{4.9}$$

One can see that it is not feasible to solve the above analytically as it is a 2 degree of freedom problem therefore a central difference numerical integration scheme is employed

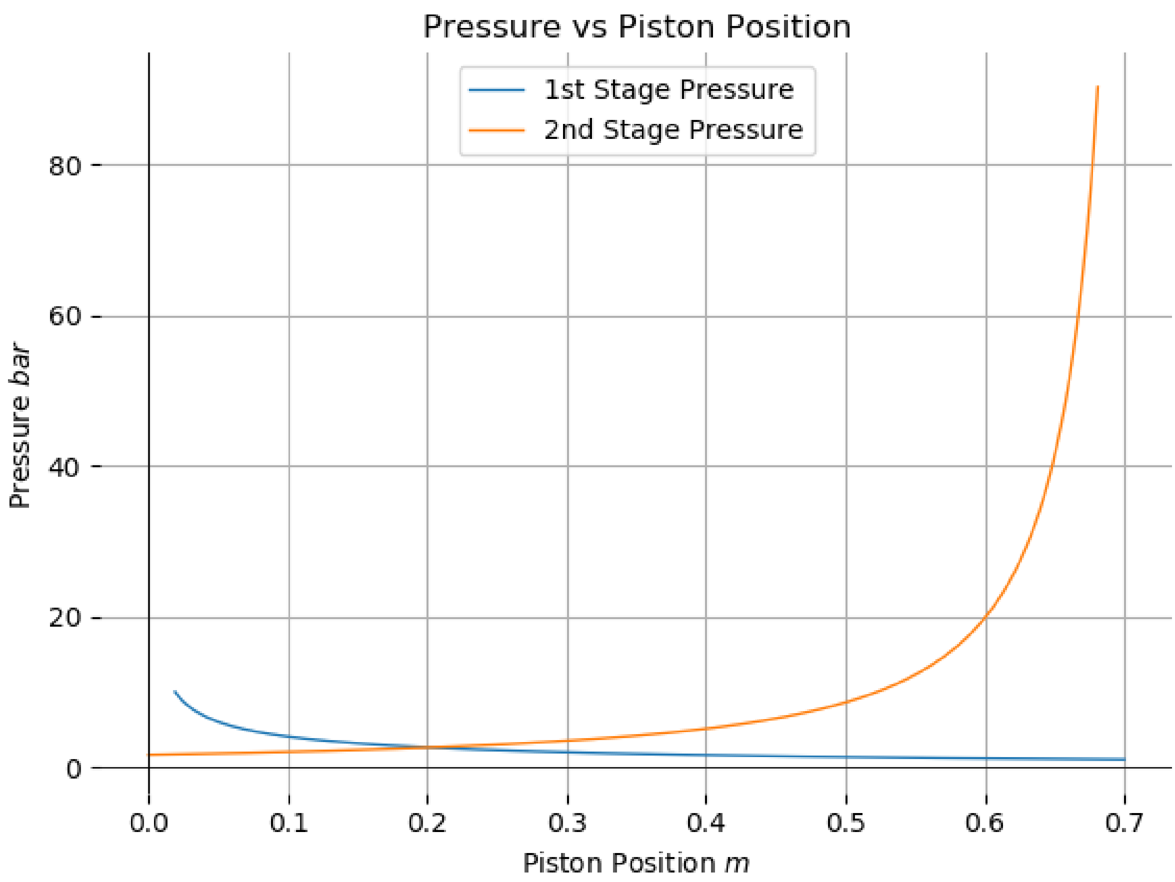


Figure 4.2: Analytical Pressure in each stage

to integrate and solve the above equations of motion. The updating variables used in the scheme are given bellow.

The Volume in the first stage expands as the piston moves down the pump tube and can be found as follows.

$$V_1 = V_0 + A_{pump-tube} x_{pist(i)} \tag{4.10}$$

The volume in the second stage decreases due to the piston closing up the space. Since the projectile starts to move during the compression, the volume increases by the amount that the projectile move in the barrel, the net effect will however be a volume decrease from its initial volume. This is calculated as follows.

$$V_2 = V_{20} - A_{pump-tube} x_{pist(i)} + A_{barrel} x_{proj(i)} \tag{4.11}$$

The pressure in the first stage P_1 can be calculated under the isentropic expansion assumption where the initial volume is the reservoir volume and the final volume is the reservoir volume plus the volume in the pump tube behind the piston.

$$P_1 = P_0 \left(\frac{V_0}{V_1} \right)^{\gamma} \tag{4.12}$$

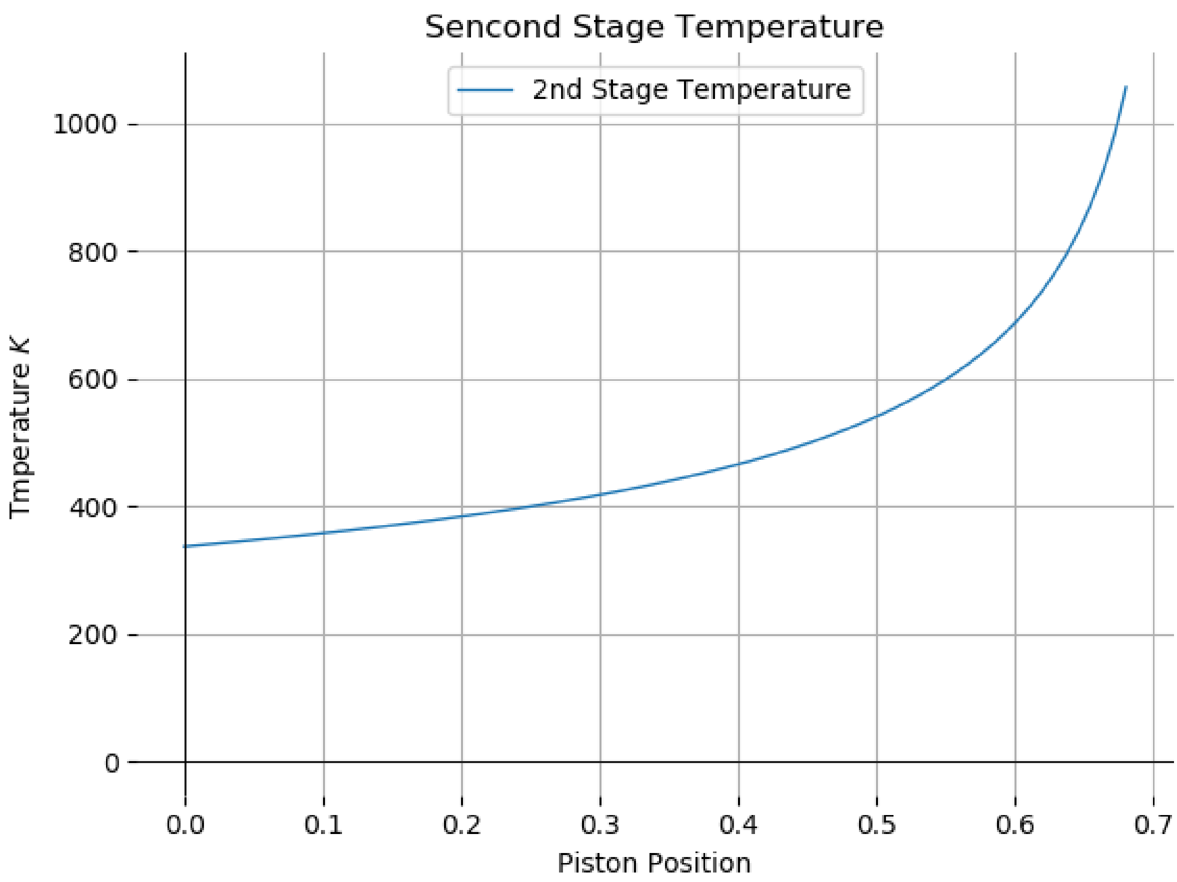


Figure 4.3: Analytical Second Stage Temperature

The pressure in the second stage can be calculated under the isentropic compression assumption where the initial volume is the volume in the pump tube ahead of the piston (including the transition piece) and the final volume is the initial volume minus the volume covered by the piston in the pumptube plus the volume created behind the projectile in the barrel

$$P_2 = P_{atm} \left(\frac{V_{20}}{V_2} \right)^{\gamma} \tag{4.13}$$

The temperature in the second stage can now be determined by using the isentropic relationship for pressure and temperature as follows.

$$T_2 = T_{20} \frac{1}{\left(\frac{P_{20}}{P_2} \right)^{\frac{\gamma - 1}{\gamma}}} \tag{4.14}$$

In order to start of the central difference method, a fictitious initial condition at the -1^{th} time step needs to be found. This is purely to start of the method and has no bearing on the rest of the approximation.

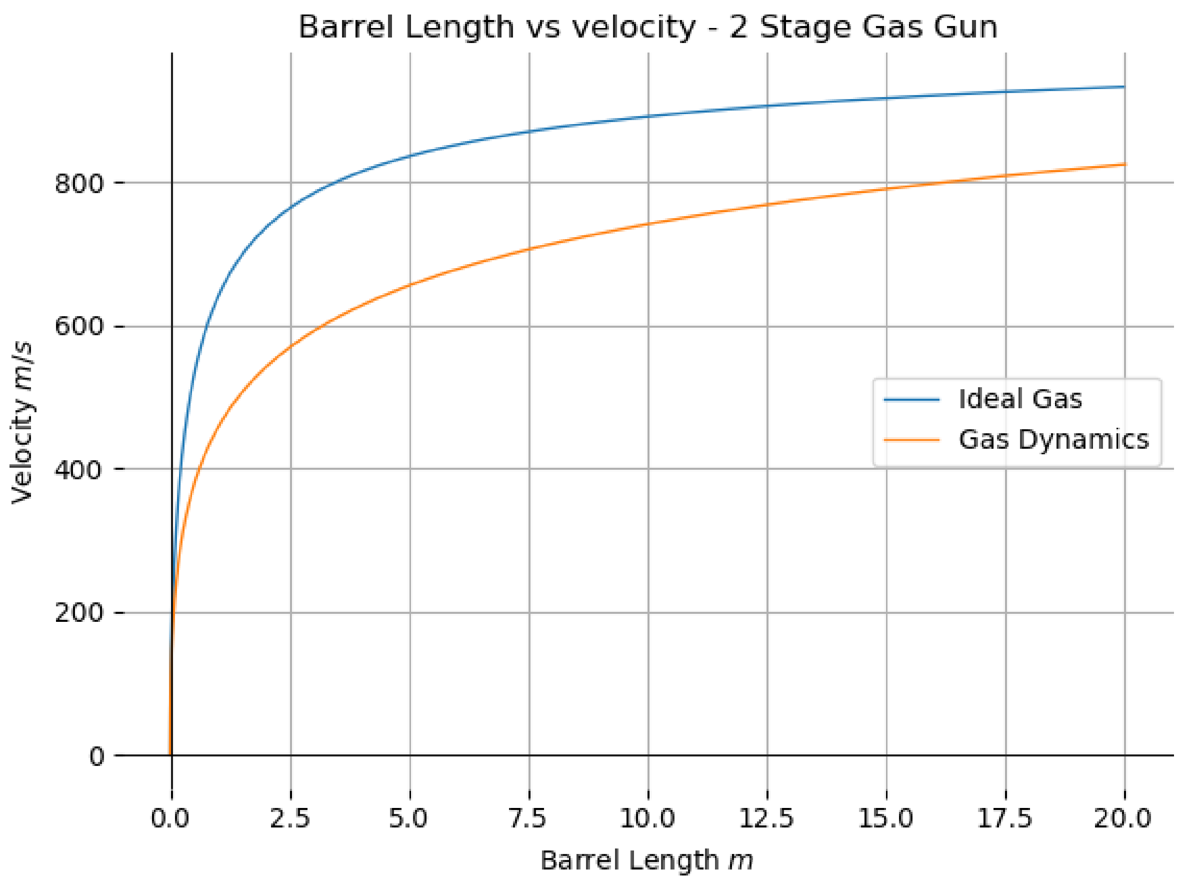


Figure 4.4: Anlytical Projectile velocity (Ideal gas vs Gas dynamics)

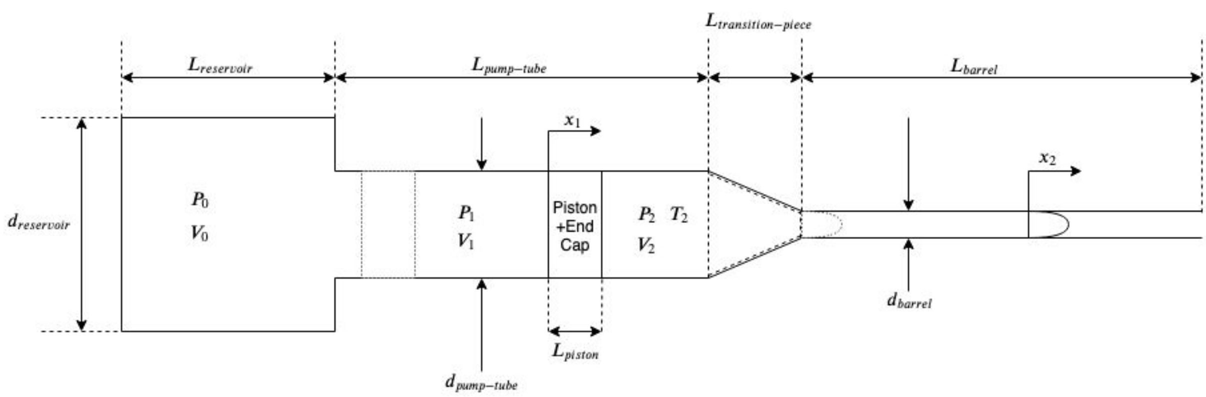


Figure 4.5: Schematic Diagram Showing Coordinates and various

$$x_{piston\_1} = x_{piston_i} - dt\dot{x}_{piston_i} + \ddot{x}_{piston_i}\frac{dt^2}{2} \tag{4.15}$$

$$x_{projectile\_1} = x_{projectile_i} - dt\dot{x}_{projectile_i} + \ddot{x}_{projectile_i}\frac{dt^2}{2} \tag{4.16}$$

The position, velocity and acceleration of the piston and the projectile can be found with the following equations for the central difference method.

$$x_{pist(i+1)} = 2x_{pist(i)} - x_{pist(i-1)} + \frac{dt^2}{m_{piston}} \left(P_1 - P_2\right) A_{pump-tube} \tag{4.17}$$

$$\dot{x}_{pist(i)} = \frac{1}{2dt} \left(x_{pist(i+1)} - x_{pist(i-1)}\right) \tag{4.18}$$

$$\ddot{x}_{pist(i)} = \frac{1}{dt^2} \left(x_{pist(i+1)} - 2x_{pist(i)} + x_{pist(i-1)}\right) \tag{4.19}$$

$$x_{proj(i+1)} = 2x_{proj(i)} - x_{proj(i-1)} + \frac{dt^2}{m_{proj}} \left(P_2 - P_{atm}\right) A_{barrel} \tag{4.20}$$

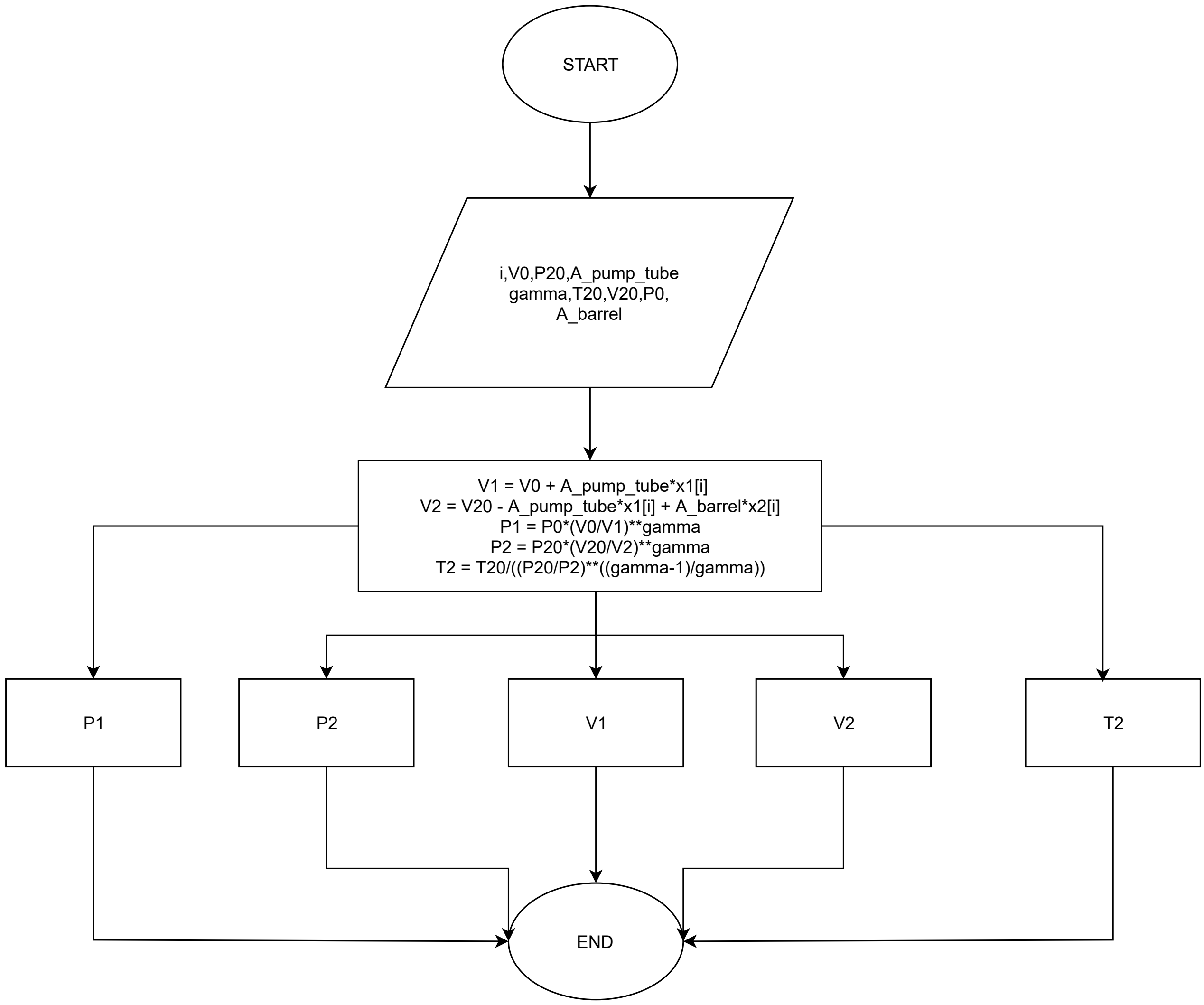
$$\dot{x}_{proj(i)} = \frac{1}{2dt} \left(x_{proj(i+1)} - x_{proj(i-1)}\right) \tag{4.21}$$

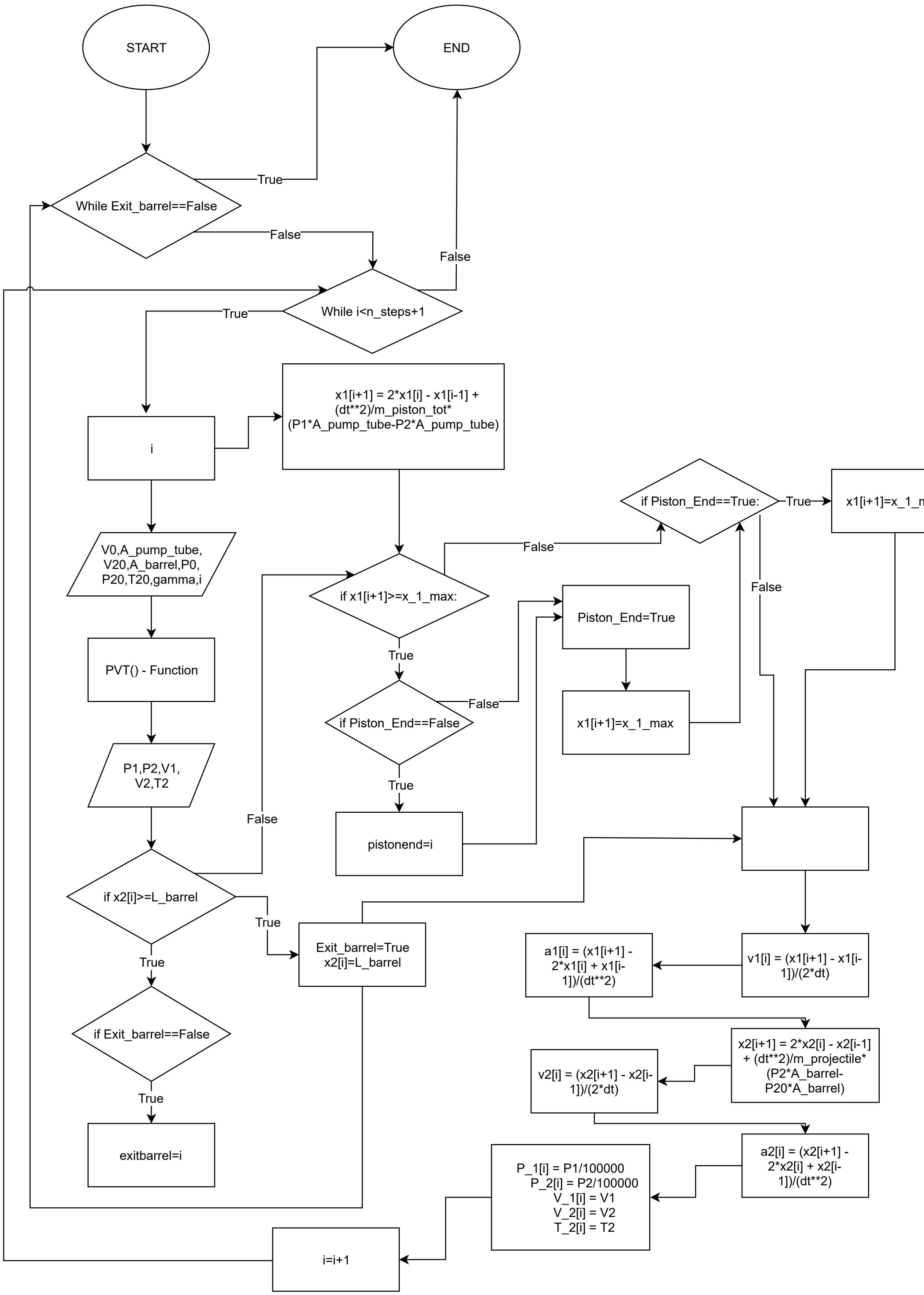
$$\ddot{x}_{proj(i)} = \frac{1}{dt^2} \left(x_{proj(i+1)} - 2x_{proj(i)} + x_{proj(i-1)}\right) \tag{4.22}$$

4.4.2 Numerical model limitations and assumptions

The model does not consider effects of air resistance and friction of the projectile and piston on the walls. It also does not account for the pressure build up ahead of the projectile due to its rapid acceleration.

4.4.3 Numerical Model Flow Chart




START
END
While Exit_barrel==False
True
False
False
While i<n_steps+1
True
i
x1[i+1] = 2*x1[i] - x1[i-1] + (dt**2)/m_piston_tot*(P1*A_pump_tube-P2*A_pump_tube)
if Piston_End==True:
True
x1[i+1]=x_1_m
V0,A_pump_tube, V20,A_barrel,P0, P20,T20,gamma,i
False
if x1[i+1]>=x_1_max:
False
Piston_End=True
PVT() - Function
True
if Piston_End==False
False
x1[i+1]=x_1_max
P1,P2,V1, V2,T2
True
pistonend=i
False
if x2[i]>=L_barrel
True
Exit_barrel=True x2[i]=L_barrel
True
a1[i] = (x1[i+1] - 2*x1[i] + x1[i-1])/(dt**2)
v1[i] = (x1[i+1] - x1[i-1])/(2*dt)
if Exit_barrel==False
x2[i+1] = 2*x2[i] - x2[i-1] + (dt**2)/m_projectile*(P2*A_barrel-P20*A_barrel)
True
v2[i] = (x2[i+1] - x2[i-1])/(2*dt)
exitbarrel=i
a2[i] = (x2[i+1] - 2*x2[i] + x2[i-1])/(dt**2)
P_1[i] = P1/100000
P_2[i] = P2/100000
V_1[i] = V1
V_2[i] = V2
T_2[i] = T2
i=i+1

4.4.4 Numerical Model Final Outputs

The results of this numerical model are given below for the initial conditions of 10 bar and 5l shown in the accompanying table.

Table 4.1: Numerial Results

projectile mass	piston mass	max temperature	max velocity	max pressure
0.004kg	0.2kg	948K	504m/s	59bar
0.005kg	0.4kg	843K	461m/s	40bar
0.002kg	0.5kg	750K	580m/s	26bar

The results for the first entry in Table**??** showed the most promising results in terms of projectile motion before the piston ends it stroke, i.e. it moved very little in comparison to the others. However, a higher maximum velocity is obtained with a projectile mass of $2g$ and piston mass of $500g$.

The graphs below are for the projectile mass of $4g$ and $200g$ to illustrate the numerical model.

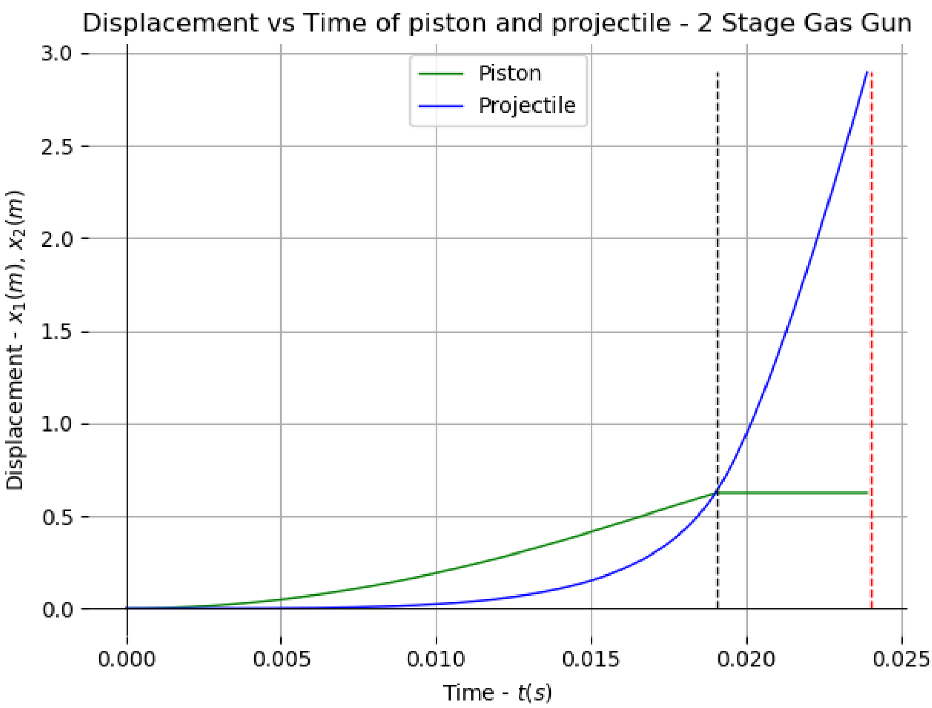


Figure 4.6: Displacement vs. Time for piston and Projectile

4.5 Numerical model Over-layed on SANS graph to show design is always in SEP

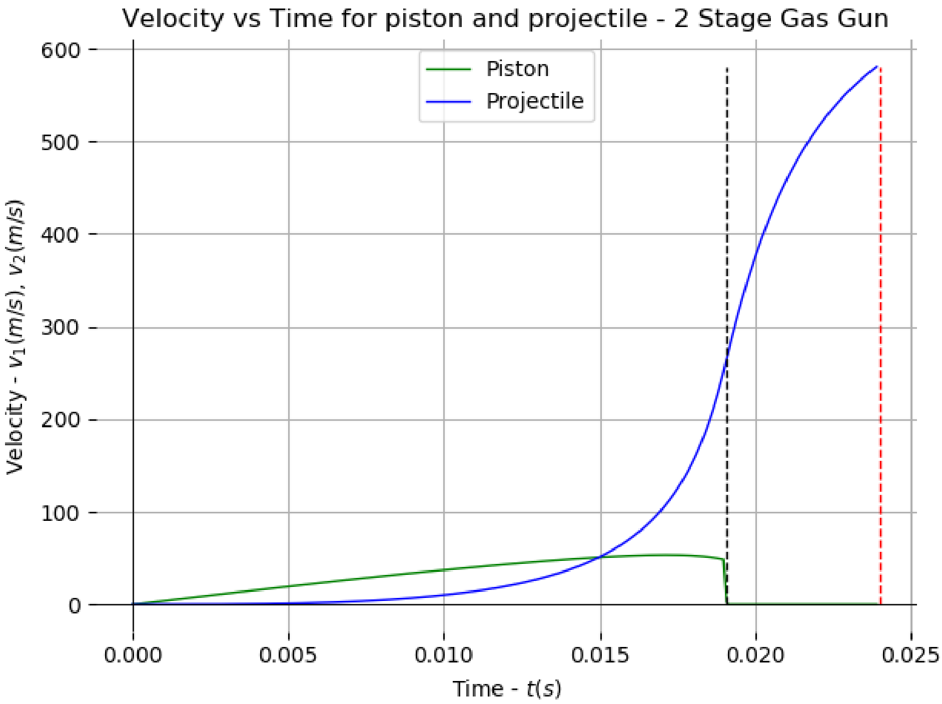


Figure 4.7: Velocity vs. Time for piston and Projectile

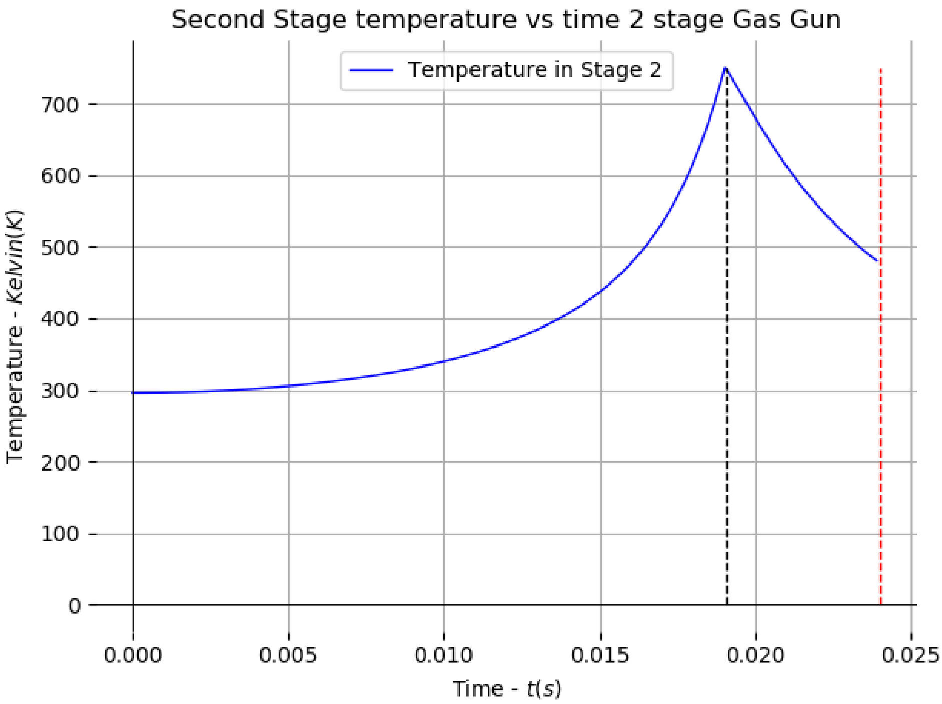


Figure 4.8: Temperature vs. Time for Second stage

Figure 4.10 shows the simulation for the gas gun pressures in the first and second stage at there respective volumes. The graph demonstrates that the pressures experienced throughout the entirety of the firing remains in the SEP(Sound Engineering Practice) region of the graph. This is a confirmation that the gun is designed to be inherently safe, as well as shows that there is room for growth in terms of the second stage pressure while still remaining in the SEP region - this will be explored later on.

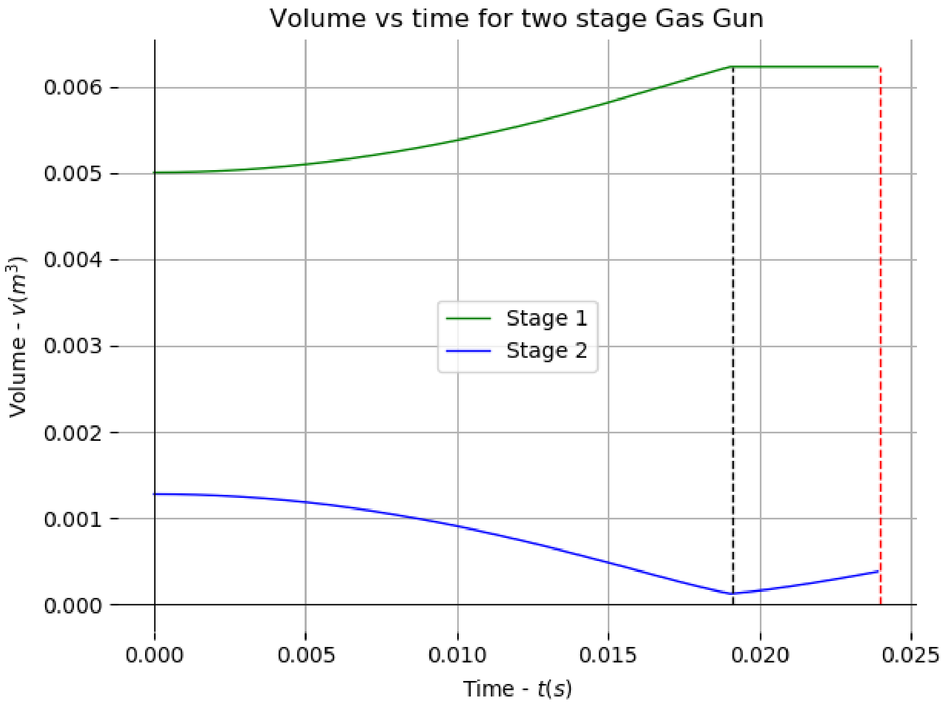


Figure 4.9: Volume vs. Time

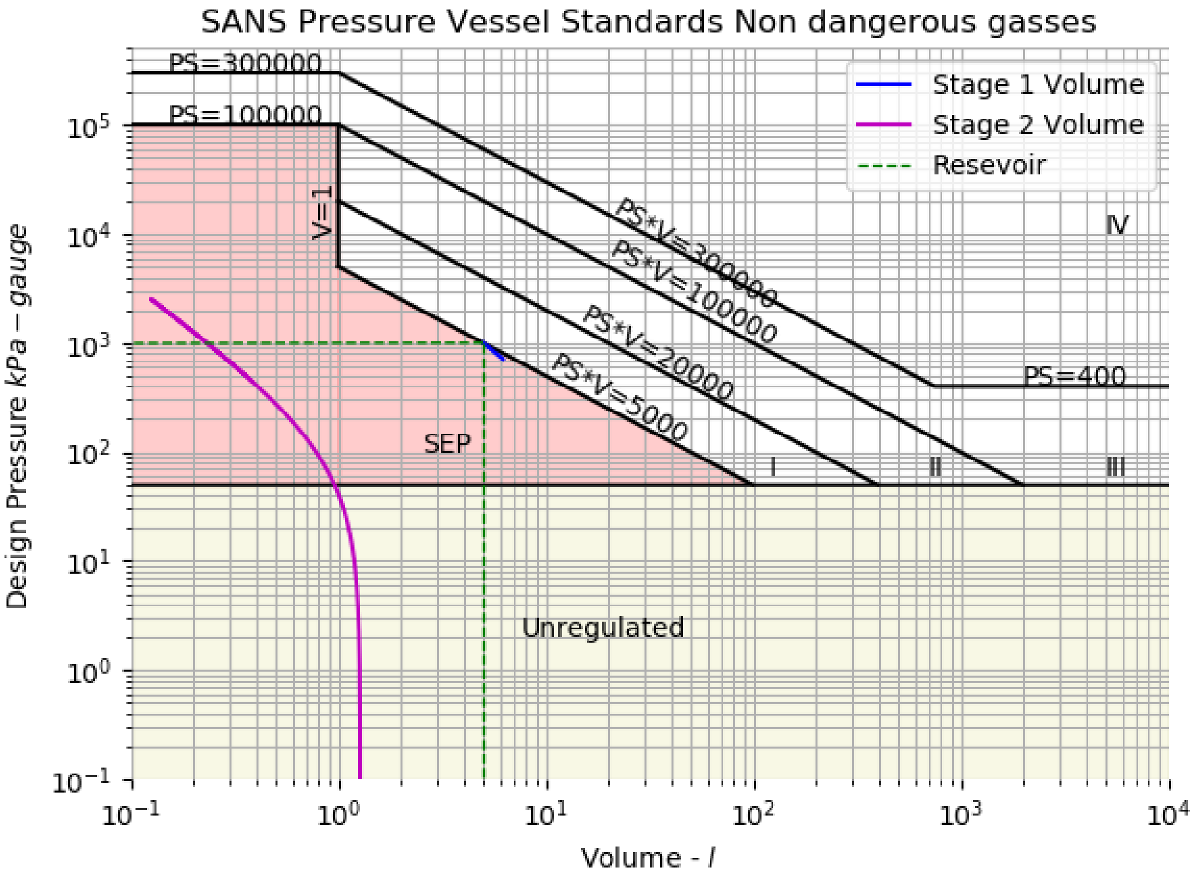


Figure 4.10: Over lay of Gas Gun Simulation on SANS Pressure Vessels Graph

4.6 2 Stage gas gun velocity vs Barrel Length (Numerical)

A plot of velocity versus barrel length for the two stage gas gun using the numerical model developed above is shown in Figure 4.12. The velocity starts to decrease after a

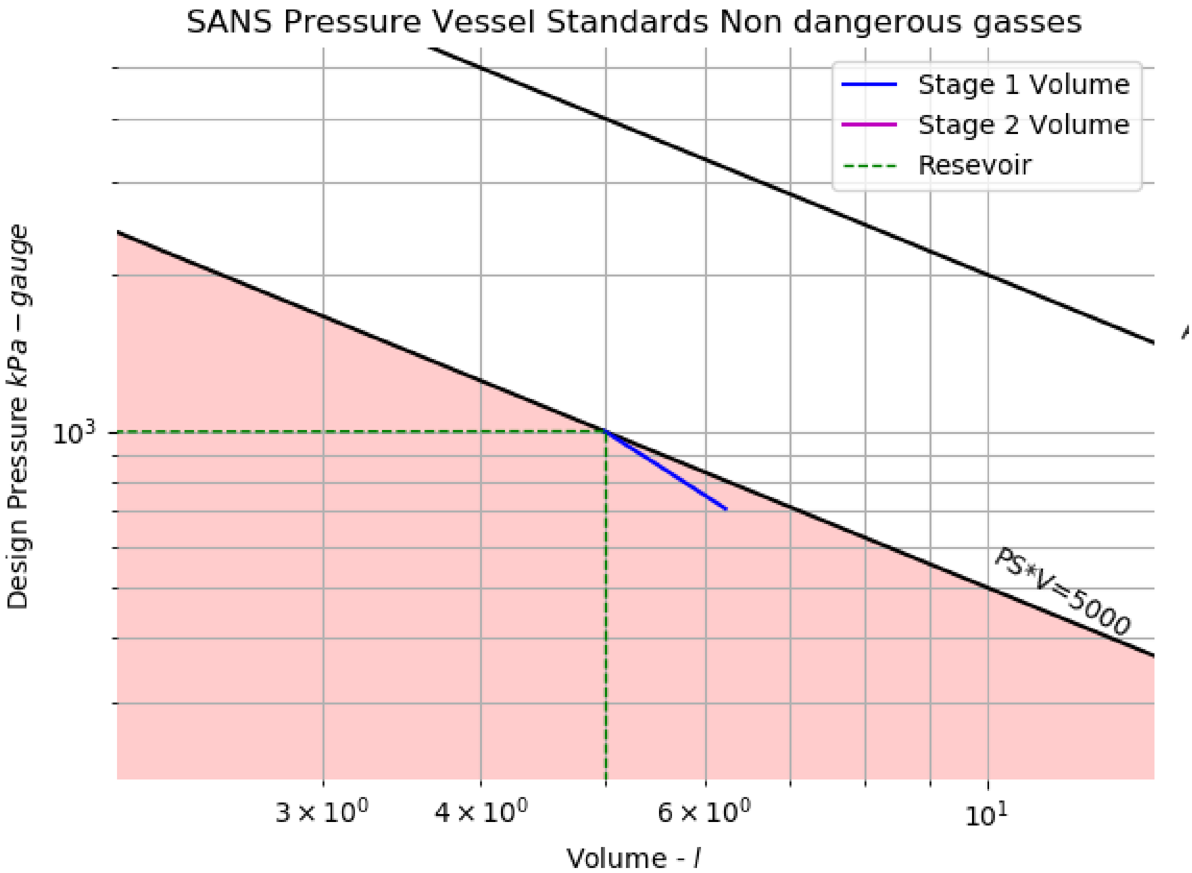


Figure 4.11: Over lay of Gas Gun Simulation on SANS Pressure Vessels Graph Closer view

certain barrel length is reached about $10m$ for the initial conditions. This seems like an artefact of the simulation as the velocity should increase with increasing barrel length. However on further examination it could potentially be due to the atmospheric pressure on the the muzzle side of the projectile and the gas reaching its optimum expansion volume.

A velocity versus barrel length for the two stage gas gun using the numerical model and assuming a vacuum on the muzzle side shows that the velocity does indeed increase with increasing barrel length. Therefore it can be reasonably be assumed that the atmospheric pressure was the cause of reduced velocity after a certain barrel length. This also shows that there is a optimum barrel length when no vacuum is puled on the barrel side. This however needs to be confirmed.

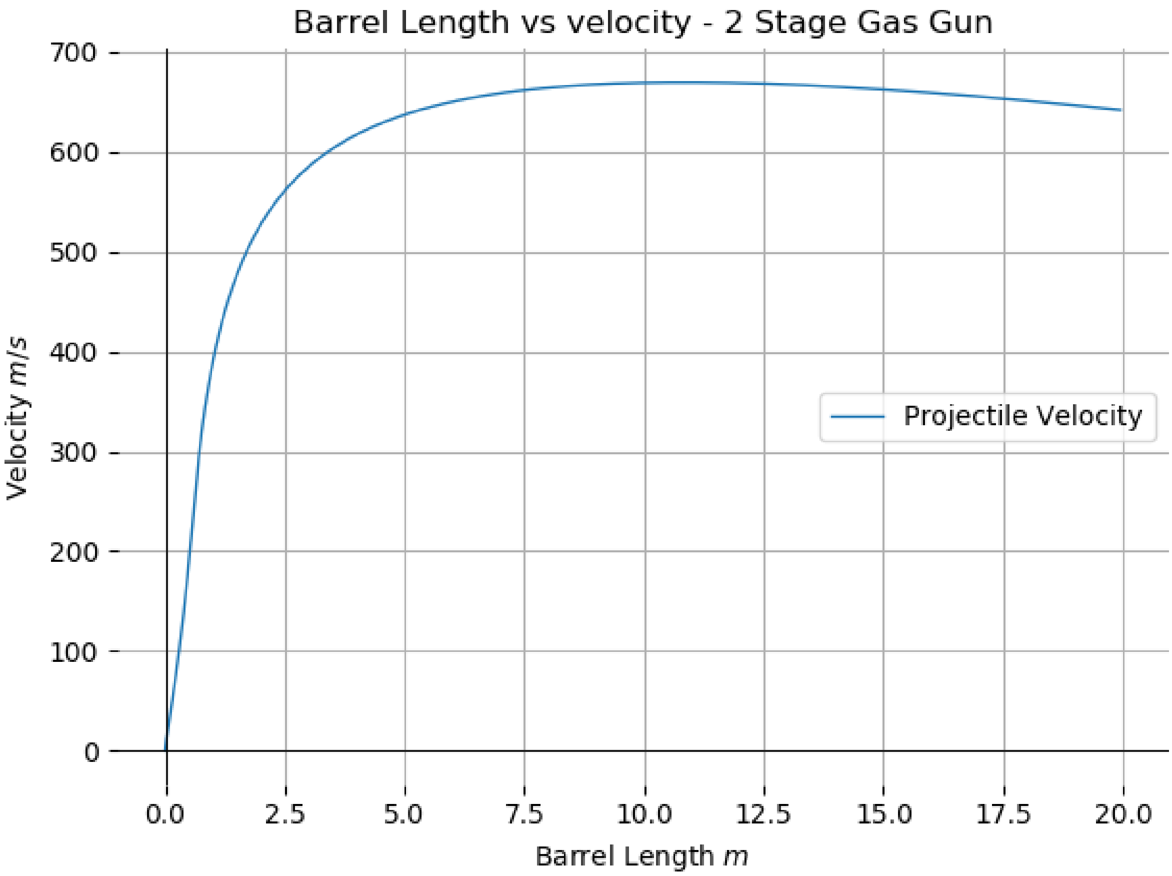


Figure 4.12: Velocity vs barrel Length 2 Stage Gas gun

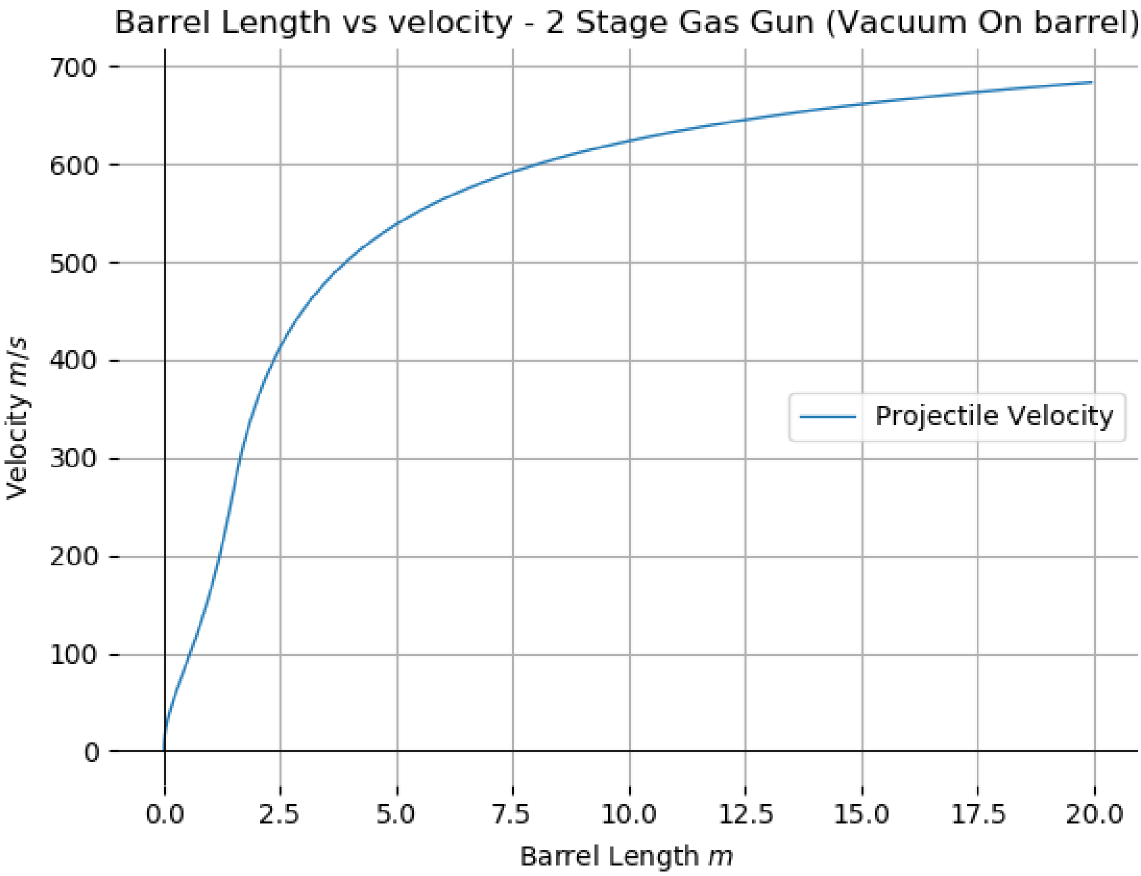


Figure 4.13: Velocity vs barrel Length 2 Stage Gas gun (Vacuum on barrel

5. Concept Design

5.1 Current Design

The current two stage gas gun design has gone through many design iterations and careful decisions have been made in the selection and design of components. This report aims to improve on the design by making it more user friendly and easier to use.

The design logic behind the selection of components for the various components (new and re-used from the previous design) will be detailed here to ensure that the full overview of the design is given as well as to allow for future improvements and modifications to be easily made.

5.2 Concept 1

The overall concept is shown in Figure 5.1. It maintains the overall design of the 2018 version. The flanges are held together by tie-rods - these are not present in the drawing.

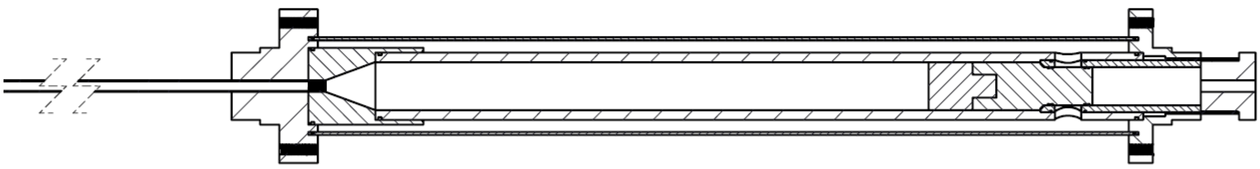


Figure 5.1: Concept 1 Overview

The main change is indicated in Figure 5.2. A sleeve is passed through the flange and welded to it on the outside edge. The pump-tube filler passes through the sleeve into the pump tube to provide a seal between the piston and pump-tube gas holes. The end of the sleeve is closed off by a threaded end cap with a valve port to supply air pressure to initiate piston motion.

5.2.1 Design use procedure

- Barrel unscrewed from transition piece and projectile placed in it
- Either a push rod or a blast of pressurised air can be supplied to the transition piece to dislodge the piston an send it back to the starting position.

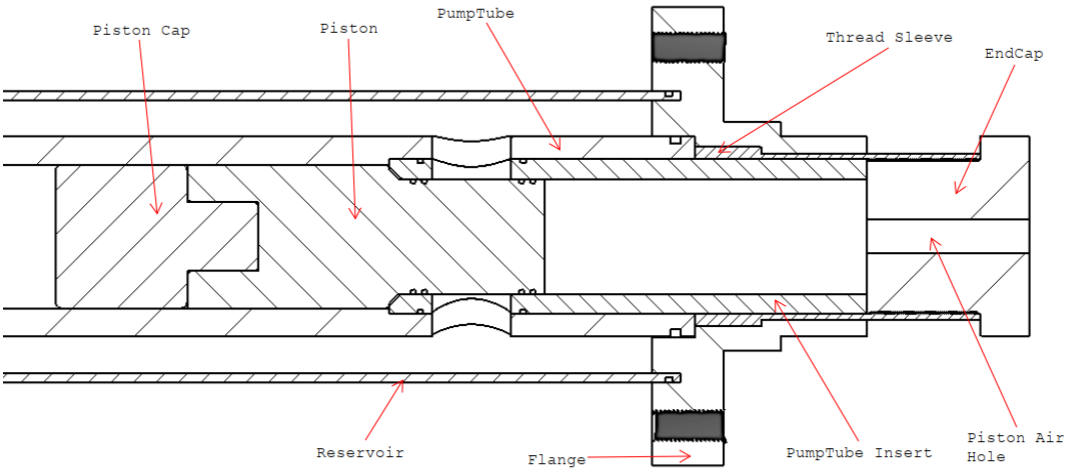


Figure 5.2: Concept showing endcap

- The endcap is unscrewed from the sleeve.
- The pump tube filler can now be removed along with the piston.
- The piston deformable section and O-rings can be inspected and replaced as necessary.
- The end cap and barrel can then be screwed back into their respective sections

In terms of cleaning the pump tube, a blast of pressurised air can be supplied to the transition piece with the opposite end opened to remove any loose debris. To remove debris that cannot be removed by the above mentioned method a brush(pipe cleaner) on a rod can be pushed through the endcap opening to dislodge any particles along the pump tube and transition piece.

5.3 Concept 2

5.3.1 Design

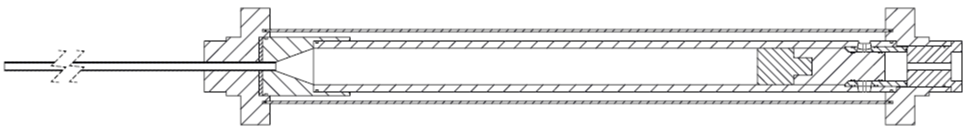


Figure 5.3: Concept two overview

Concept 1 was improved on by having a thread insert press fitted into it from the inside allowing it to sit on an internal shoulder. A thread insert is used as the flange was to be made of aluminium and this cant be threaded as it is a soft material and the threads would strip. A pump tube insert with a reduced diameter is used to seal with the pump tube and piston as

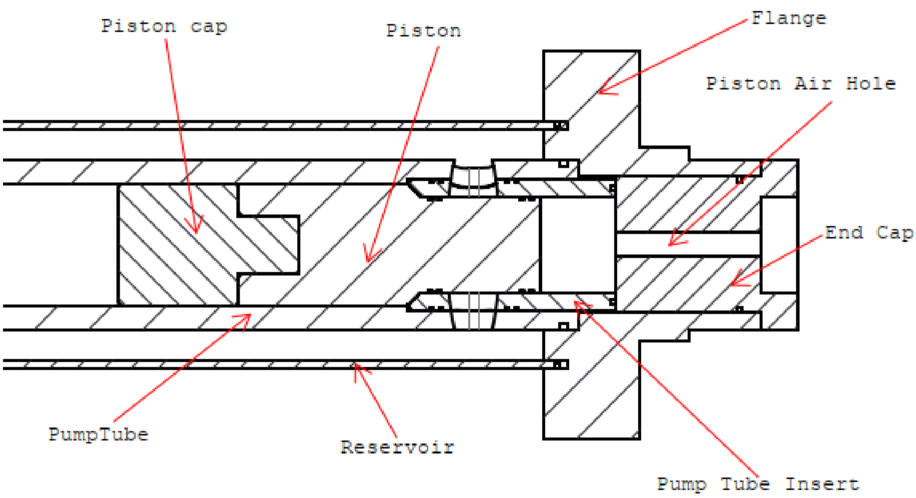


Figure 5.4: Concept two overview

5.4 Concept 3

5.4.1 Design

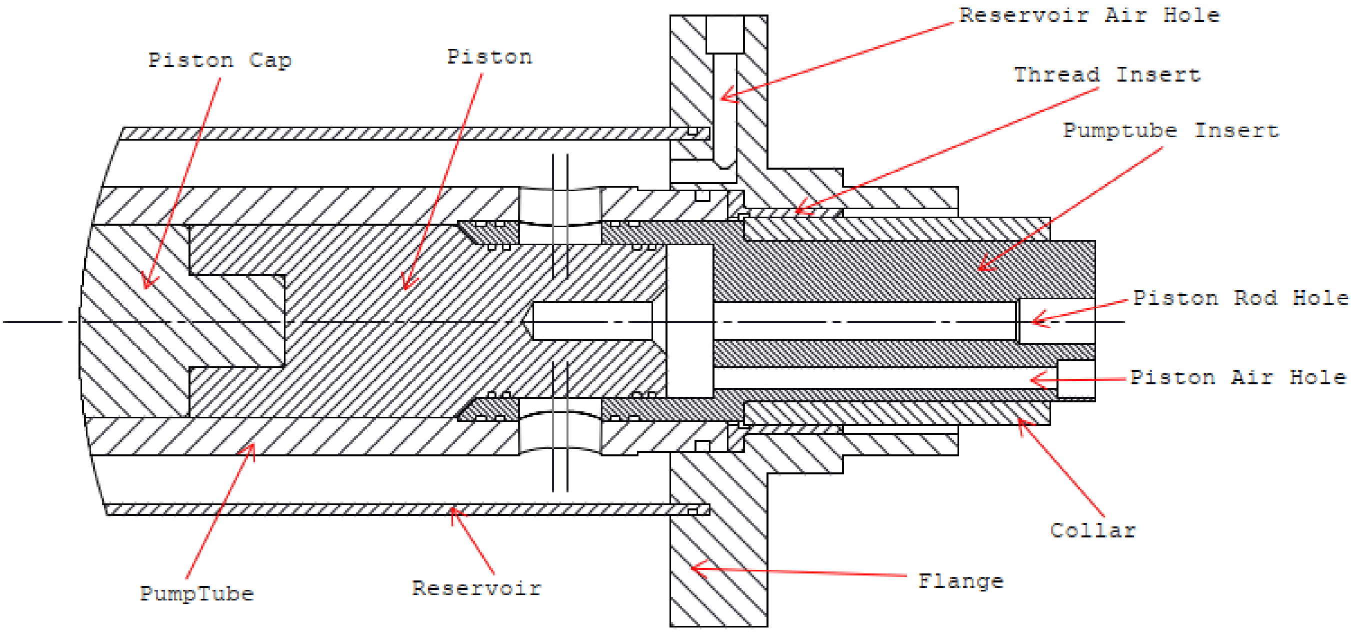


Figure 5.5: Concept three detail view

Concept 3 was the chosen concept to take into further detailed design as it was an improvement on both concept 1 and 2 and made provisions fro piston position tracking.

6. Final Design

6.1 Design Overview

After concept the concept generation phase has been completed, the designs were reviewed and the detailed design could be completed. The detailed design considered the various aspects of the concepts, modifying and improving on them to yield an effective and safe design. The design is developed such that it should be able to reach the initial goals of the prototype while still remaining within the initial set constraints. The design aims to re-use as many existing components as possible and keep the total part count to a minimum. The design needs to ensure ease of assembly ease of assembly and a quick piston removal procedure. Standard sizes are used where possible, and parts are designed with ease of manufacturing in mind. The modifications and new parts were designed to keep costs low, ensure sustainability of the components while ensuring that the design is safe to operate. Material selection was a key decision in terms of the budget, ease of use and sustainability of the gun. Materials were selected to reduce the overall weight of the gun as well as to eliminate the possibility of rusting and corrosion. Materials were also selected to improve the safety aspect of the design. The design of the various components and the reasoning behind there design and material choices are discussed in detail bellow.

6.2 Component Design

6.2.1 Pump Tube

Due to budget constraints the pump tube was re-used from the 2018 design. The pump tube was modified to fit the new design, the modification involved machining the end with the press fitted piece down to a 52mm diameter to make room for the removable pump tube insert.

This design makes use of a pump tube insert that has matching slots that line up with and seal against the pump tube inside diameter. This creates a path for the air to flow from the reservoir through the slots in the pump tube and pump tube insert. The piston then acts as the seal of this air path inside the pump tube insert. Once the piston is

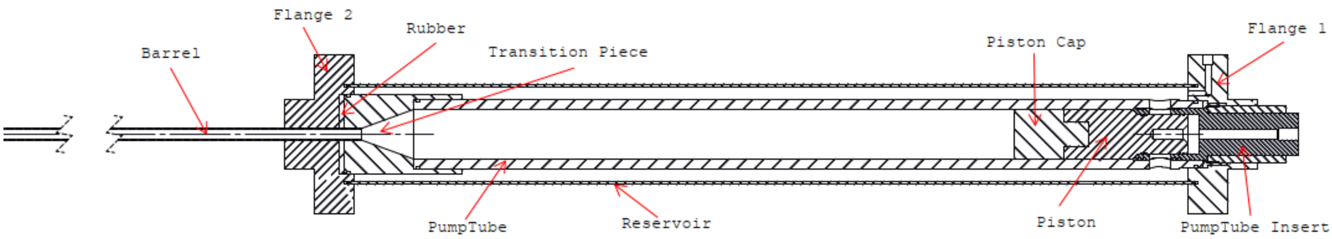


Figure 6.1: Cross Section Overview

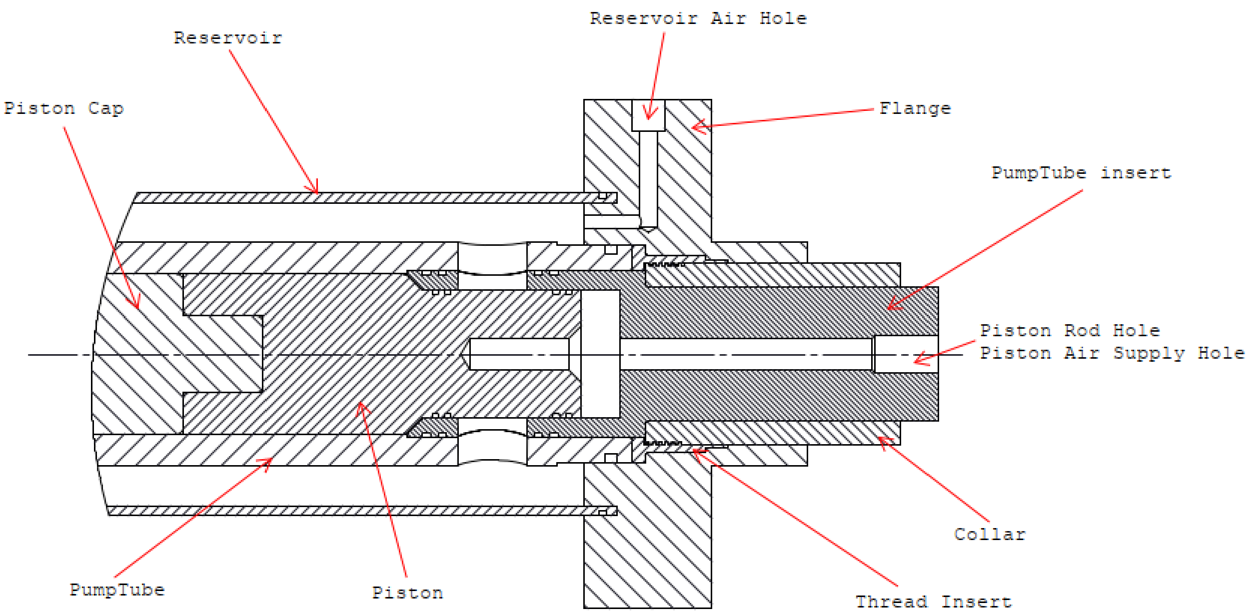


Figure 6.2: Cross Section Detail View

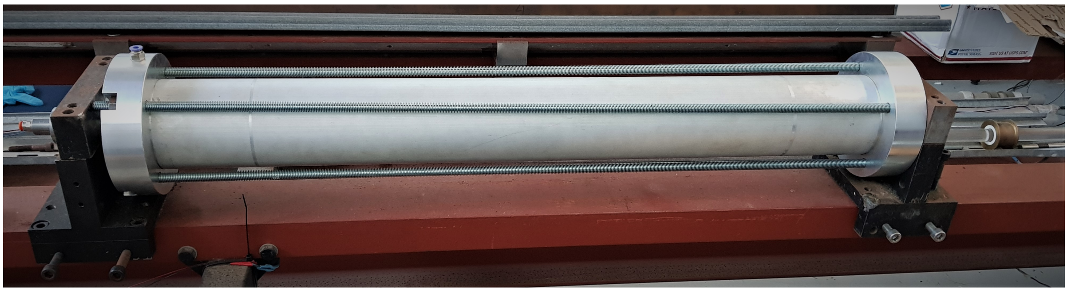


Figure 6.3: Assembly view 1

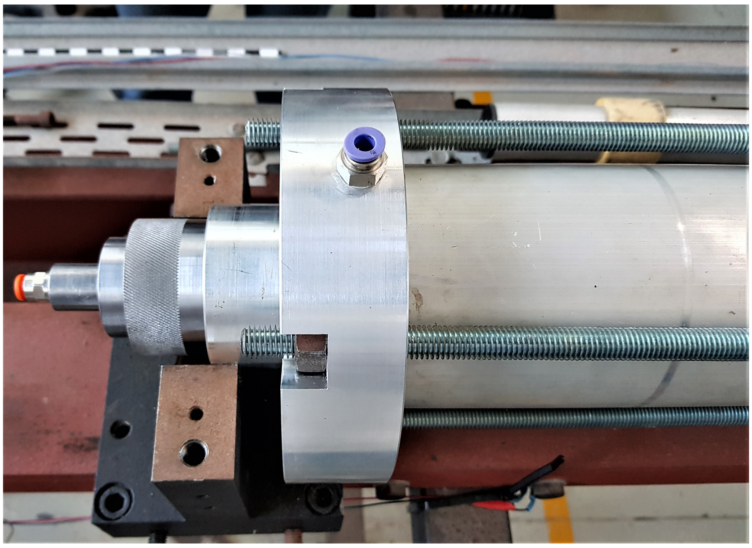
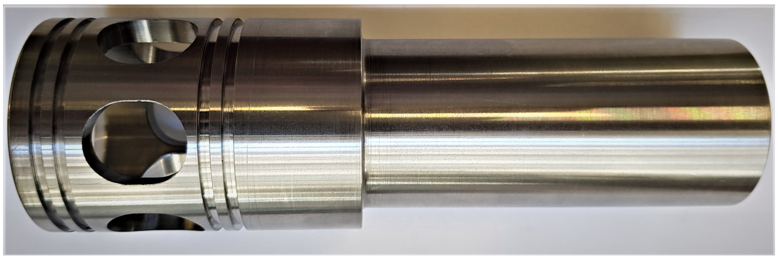


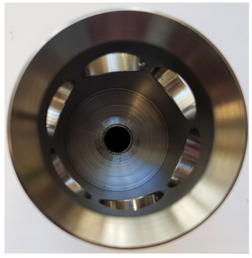
Figure 6.4: Assembly view 1

forced past the seals an inrush of the 10 bar air through the slots drives the piston. Since the seal acts on a smaller diameter, the o-rings on the piston do not rub against the pump-tube wall during the rest of its stroke, reducing friction. Calculations done earlier show that the leakage, due to no o-rings sealing between the piston and pump-tube, is minimal/insignificant.

6.2.2 Pump Tube Insert



(a) Side view of pump tube insert



(b) Top view of pump tube insert

The pump tube insert is a new component that was designed to improve the usability of the gun in terms of piston cap replacement. It essentially replaces the previously press fitted piece in the pump tube to allow for the piston to seal the pump tube air slots. The problem with this design is that the piston could not be removed due to the sealing diameter being smaller than the piston cap diameter.

The pump tube insert has matching slots that line up with the pump tube slots. Four o-rings, two on either side of the slots, seal between the insert slots and pump tube slots when the parts are fitted together.

The insert also has a straight through hole that is threaded on the outside end to allow for pressurised air to force the piston past the slots, to fire the gun as well as to insert a rod that threads in to the end of the piston to bring it back to the starting position.

Alignment markings are made on the outside end of the insert to allow the user to easily align the slots with the pump tube slots, as this part is to be removed relatively frequently.

6.2.3 Piston

The pistons from the 2018 and 2015 projects were reused to reduce costs and machining time, both these pistons are in good condition and fit the existing pump tube. The piston with a plastic end is modified to have an $M10$ threaded hole to allow for a rod to remove the piston from the transition piece after firing.

The full aluminium piston was hollowed out on the back end to reduce it weight ($425gweighpiston$) making it lighter than the plastic and aluminium piston ($weighpiston$). Both of these pistons will be used in testing to obtain data on the effects of a lighter piston, to compare against the simulation.

(a) Side view of
full aluminium piston

(b) Side view of aluminium
and plastic piston

The Has a stepped diameter, the smaller diameter has o-rings to seal the initial 10 bar pressure in the reservoir, an the larger diameter has a close running fit with the pump tube. This was a strategic design to reduce friction on the pistons stroke as the external o-rings are not on the main stroke diameter.

The calculation below shows the effects of pressure leakage due to the gap between the piston and pump tube.
$insertcalculation$

It can be seen from the above calculation that the leakage and pressure loss due to the gap is insignificant and the reduced friction is more beneficial than a better seal.

A semi disposable/replaceable piece called the piston cap is attached to the front end of the piston. This piece is designed to be deformed in the transition piece during operation and is therefore consumable. These parts are used from the remaining stock of the 2018 design where two soft plastics, HDPE(High Density Polyethylene) weighing $100g$ and polyethylene weighing $95g$ were manufactured. The condition of this component will be monitored during testing to characterise how many shots can be done before the part needs replacing.

6.2.4 Flanges

The flanges were redesigned. The purpose of the flanges is to hold and seal the gas gun assembly. There are two concentric slots on both flanges that the pump tube(flange 1)/transition piece(flange 2) and reservoir will slot in with o-rings to prevent leakage.

The flanges have four recesses on each. One of the flanges have a recess that fits an $M12$ Nut that doesn't permit rotation, the other has a recess that fits a socket head and

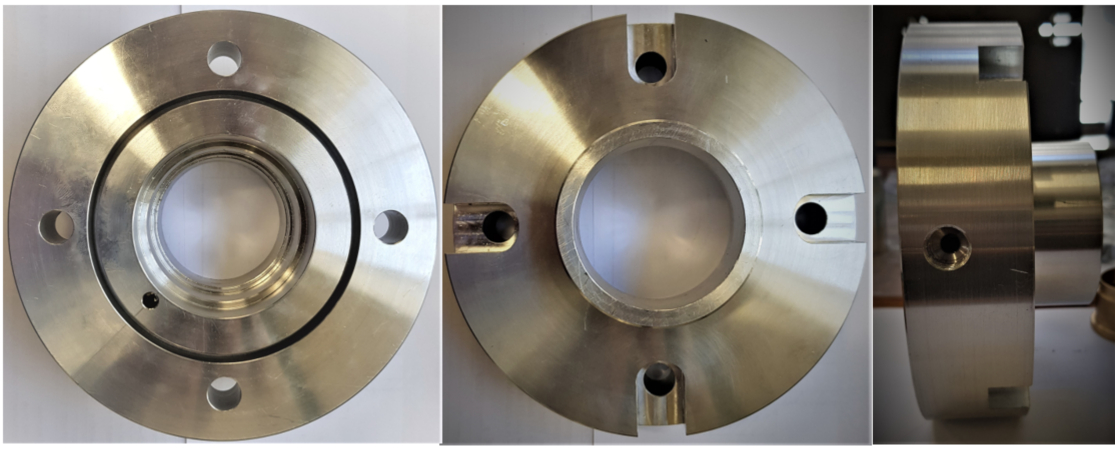


Figure 6.7: Flange 1 Back, Front and Side View

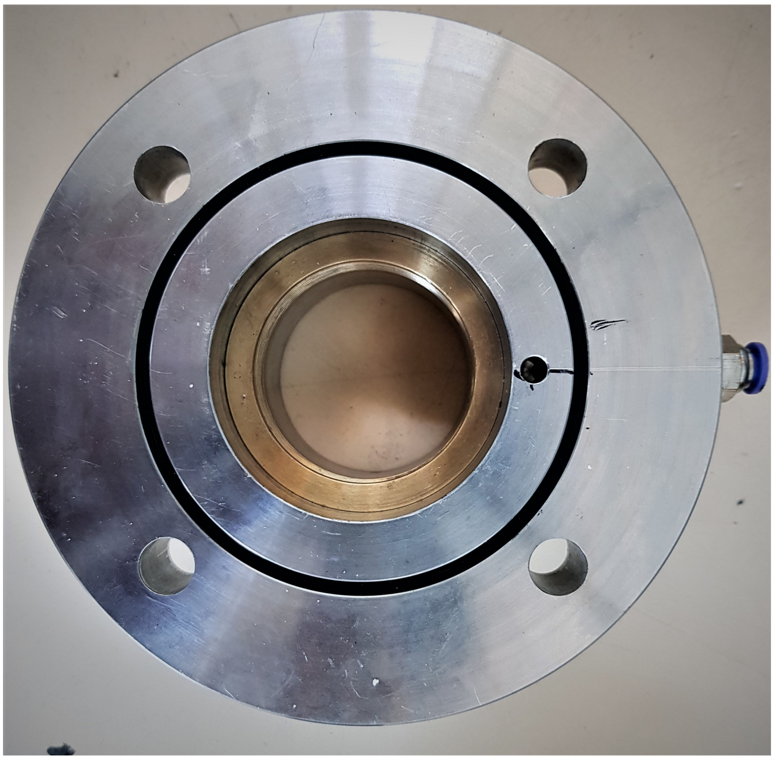


Figure 6.8: Flange 1 with the brass thread insert pressed in

permits nut rotation. The rationale behind this it to make assembly easier as it eliminates the need for two people needed to tighten the assembly, the nut is placed in the recess and the tie rod threaded through and tightened from one end of the. assembly.

The first flange has bore that allows for the pump tube insert and piston to be removed when required. A brass thread insert is press fitted from the inside of the flange and presses on a flange shoulder to ensure that if it comes loose it won't shoot out.

The first flange has an air input on the top to charge the reservoir to the required pressure.

The second flange has a hole that align the barrel and allows it to pass through and thread in the transition piece.

Figure 6.9: Flange 2 Back, Front and Side View

(a) Top view of Thread insert (b) Side view of Thread insert

The flanges are to fit on the already existing mounts available in BISRU. The mounts require a $70mm$ diameter and a shoulder to rest against, the shoulder in this design is the face of the flange as the recesses provide enough room for tightening the nuts. This saves material by making the flanges shorter.

The flanges are different in terms of the slots and bore sizes, this prevents incorrect assembly of components.

6.2.5 Thread Insert

The brass thread insert serves as a threaded section on the flange so that the pump tube insert can be secured by means of a threaded collar. A thread insert had to be designed as the flanges are made of aluminium and since this is a soft material having threads on it that are frequently used is not feasible as the threads would eventually strip.

The thread insert is press fitted from the inside of the flange and sits against and internal shoulder. This was done to ensure that if the press fit were to loosen the part would not shoot out the end of the flange.

An undercut was machined on the part to allow the collar to thread past the last thread to ensure full contact with the pumptube insert.

Figure 6.11: Side view of Collar

6.2.6 Collar

The purpose of the collar is to secure the pump tube insert in place by threading on the thread insert and pressing against a shoulder on the pump tube insert.

A 2cm knurled section on the outside of the collar is machined to allow for grip when tightening and loosening this component.

Pump tube insert adaptor

Figure 6.12: M12 to 1/4 BSP Adaptor

Initially two holes were to be drilled in the insert one for the air supply and the other for a rod that attaches to the piston to remove it. The second hole had a plug that sealed it off when not in use. However due to a design flaw in the holes being to close and the lack of time to obtain a smaller air fitting an adaptor for the second M12 hole to 1/4 BSP air press in fitting was designed.

This allows for the rod to be used to remove the piston after a shot by unscrewing the adaptor. and allows for a 1/4 BSP press in fitting to supply initial air to the piston to fire it.

The reason for having two holes was to allow for the tracking of the piston by having the rod attached to it during firing and tracking a position on the rod. This is however sufficient for the next iteration of this project.

6.3 Unmodified Components

6.3.1 Transition Piece

The transition piece was reused from the 2018 design as it was still in good condition and did not need any modification or redesign.

The transition piece has a conical section at the end that leads into a threaded hole for the barrel to thread in, this allows for the projectile to be positioned at the end of the conical section.

The conical section allows for the piston cap to deform and become lodged in the section. This allows for a better seal and higher final pressure. This also prevents the piston from rebounding after it completes its stroke which would result in undesirable back pressure.

The transition piece fits over the pump tube to make full use of the pump tube length. The other reason for this is that if the transition piece were to deform it would not get stuck or expand in the pump tube causing damage. If this were to occur the transition piece could be replaced at a low cost as opposed to replacing the costly pump tube.

There is also a rubber piece with cut out for barrel at the end of the transition piece to absorb some of the impact as a result of the piston collision.

6.3.2 Reservoir

The reservoir from the 2019 project is also being reused as it was in good condition and the redesign did not require a different size reservoir.

Since the reservoir is to hold a static pressure of 10 bar it needs to conform to the SANS pressure vessel standards for no dangerous gasses. According to theses standards to remain in the SEP region of the graph the total volume needs to be less than or equal to $5l$.

Since the gun is concentrically mounted the total reservoir volume is the reservoir volume less the volume of the components inside it (pump tube and transition piece).

To maximise the reservoir volume would require the flange outside diameter to significantly increase to accommodate the reservoir and this would result in the flanges costing a lot more and the project running out of budget. The simulation showed that the increase in volume in terms of velocity improvement did not warrant the additional cost.

A failure analysis on the reservoir will be completed below to confirm that the reservoir should not fracture or yield under the design pressure. This is done for the sake of completeness as these calculations were conducted in the 2018 report.

Aluminum was selected as it has a low fracture toughness and will leak instead of explode

6.3.3 Barrel

The 2.9m barrel that was used in the 2015 and 2018 project will be reused as the component is in good condition and will save costs in the current project.

New barrels of varying length were purchased in co project 82 to obtain results on various barrel lengths. This is beneficial as it allows one to gather more data and compare the simulations to.

The barrels have a threaded section welded onto their ends to thread into the transition piece. The section was welded on to reduce the effects of distortion and reduce the heat affected zone as this would affect the fit of the projectile in the barrel.

The effects of air leakage between the barrel and transition piece at the breach needs to be considered as this affects the projectile velocity. Since the barrel threads into the transition piece a labyrinth seal is created. A labyrinth seal is essentially a long winding path for leakage to occur along, in this case the threads of the two pieces. Since the total firing time is extremely short ($< 0.0125s$) the leakage effects will be minimal. To reduce the effects thread tape can be placed on the barrel threads.

A rudimentary calculation can be done for the leakage from the transition piece to the barrel, if one were to consider the barrel being a straight piece that fits in the transition piece with some small clearance. A Hagen Poisuell volume loss can then be calculated. This will be significantly higher than the actual pressure loss, but provides a good first order approximation. The calculation is done below.

$$Q = \int_b^a u 2\pi r \mathrm{dr} = \frac{\pi}{8\mu}\left[-\frac{\mathrm{d}}{\mathrm{dx}}(P+\rho g z)\right]\left[a^4 - b^4 - \frac{(a^2-b^2)^2}{\ln a/b}\right] [9] \tag{6.1}$$

6.3.4 Projectile

The 6 projectiles, 3 hollow and 3 solid, are also reused from the 2019 project as they did not seem to need replacing.

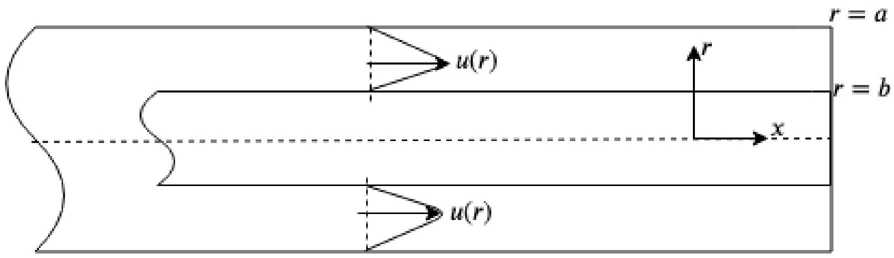


Figure 6.13: Axial Flow in Annular Gap

All the projectiles are based on an ogive profile which is the same profile on which may bullets and projectiles are based. The profile is essentially a cylindrical section that is the diameter of the barrel bore and has a chamfer on the back end and the front end tapers to a point, where the radius center is at the cylinder center.

The hollowed out projectiles weight is $2.48g$ whereas the solid projectiles weight is $3.58g$. The reasons for having two different weight projectiles is that lighter projectiles showed to result in higher muzzle velocities compared to heavier ones. The two weights allow for data to be collected on this to draw a conclusion on this.

The aerodynamics of the projectiles are not a significant factor as they are not in free flight for a significant distance, the muzzle is positioned very close to the wax billet.

6.3.5 Tie Rods

The same M12 tie rods from the 2019 project are reused. The reason for using tie rods is that they are low cost and make for an easier assembly of the gas gun.

Four tie rods were chosen as opposed to 3 as it allows for an even distribution of force over the flange. Each of these tie rods can support $10kN$ in tension which is more than sufficient to support the forces in the set-up.

6.4 Design Safety Considerations

The gas gun can only be assembled in one way, i.e. incorrect parts cannot be assembled together as they will either not fit together, or the holes will be to big. This ensures that the design is safe to assemble and eliminates the risk of incorrect assembly that could result in damage to the gun and potential failure.

The pneumatic circuit is a means of safely pressurising, firing and de-pressurising the gun. It also provides a way to bleed the pressure if for some reason it becomes over pressurised or jammed.

The design is also made in such a way that it will leak before failure. The threads in both the first and second stage act as labyrinth seals that seal the air path during the short firing time, however will not allow for a static pressure to be held. This ensures that if a jam is to occur, then the air pressure will leak out slowly. Calculations were performed using a Hagen Poisuell method for leakage between two concentric cylinders and it was found that the approximate volume flow through the gap is $Volumeflow$

6.5 Design Ease of Use and Assembly Considerations

The flanges have different sized slots and holes for the bolts that hold the tie rods to the flange. The first flange has slots milled into it that allows for the nut to sit in it without rotating while the other has a counter-bore that allows for a washer,nut and socket head to fit in. The rationale behind this is to allow for assembly to be done by one person. This is achieved by only needing to tighten the assembly from one end as the slot acts as the second spanner.

In theory the pump tube insert and piston should be easy to remove as per the design. The collar is unscrewed and the pump tube insert is removed along with the piston allowing for easy inspection and/or replacement. This however did not turn out to be as simple as intended as the tolerances on the components were too tight and made the fit between the components very tight when the orings wer on it making the removal a difficult process. The solution to this would be to machine down the outer diameter of the insert to loosen the fit. Time was however an issue and this could not be completed, however in theory this should be a fairly easy solution.

6.5.1 Assembly Procedure

The second flange is placed on the floor and the rubber padding is placed in it. An oring is placed in the groove for the reservoir on the flange. An oring is fitted to the transition piece and oil is applied to it to allow it to slide into the flange. This is shown in Figure 6.14

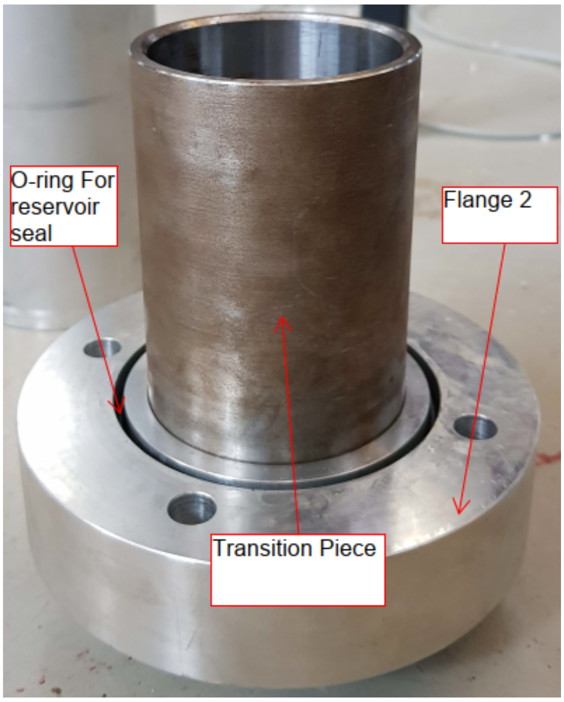


Figure 6.14: Transition Piece and Flange 2 Sub assembly

Four o-rings are placed on the transition piece and it is lubricated with oil. The piston cap is then placed in the piston and the 4 o-rings are placed on the piston, the piston is lubricated and placed in the pump tube insert. Figure 6.15 shows the sub assembly.

Figure 6.15: Piston Sub Assembly

The piston sub assembly is then placed in the pump tube an orings ar placed on the pump tube as shown in Figure 6.16. Care is taken to align the slots on the insert and pump tube during this process and alignment marks are made.

Figure 6.16: Pump Tube Sub Assembly

The previous assembly is placed in the transition piece as shown in Figure 6.17 and the reservoir slid over the pump tube into the flange. An o-ring is placed in flange 1 for the reservoir. The flange is then placed over the reservoir and pump tube and the collar screwed in. Tie rods are placed through the flanges and secured with bolts.

Figure 6.17: Assembly

The air fittings are then screwed into place ensuring to place thread tape on all threads. A 1/4 BSP thread 6mm press in fitting is threaded into flange 1 and into the adaptor that is threaded into the pump tube insert. This is shown in Figure

6.6 Pressure Leakage Calculations

6.7 Pneumatic Circuit

The Pneumatic circuit shown in Figure 6.19 was designed in co-project 81 to safely pressurise

6.7.1 Brief Overview of control circuit

The Pneumatic circuit consists of 5 valves that are used to safely pressurise, fire and de-pressurise the gas gun.

The valves on the board are as follows, inlet pressure valve; Reservoir valve; intermediate valve; Piston control valve; relief valve.

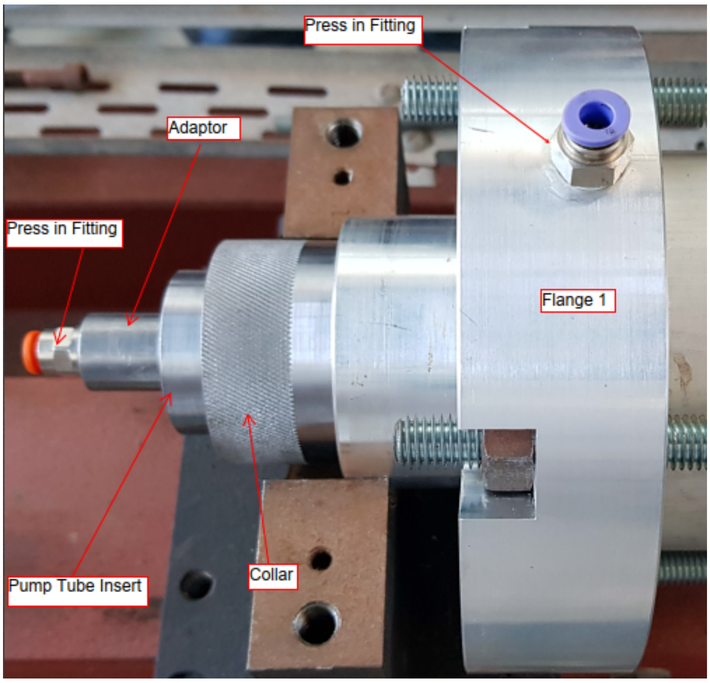


Figure 6.18: Air Fittings on Flange 1

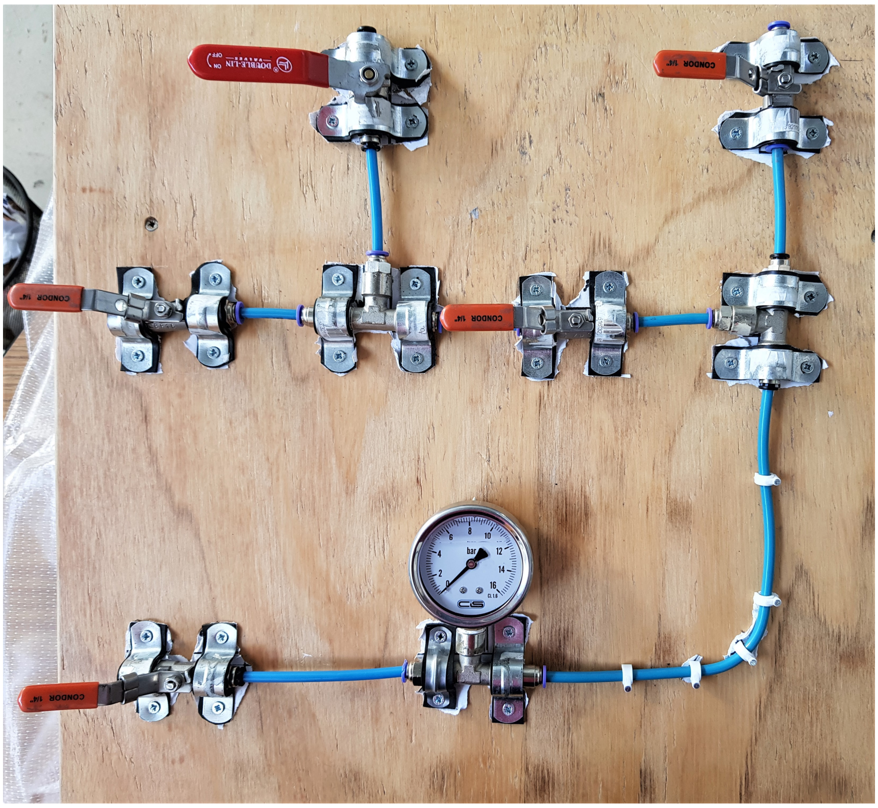


Figure 6.19: Pneumatic Circuit

6.8 Light Trap

6.8.1 Brief Overview of Light Trap Design

The light trap shown in Figure 6.20 was designed in co-project 82 and is used to obtain the velocities of the projectiles. Figure 6.21 shows the new light trap as well as the one used in the previous project mounted to the barrel.

The Light traps basic operating principals are a laser that shines a beam on a photo diode which is connected to a oscilloscope. When the projectile passes through the light trap the circuit is essentially broken as the laser is no longer shining on the photo diode. This cases a voltage drop on the oscilloscope signal . the distance between these sensors are know (40mm) and the time can be obtained from an oscilloscope read out so the velocity can be inferred.

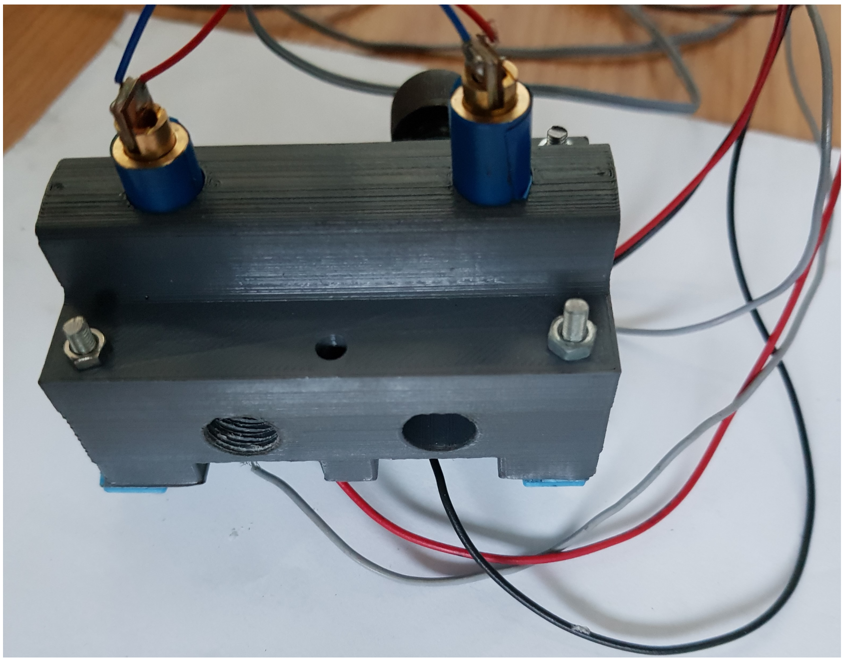


Figure 6.20: Light Trap

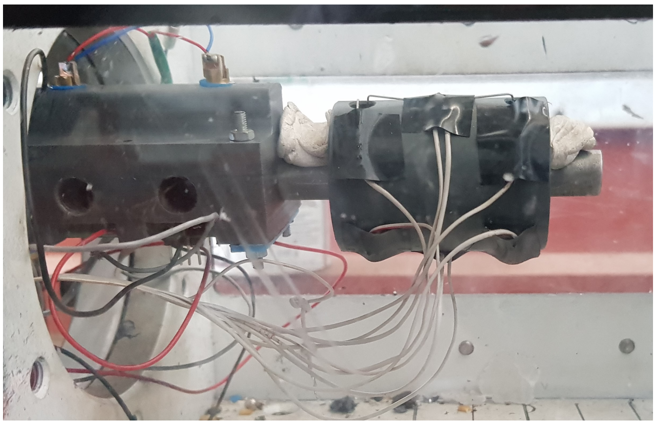


Figure 6.21: Old and New Light Trap Mounted on Barrel

6.9 Catch Box

The existing catch box in BISRU was modified in co-project 81 to allow for mounting of plate targets. This catch box was also used to catch the projectiles in a wax billet. Figure 6.22 shows the catch box.

Table 6.1: Add caption

Part	**Material**	**No Pieces**	**Cost Per Piece**	**Total Cost**	**Excluded Costs**	**Final Cost**
Flanges	Aluminium	2	300	600		600
Pump Tube	EN8 Steel	1	*900*	900	900	0
Pump Tube Insert	EN8 Steel	1	96.35	96.35		96.35
Collar	EN8 Steel	1	62.22	62.22		62.22
Thread Insert	Brass	1	126	126	126	0
Piston	Aluminium	2	*100*	200	200	0
Piston Caps	HDPE/PE	5	*28*	140	140	0
Transition Piece	EN8 Steel	1	*190*	190	190	0
Reservoir	Aluminium	1	*292*	292	292	0
Tie Rods	Steel	4	*28*	112	112	0
Projectiles	Aluminium	6	*10*	60	60	0
Flange Rubber	Rubber	1	*60*	60	60	0
O-Rings	Rubber	TOTAL	25	25		25
Air Valve	N/A	2	18	36		36
Adaptor	EN8 Steel	1	40.54	40.54		40.54
Piston Rod (Remover)	Aluminium	1	54	54		54
				2994.11	2080	**914.11**

Table 6.2: Add caption

Part	**Alternate Material**	**No Pieces**	**Cost Per Piece**	**Total Cost**	**Excluded Costs**	**Final Cost**
Flanges	Stainless Steel	2	450	900		900
Pump Tube	Stainless Steel	1		0	0	0
Pump Tube Insert	Stainless Steel	1		0		0
Collar	Brass	1		0		0
Thread Insert	Stainless Steel	1	120	120	120	0
Piston	PVC	2		0	0	0
Piston Caps	Nylon/Teflon	5		0	0	0
Transition Piece	Stainless Steel	1		0	0	0
Reservoir	-	1	490	490	490	0
Tie Rods	-	4		0	0	0
Projectiles	Nylon	6		0	0	0
Flange Rubber	Silicon	1		0	0	0
O-Rings	Vitron	TOTAL	100	100		100
Air Valve	-	2		0		0
Adaptor	Brass	1		0		0
Piston Rod (Remover)	Wood/ Dowel Stick	1		0		0
				1610	610	**1000**

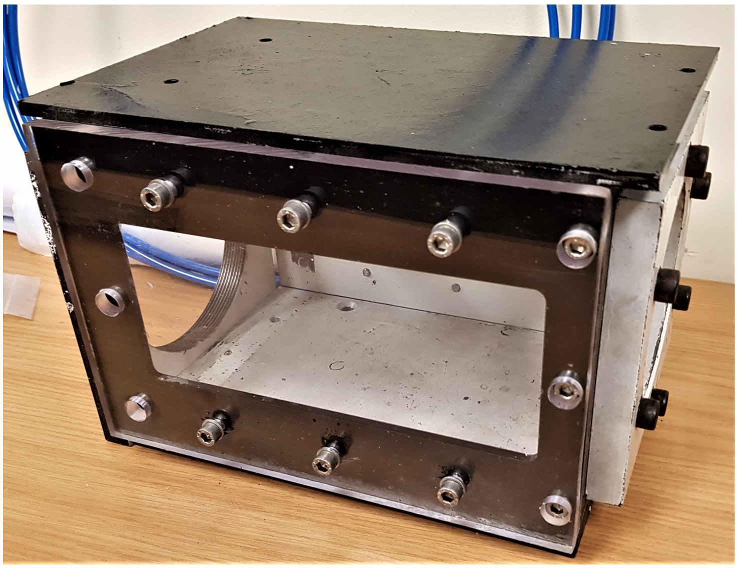


Figure 6.22: Catchbox

6.10 Costing

6.10.1 Budget Report

6.10.2 Variance Report

Table 6.3: Add caption

Part	**Material**	**No Pieces**	**Final Cost Per Piece**	**Total Cost**	**Excluded Costs**	**Variance Costs**	**Fina Cos**
Flanges	Aluminium	2	300	600			
Pump Tube	EN8 Steel	1	*900*	900	900		
Pump Tube Insert	EN8 Steel	1	96.35	96.35			
Collar	EN8 Steel	1	62.22	62.22			
Thread Insert	Brass	1	126	126	126	126	
Piston	Aluminium	2	*100*	200	200	200	
Piston Caps	HDPE/PE	5	*28*	140	140	140	
Transition Piece	EN8 Steel	1	*190*	190	190		
Reservoir	Aluminium	1	*292*	292	292		
Tie Rods	Steel	4	*28*	112	112		
Projectiles	Aluminium	6	*10*	60	60		
Flange Rubber	Rubber	1	*60*	60	60		
O-Rings	Rubber	TOTAL	25	25		65	
Air Valve	N/A	2	18	36			
Adaptor	EN8 Steel	1	40.54	40.54			
Piston Rod (Remover)	Aluminium	1	54	54			
				2994.11	2080	531	**144**

7. Testing

7.1 Safety Consideration

All the tests will involve firing a projectile at high velocities, some of which are supersonic using a high pressure gas. There are various safety considerations that need to be understood and the proper procedures to reduce risks involved followed. Firstly all the relevant risk assessments are completed and filled out and approved by both the project supervisor and area safety warden.

The gas gun assembly is pressure tested to 1.5 time the designed for pressure in the blast chamber. The gas gun was placed in the blast chamber and the reservoir connected to the pneumatic circuit outside the blast chamber (the door was closed with a small gap for the air line). The reservoir was pressurised to 16 bar using a gas cylinder. The assembly did not leak or fail in any way and was therefore deemed safe to operate. A picture of the pressure gauge is included bellow as required by the risk assessment.

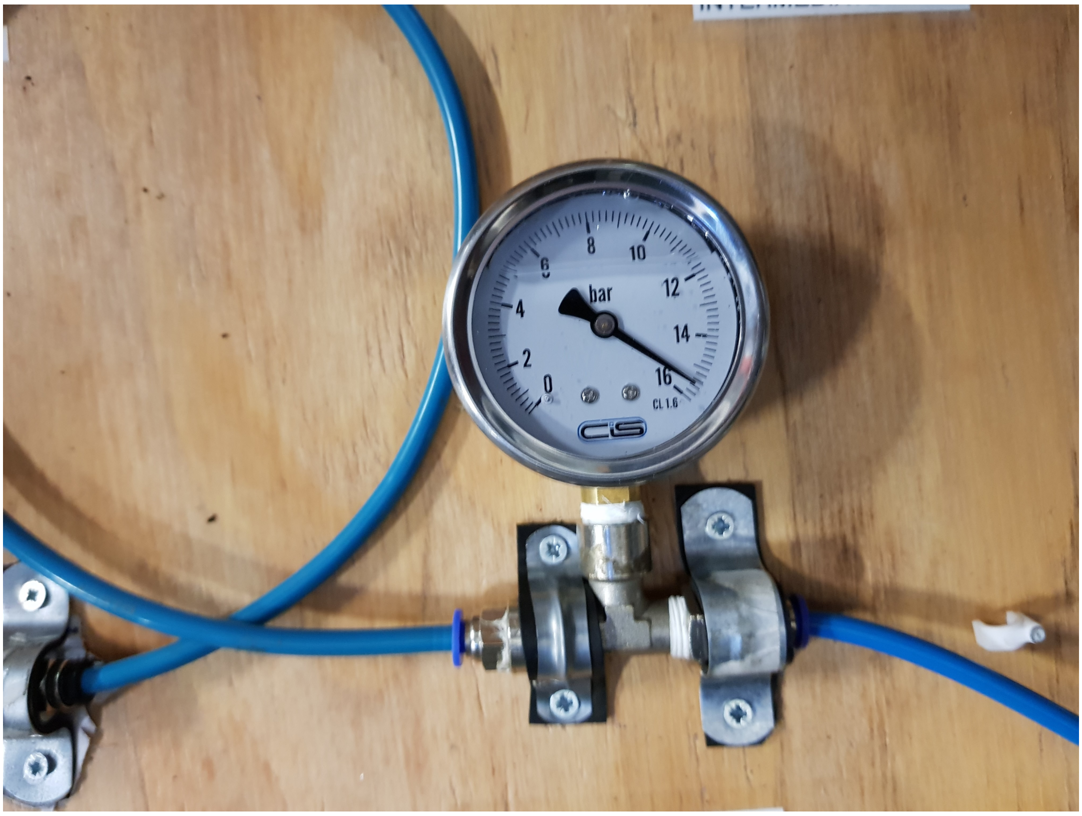


Figure 7.1: Pressure Gauge demonstrating Reservoir Pressure during Pressure Test

A catch box that houses a wax billet is used to trap the projectile and ensure that it is not in free flight and prevent ricochets or collisions with people or other instruments in the area. All people in the direct vicinity of the gas gun are to wear ear muffs and safety glasses when firing is to take place. A warning is shouted out, then an alarm sounded before the shot is fired to alert everyone as to what is about to occur.

7.2 Assembly Procedure During Testing

The gas gun redesign allows for easy removal and resetting of components without the need for disassembly. The Procedure used during testing will be described here.

The gas gun was assembled as described previously and mounted in the I-Beam Mountings. These mountings were aligned and secured in place. The gas gun was fixed in place and the catch box was moved to accommodate various barrel lengths. Alignment on the catch box and barrel mounts were checked checked with a ruler each time the barrel was changed as shown in Figure 7.2.

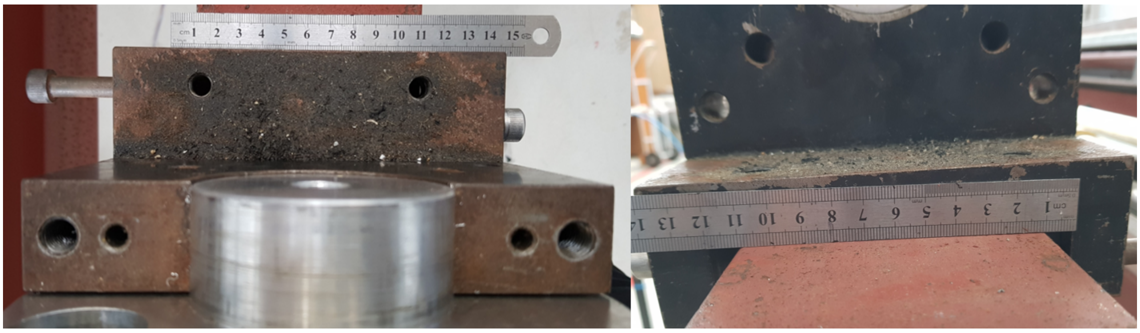


Figure 7.2: Mounting Alignment

The Piston was reset by removing the 1/4 BSP press fitting adaptor that supplies the air to supply the initial piston movement and passing the piston rod through the hole and threading into the piston. The rod and piston were then pulled back to the initial position. This is indicated in Figure 7.3

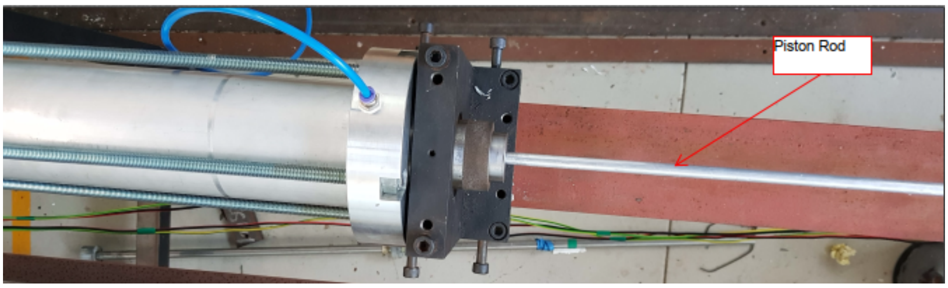


Figure 7.3: Piston reset using piston rod

If the piston needed to be removed the collar needed to be unscrewed and the pump tube insert pulled out through the flange, the o-rings used were slightly too big and made the seal to tight to do this frequently, it did however work. Alignment markings were made to ensure than when these components were replaced the slots on the pump tube insert and pump tube lined up. Figure

7.3 Leak Test

A leak test was conducted to find any sources of leaks in the pneumatic circuit as well as in the gas gun before the pressure test can be done.

The procedure for this test was as follows. The pressure lines were checked to ensure they were all secure and connected to the correct places. The valves on the pneumatic circuit were then all set to the closed position. The piston fire valve is then opened, the relief valve is opened, The intermediate valve is closed and the reservoir valve is closed. The pressure line is then connected to the supply and the inlet valve is slowly opened and the gauge is pressurised to 2 bar. The inlet valve is closed and the gauge is checked to see if the pressure drops.

The pressure on the gauge initially dropped so soapy water was applied around the connections where air was flowing to see if air bubbles formed. No bubbles formed so the pneumatic board was undone and each fitting was individually submerged in water to see if bubbles form (indicating a leak)as can be seen in Figure 7.4. These fittings were then removed and thread tape reapplied liberally and tightened sufficiently. They were then submerged again with pressure flowing to ensure to leak was fixed. This process was repeated on the pneumatic circuit until all the leaks were resolved.

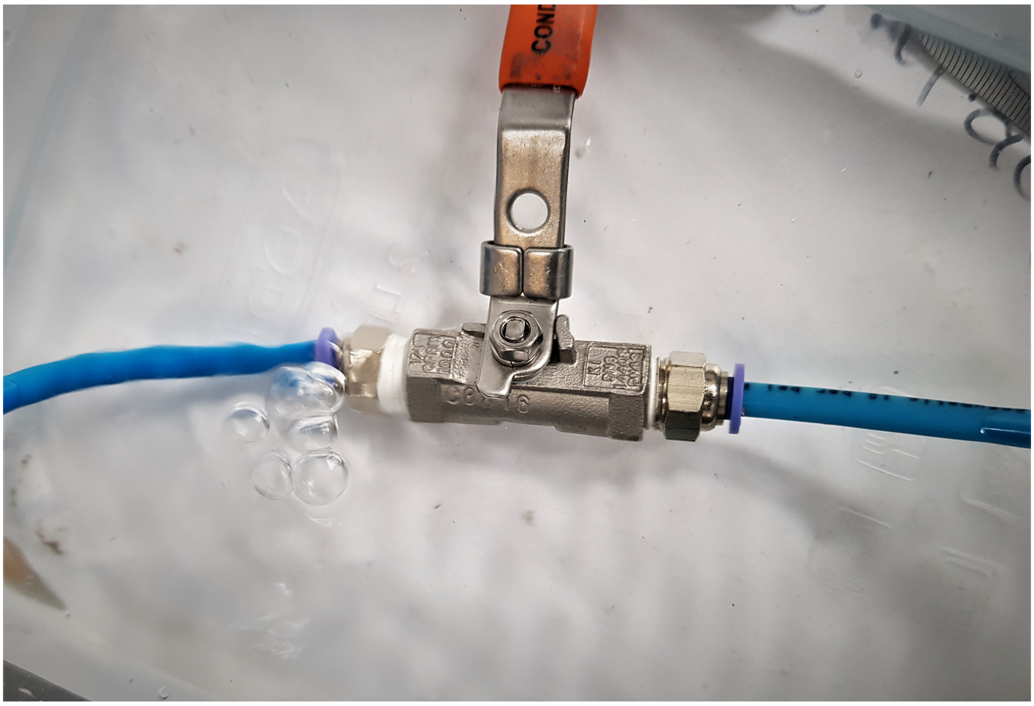


Figure 7.4: Air Leak on Pneumatic Circuit

The reservoir was then pressurised at 3 bar for the leak test on the gas gun once all the leaks on the pneumatic circuit were found and resolved. This was done as follows

The pressure gauge started to drop off initially indicating a leak in the reservoir. Soapy water was applied to the potential leak sites on the gas gun and the reservoir re-pressurised. The leak was immediately found as soap bubbles started to form at the reservoir press in fitting as can be seen in Figure 7.5. This was resolved by reapplying thread tape and checking again for leaks.

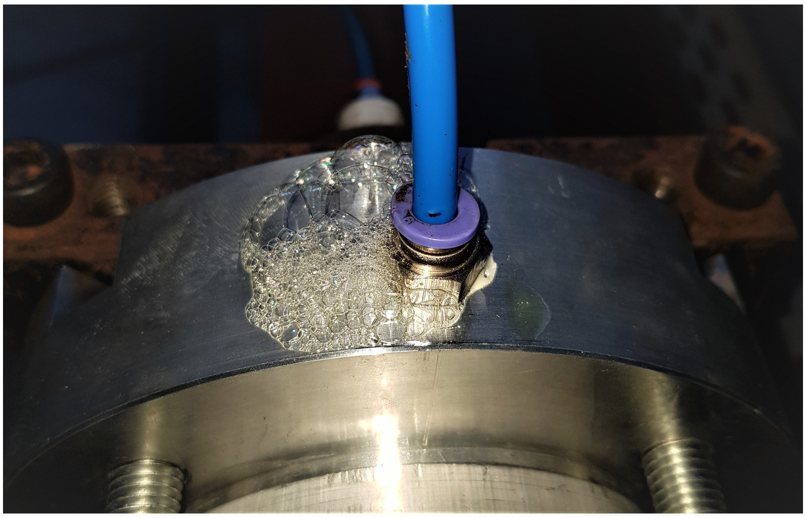


Figure 7.5: Air Leak on reservoir Pressure Input

7.4 Pressure Test

Once the leak test was complete and all leaks were resolved a pressure test of the reservoir could be conducted to ensure that the gun is safe to operate. This test was to pressurise the reservoir to 1.5 times the operating pressure designed for.

The pressure test was conducted in the blast chamber at BISRU. This was done to ensure that if the vessel were to fail in anyway, it would occur in a controlled environment removing the risk of injury due to said failure.

A Nitrogen gas cylinder was used to conduct the pressure test as the air pressure lines at BISRU do not go above 10 bar. The necessary connections were found and the cylinder and pneumatic circuit were set up just outside the blast chamber. The gun was then placed inside the blast chamber and the pressure line to the reservoir connected. The blast chamber door was then closed and the door closed almost fully (leaving a small passage for the pressure line. The piston valve was opened as well as the relief valve. The intermediate valve was closed and the reservoir valve opened. The gas cylinder was opened and the reservoir was pressurised up to 16 bar. The gauge was checked and a picture of the gauge was taken at the maximum pressure. The reservoir was de-pressurised and the test completed.

7.5 Test Design

The testing design for this project will involve firing projectiles with 2 different weights at initial pressures varying from 4 bar up to 10 bar, and varying barrel lengths from 0.65m up to 4m.

The volume deformation of the piston cap will also be measured to infer the second stage volume.

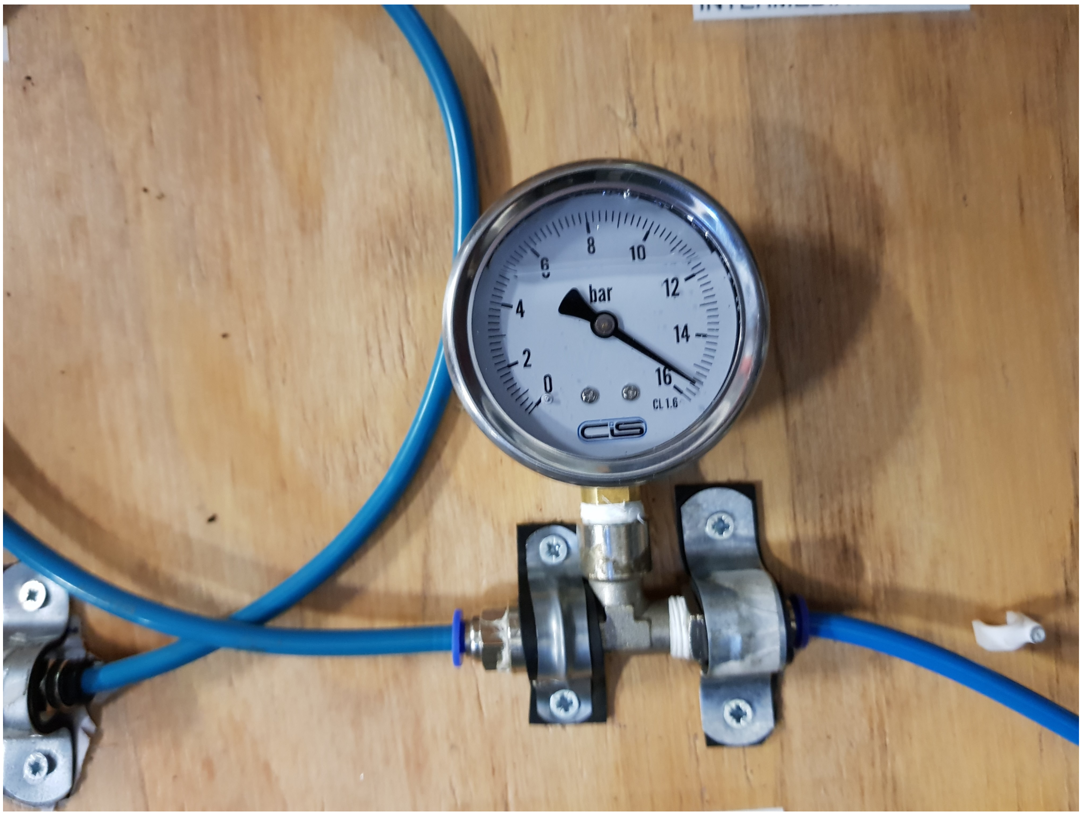


Figure 7.6: Pressure Gauge demonstrating Reservoir Pressure during Pressure Test

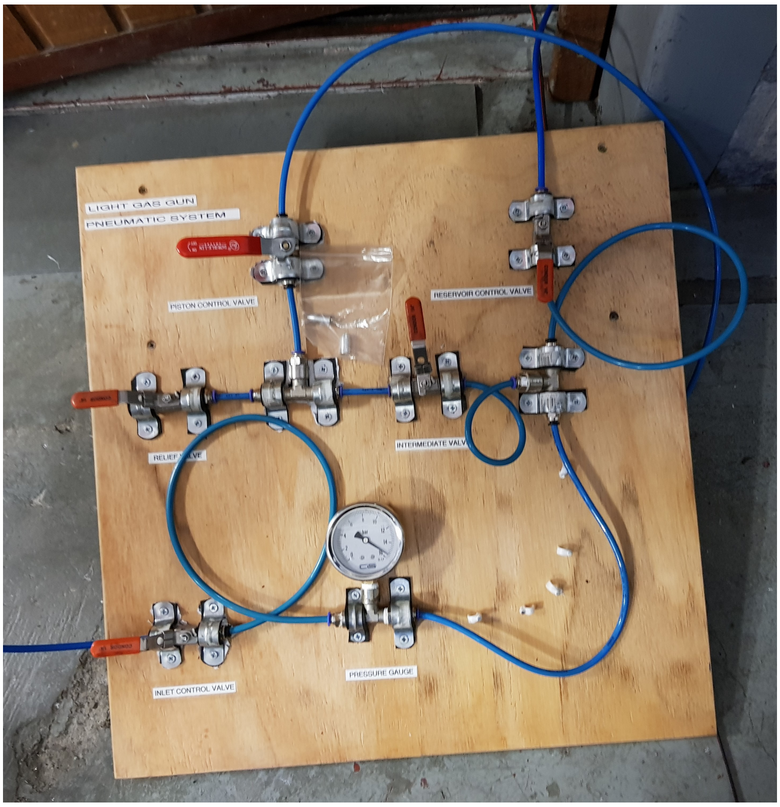


Figure 7.7: Pneumatic Circuit during Pressure Test

7.6 Testing Procedure

In order to set up for a test the gas gun had to be assembled. All fasteners were checked to ensure that they were secure. The piston was then set in the starting position

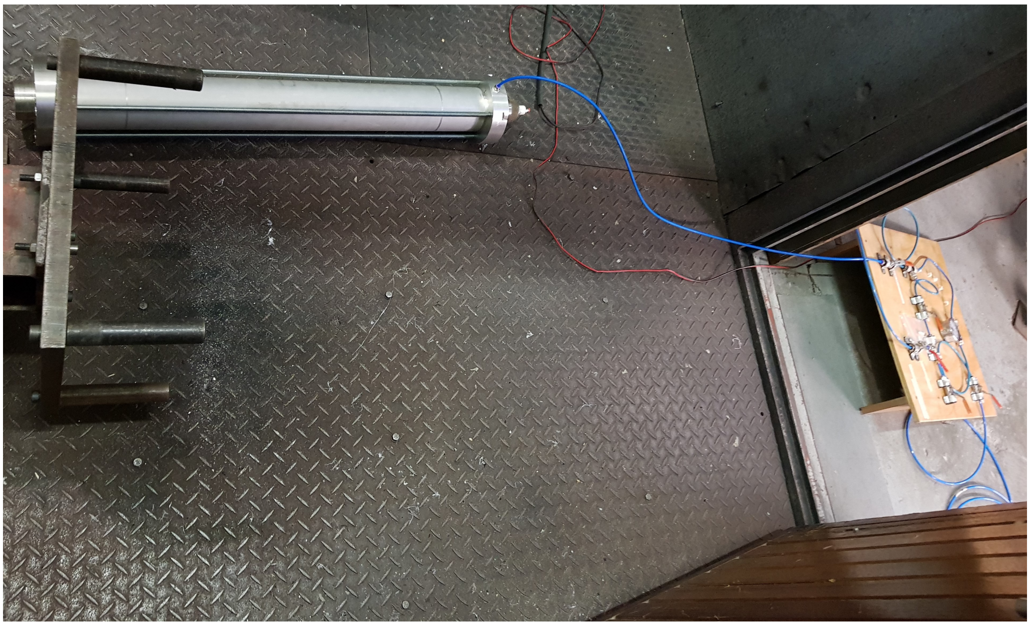


Figure 7.8: Gas Gun Set up during Pressure Test

using the pull rod. The pneumatic circuit was set up an the valves set to the correct position to start testing (pressure inlet:closed;Reservoir:closed;Intermediate:closed;Piston Control:open;Relief:open). The main pressure line; piston air line; and reservoir pressure line were connected to the circuit. The Mounts on the gun and barrel were checked for alignment an secured in place a projectile was placed in the chosen barrel an it was threaded into the transition piece. The light trap was then mounted and checked for alignment. The was billet was then placed in the catch box and the box closed. The reservoir could now be pressurised and a firing warning given out before proceeding to fire.

There was a setback during testing that caused a delay with some of the results and the tests were unable to go up to the intended 10 bar. The pressure line that was connected to the nitrogen cylinder exploded during the 6 bar test. Figure 7.9 shows the pressure line after it exploded. The nitrogen cylinder was used as the compressor in BISRU did not have a pressure up to the required 10 bar and on the day of testing was only pressurised up to 7 bar. Fortunately nobody one was injured however, this could have potentially been a very dangerous situation. The incident was reported as a near miss and testing was continued with the use of the air supply lines. The exact reason for the explosion is unknown. A pressure regulator should have been used with the set up to ensure that only the intended pressure is sent through the lines to avoid such occurrences.

During two tests the projectile fell through the barrel in the transition piece as shown in Figure 7.10. Care was taken when threading the barrel in after this occured to ensure that this did not occur again as it could cause damage to the transition piece. This was most likely due to a jerking motion while screwing in the barrel. In Future it can be designed such that the projectile cannot fall back through the transition piece, by making the transition piece end diameter slightly smaller or having a slight lip/shoulder to prevent this.

Figure 7.9: Exploded Pressure Line

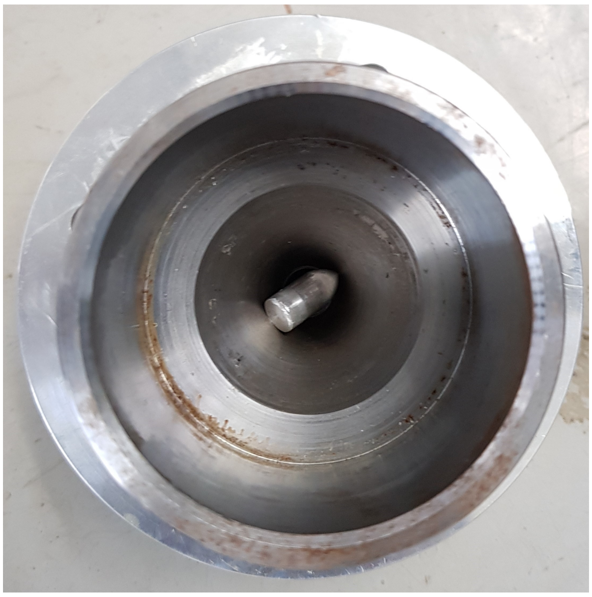


Figure 7.10: Projectile in Transition Piece

8. Results

8.1 Recorded Data

Table 8.1 on page 60 shows the results from the light trap for various barrel lengths and pressures.

The times were read off at both the start and end of each signal in the light trap to give two velocities for the same projectile and an average of these two were taken as the actual velocity of the projectile. In the case of some of the results two average velocities are quoted, this is because the new light trap from the current year as well as the one from the previous year were used on the same test.

The piston deformation was not measured for every test as the velocity measurement was of greater concern. Time was running short and a call was made to get more results in terms of velocity as there were 3 dependent projects on the apparatus. Two measurements were taken to get an idea of what the final volume in the transition piece was.

Table 8.1: Results

Projectile (Type)	Pressure (bar)	Barrel (m)	Test (#)	Distance (mm)	Time 1 (s)	Time 2 (s)	delta t 1 (s)	Time 3 (s)	Time 4 (S)	delta t 2 (s)	Velocity 1 (m/s)	Velocity 2 (m/s)	Average Velocity (m/s)
03/10/2019													
Solid	4	0.65	1	40	2.438	2.44	3E-04	2.44	2.439	0.0003	132.89	117.994	125.442
Solid	4	2.9	2	40					Inconclusive				
Solid	4	2.9	3	40					Inconclusive				
Solid	4	2.9	4	40	3.846	3.85	2E-04	3.85	3.847	0.0002	167.364	210.526	188.945
Solid	4	2.9	5	40					Inconclusive				
04/10/2019													
Hollow	1	0.65	1	40	2.777	2.78	9E-04	2.78	2.778	0.0008	45.8716	47.1143	46.493
Hollow	2	0.65	2	40	2.325	2.33	6E-04	2.33	2.326	0.0006	72.3327	72.4638	72.398
Hollow	3	0.65	3	40	4.695	4.7	5E-04	4.7	4.696	0.0003	86.7679	131.148	108.958
Hollow	4	0.65	4	40	4.159	4.16	3E-04	4.16	4.159	0.0003	129.87	125	127.435
Hollow	5	0.65	5	40	5.582	5.58	2E-04	5.58	5.582	0.0003	176.991	153.471	165.231
Hollow	6.4	0.65	6	40	3.893	3.89	2E-04	3.89	3.894	0.0002	205.383	218.579	211.981
Hollow	6.45	1	7	40	4.974	4.97	2E-04	4.97	4.975	0.0002	236.967	227.349	232.158
Hollow	6.95	1	8	40	2.997	3	1E-04	3	2.998	0.0001	305.39	301.232	303.311
Hollow	6	2	9	40	0.26	0.26	2E-04	0.26	0.261	0.0002	257.732	257.732	257.732
Solid	7	2	10	40	0.681	0.68	2E-04	0.68	0.682	0.0002	244.948	245.098	245.023
Sabot	2	2	11	40					Inconclusive				
Sabot	4	2	12	40	1.405	1.41	2E-04				202.02		202.020
Sabot	6	2	13	40	1.027	1.03	1E-04	1.03	1.027	0.0001	275.329	277.418	276.373
Sabot	7	2	14	40	1.892	1.89	1E-04	1.89	1.892	0.0001	314.961	384.615	349.788
	Light trap 2			40	1.892	1.89	1E-04	1.89	1.892	0.0001	307.636	307.572	307.604
Sabot	7	2	15	40	2.616	2.62	1E-04	2.62	2.616	0.0001	317.543	314.592	316.068
	Light trap 2			40	2.616	2.62	1E-04	2.62	2.616	0.0001	302.113	308.181	305.147
Sabot	2	2	16	40	5.962	5.96	3E-04	5.96	5.963	0.0003	123.203	116.298	119.750
	Light trap 2			40	5.962	5.96	3E-04	5.96	5.962	0.0003	117.199	119.235	118.217
Sabot	5	2	17	40	5.949	5.95	-2E-04	5.95	5.949	-2E-04	-244.91	-236.92	-240.919
	Light trap 2			40	5.949	5.95	-2E-04	5.95	5.949	-2E-04	-235.38	-234.93	-235.157

9. Discussion

9.1 Wax Billets After Shots

Figure 9.1 shows the wax billets after shots were fired into them. It can be seen that the projectiles do not enter the billet straight every time. The only shot that entered perfectly straight was a low pressure($4bar$) shot with a hollow projectile. This is shown in the middle picture on the bottom row. It would be possible to obtain a velocit measurement from the depth of penetration, however due to the skew entry of most of the shots measuring the depth would not be feasible.

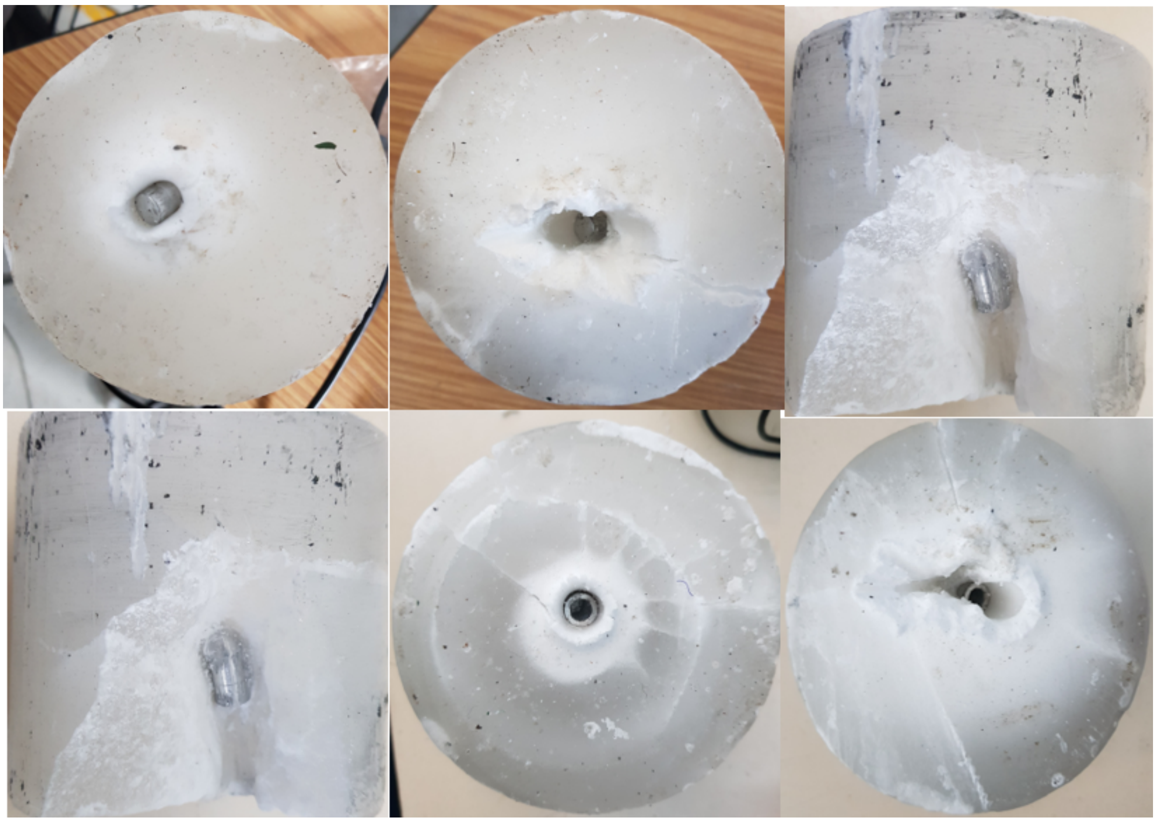


Figure 9.1: Wax Billets With Projectiles Lodged Inside

9.2 Projectile

9.3 Projectile Before and After Use

The projectiles had deep scratches after the first shot, this is potentially due to a rough surface finish on the inside diameter of the barrel and a tight fit between the projectile

Figure 9.2: Projectile after shot

and barrel. Another reason for this could be that since steel tubes are toleranced on the outside diameter and not on inner diameter, the inner diameter could vary over the barrel length resulting in tighter fits in certain spots.

The velocities after the projectiles were removed from the wax billet and reused increased when the same test was run. This is potentially due to the slight residual wax coating on the projectile creating a better seal between it and the barrel. The results for this were unfortunately not documented.

9.4 Projectile Weight Influence

3 different projectile weights were used in testing namely Solid Projectile, Hollow Projectile and A Sabot with ball bearing in order of weight from heaviest to lightest. It was clear from the data recorded that the lighter projectiles had a higher velocity. This makes sense as mass is inversely proportional to velocity squared as per the work energy relation ship developed earlier.

9.5 Piston Cap Effects

Due to time constraints the piston cap deformation was only measured for two shots. This should however be done for each shot as it gives valuable data in terms of the final second stage volume which can be used to infer the final pressure

9.6 Variance from Numerical Results

9.7 Comparison to Single stage Theoretical Model

9.8 Components before and after use

9.9 Assembly time and Usability

9.10 Results Interpretation and Discussion

9.10.1 Solid Projectile at 4 bar

Table 9.1: Add caption

Projectile	Pressure (bar)	Barrel (m)	Velocity (m/s)
Solid	4	0.65	125
Solid	4	2.9	189

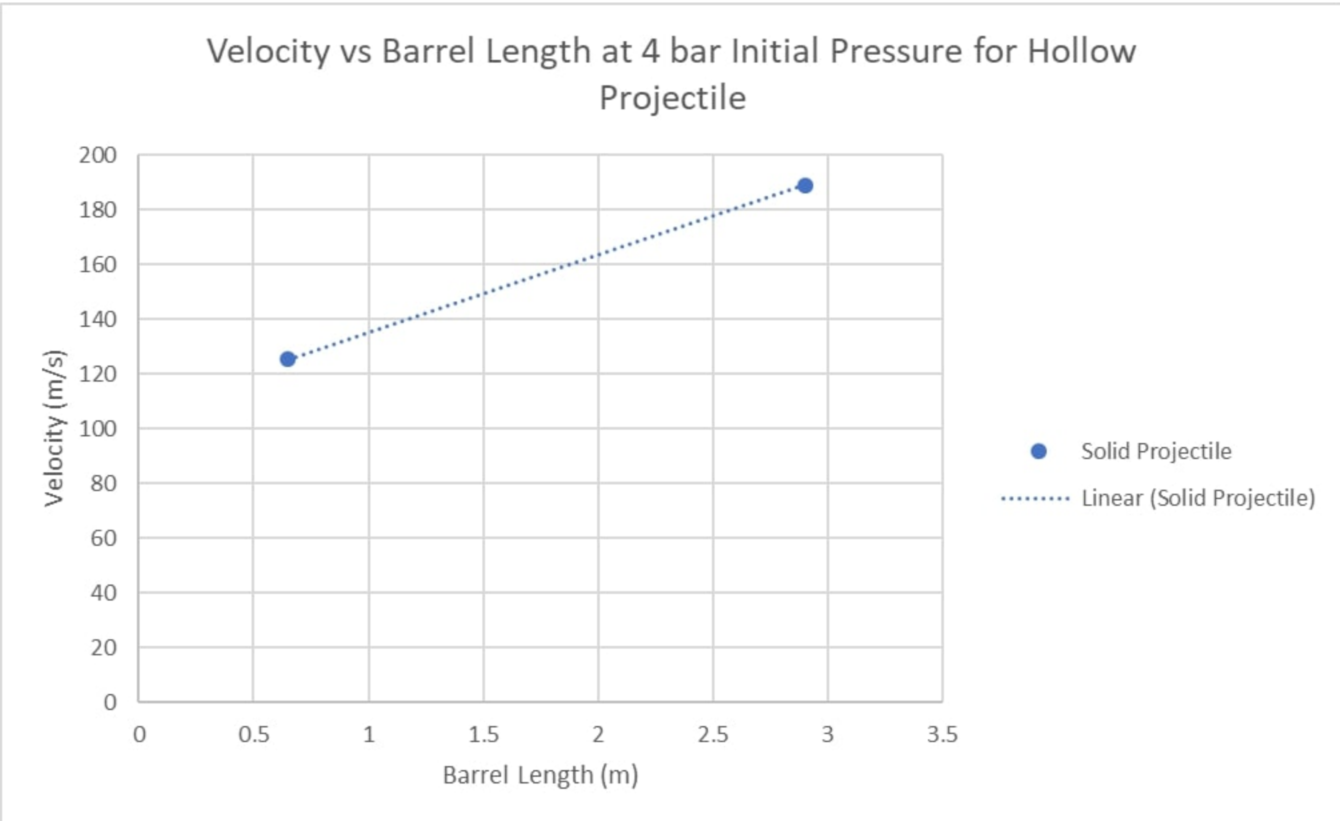


Figure 9.3: Velocity vs Barrel Length at 4 bar Initial Pressure for Hollow Projectile

Table 9.2: Add caption

Projectile	**Pressure (bar)**	**Barrel (m)**	**Velocity (m/s)**
Hollow	1	0.65	46
Hollow	2	0.65	72
Hollow	3	0.65	109
Hollow	4	0.65	127
Hollow	5	0.65	165
Hollow	6.4	0.65	212

Table 9.3: Add caption

Projectile	**Pressure (bar)**	**Barrel (m)**	**Velocity (m/s)**
Hollow	1	0.65	46
Hollow	2	0.65	72
Hollow	3	0.65	109
Hollow	4	0.65	127
Hollow	5	0.65	165
Hollow	6.4	0.65	212
Hollow	6.45	1	232
Hollow	6.95	1	303
Hollow	6	2	258

Table 9.4: Add caption

Projectile	**Pressure (bar)**	**Barrel (m)**	**Velocity (m/s)**
Solid	4	0.65	125
Solid	4	2.9	189
Solid	7	2	245
Hollow	1	0.65	46
Hollow	2	0.65	72
Hollow	3	0.65	109
Hollow	4	0.65	127
Hollow	5	0.65	165
Hollow	6.4	0.65	212
Hollow	6.45	1	232
Hollow	6.95	1	303
Hollow	6	2	258

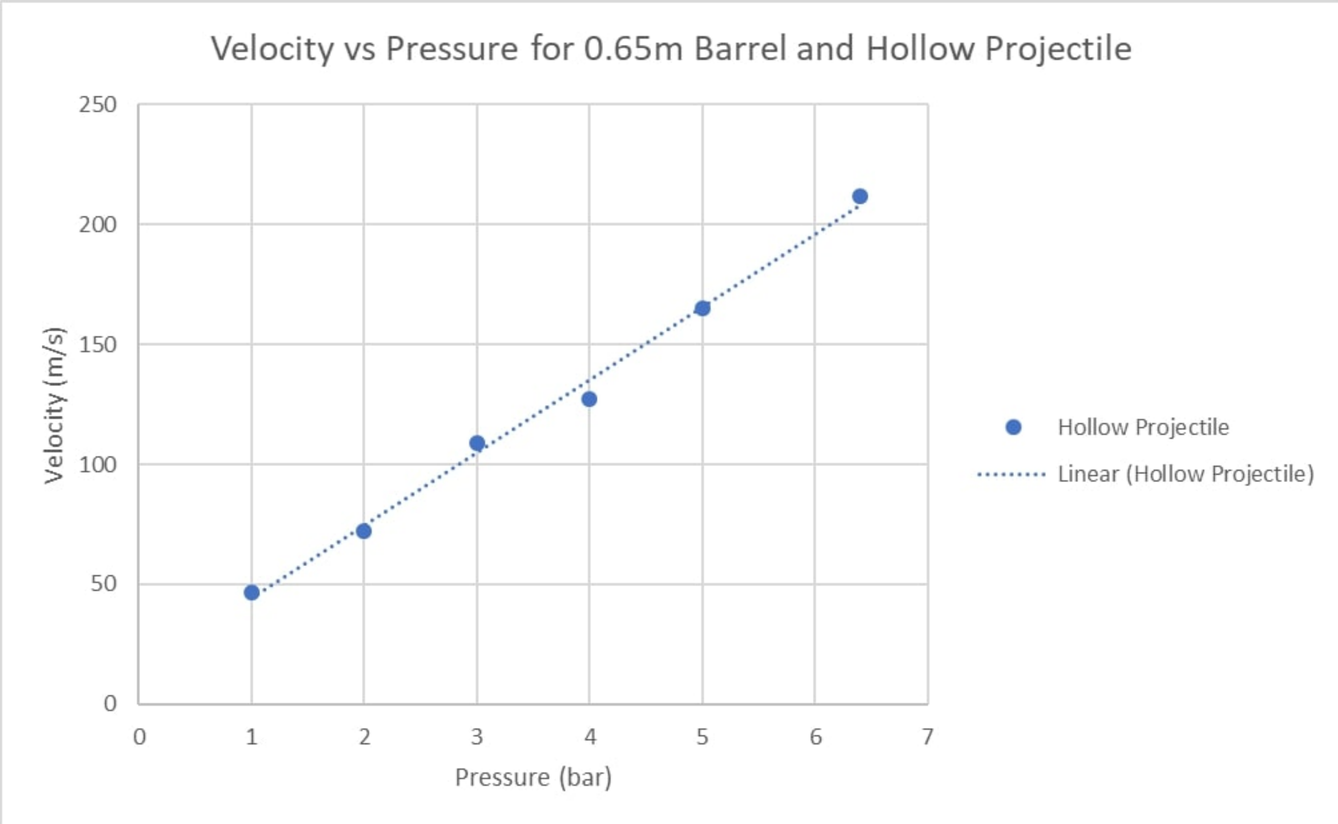


Figure 9.4: Velocity vs Pressure for 0.65m Barrel and Hollow Projectile

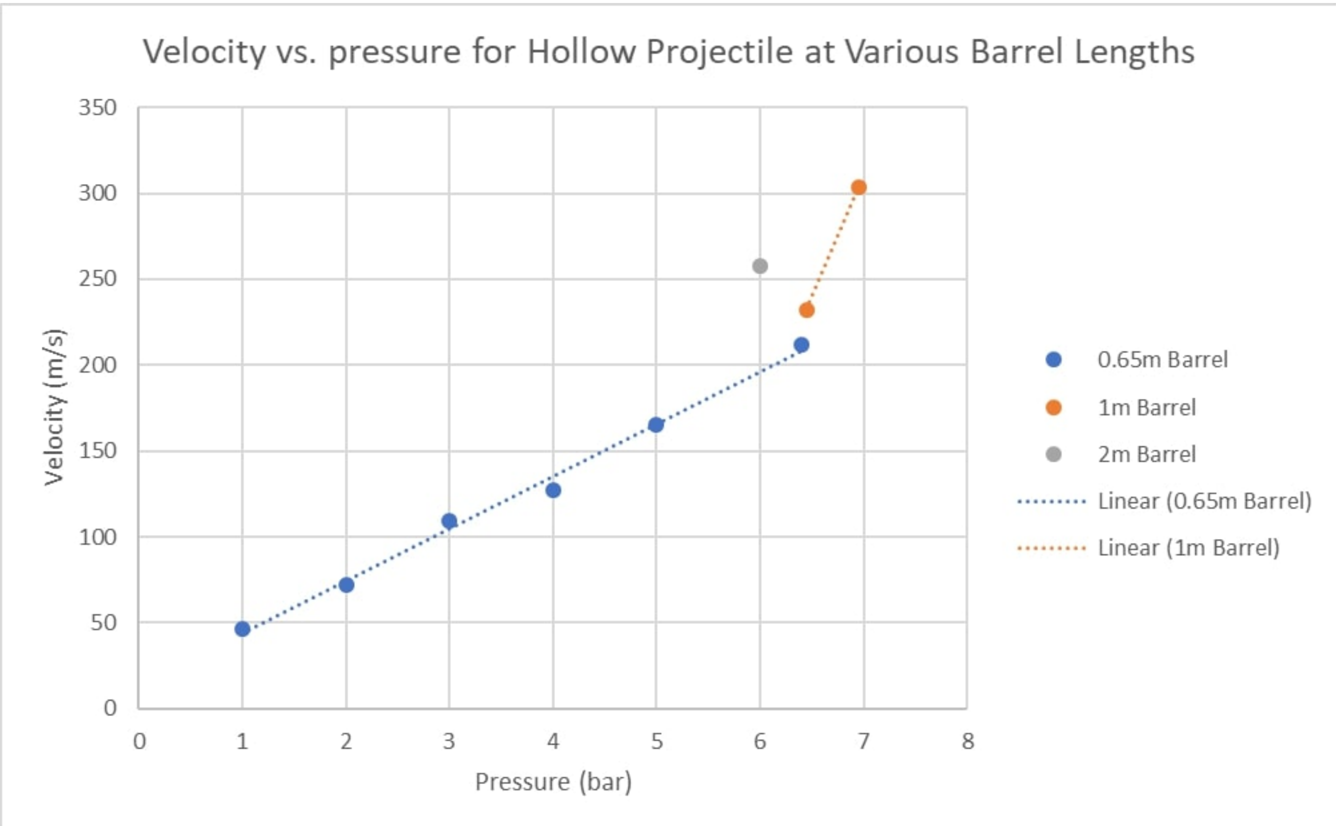


Figure 9.5: Velocity vs. pressure for Hollow Projectile at Various Barrel Lengths

9.10.2 •

9.10.3 •

9.10.4 •

9.11 Oscilloscope Readings

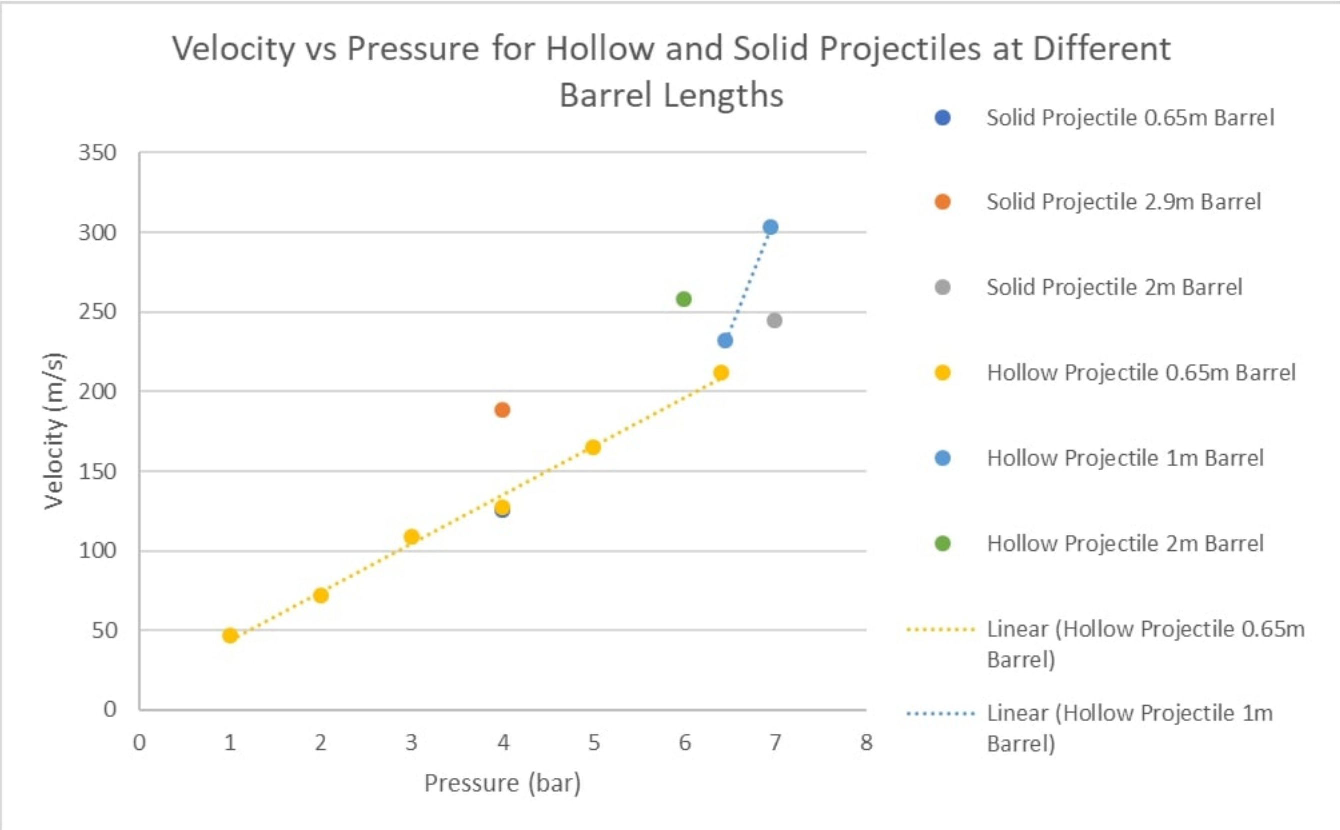


Figure 9.6: Velocity vs Pressure for Hollow and Solid Projectiles at Different Barrel Lengths

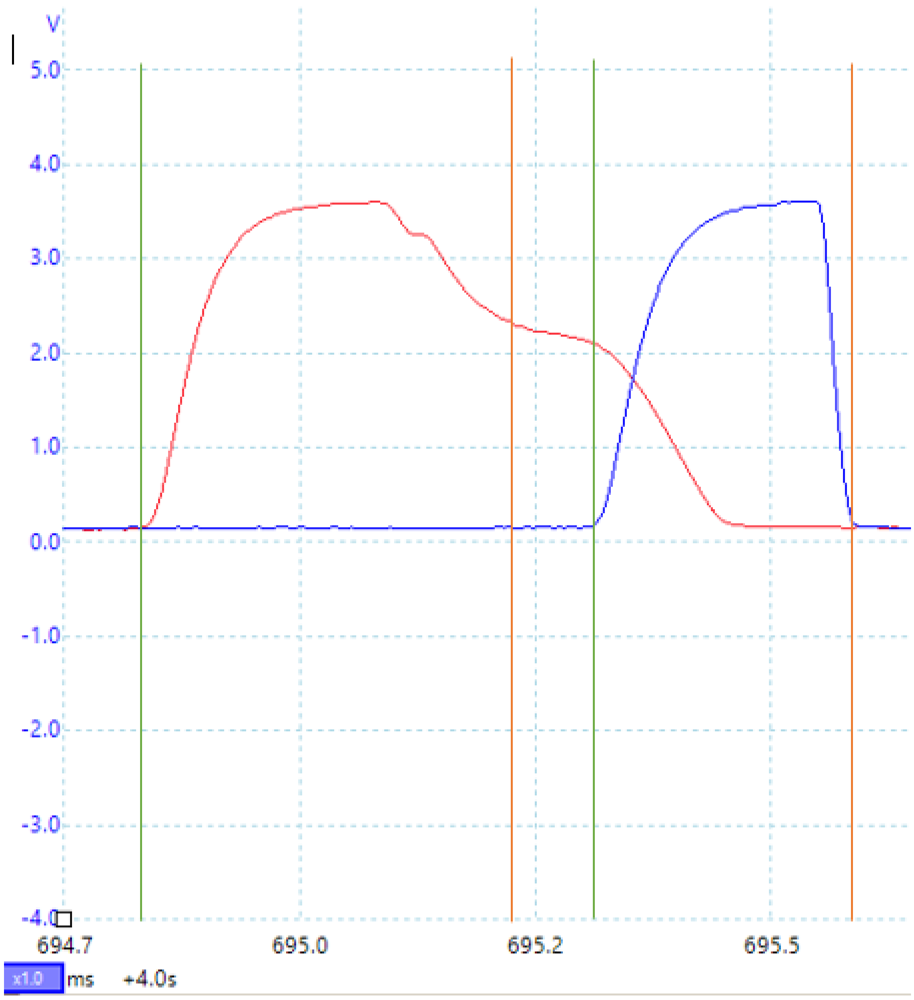


Figure 9.7: 3 Bar Hollow Projectile 0.65m barrel Oscilloscope readout

10. Measurement of Other Variables

10.1 Potential ways to track piston position

Provisions have been made in the design to track the position of the piston in the pump tube, however due to time constraints the necessary fitting to allow for an air line was not obtained. The design was altered to allow for tracking to be an option in the future.

The Idea behind tracking the piston is to have a rod that screws into the piston(that also serves as the piston reset mechanism) remain attached to the piston and stick out of the pump tube insert so that optical reflective sensors (or a high seed camera) can be used to track the position of a point of the rod. This can then be used to infer the piston position at any given time.

The rod will be supported by supports similar to that of the barrel, but allow for the rod to slide easily with minimal friction. The rod is made out of a thin walled aluminium tube, to ensure that it does not add a significant mass to piston.

Another consideration is the leakage that occurs through the space between the rod and the hole it slots through. This is an important factor as it can result in pressure losses that reduce the gas gun efficiency. A Hagen Poissell calculation for flow between two concentric cylinders was done to calculate the volume flow through the gap. Since the entire firing process occurs in approximately $0.0125s$ and the volume flow through the section is $EDITm^3/s$, the total volume loss is $volumeloss$. This results in a pressure loss of $pressureloss$ which translates to a % loss, which is not significant.

Potential ways to measure Pressure in the second stage

A Hopkinson bar can be used to infer the final pressure in the second stage.

10.2 Potential ways to measure temperature in second stage

If the pressure can be determined in the second stage, then it can be used to approximate the temperature. Another way to this is to place a set of materials in the second stage(at the transition piece) that combust at known temperatures. The gun can then be fired and the then disassembled, if the material has combusted then an approximate final temperature can be assumed.

11. Conclusion

The objective of firing a projectile at supersonic speeds was not achieved due to a set back of not having a pressure regulator to use with the gas cylinder. This was needed as the air pressure in BISRU did not reach 10 bar as required to reach these speeds. It can however be seen from the trend o the results obtained that if a 10 bar pressure source was used the velocities would have reached if not exceeded supersonic speeds.

The overall design objective of making the testing apparatus easier to use for routine testing was achieved as the piston could now be easily reset. The removal of the piston from the pump tube without disassembly did work, however it was a bit more difficult than expected due to the o-ring sizes on the pump tube inset required not being available. The functionality is there and if the correct sized o-rings are obtained the removal and re-insertion of this component would be an easy process.

In terms of the budget the project remained within the initially set budget of R1500-00 excluding VAT. The project would have been under budget, however the thread insert had to be re-designed and manufactured due to a design error in the fit that prevented the removal of the piston with o rings attached.

The entire design cycle was completed, i.e. the problem statement was defined, potential solutions were generated and improved upon. Material selection and basic design calculations were conducted to size and select parts. The detail design phase was completed to the prototype manufacturing stage and testing and validation of results was completed. A fully functional 2 stage gas gun that is capable of routine testing was created.

12. Recommendations and Future Considerations

The two stage gas gun final year project is a recurring project with modifications and improvements to the design being made on each run. This particular iteration of the project aimed to improve the usability of the gas gun to make a viable routine testing apparatus.

Recommendations on future modifications and improvements to the new design will be outlined and suggested here to aid in the further development of this project, with the hope of it eventually becoming a fully functional testing apparatus, or even being scaled up to achieve higher velocities.

- The pump tube insert can be made of stainless steel to avoid rusting. The insert length should also be increased and the end knurled to give a gripping surface to the user to remove it. The diameter of the piece that sticks out the gun in assembly should be made larger in diameter to allow for a air valve to be placed off center to ensure that the piston rod hole is usable during operation (to track the piston).
- Rubber pads could be placed around the the flange mounting diameter to reduce damage to this component.
- An adjustment or add on to the existing mounts could be designed to allow for easy barrel alignment, as the current design needs to be manually aligned.
- An alternate material can be used for the piston cap as a softer material will allow for greater deformation and therefore have a better seal in the transition piece, resulting in potential velocity increases.
- Different weight projectiles can be made to gain more data on the performance of the gun.
- A new pump tube can be designed and made to be lighter than the current one as this is a major contributor to the assembly weight. The pump tube should also be longer and have a bigger diameter to increase the effectiveness of the 2 stage gas gun.
- A larger reservoir can be used (This will however require new flanges to be made- so a cost vs benefit study should first be done) as the current volume is much less than the $5l$ maximum.
- A regulator can be added to the pneumatic circuit so that a pressure can be set and eliminate the need to control this with ball valves (This will make the design safer and eliminate to possibility of over-pressurising the reservoir)

- The transition piece can be made out of a different material such as stainless steel that is less susceptible to rusting.
- A better method of slot alignment of the pump tube and pump tube insert slots can be designed, such as locating features.
- The piston position tracking method should be completed to gain more information of the internal operations of the gun. Provisions for a rod that attaches to the piston has been made, it is currently used to reset the piston. It can however be used to track the piston if optical reflective sensors are paced on the tube and tracked.
- The number of turns on the collar can be reduced to improve usability as it is not necessary for it to be as much as it currently is (4-5 turns would be sufficient). One just needs to ensure that the flange material is not thinned too much to make room for a higher pitch thread insert and also ensure that enough clearance is available for the piston with o-rings to pass through the thread insert without it tearing.
- Orings should be selected more carefully to ensure that the fit is correct between the components with them on, as the tolerances are very tight on these components.
- A vacuum can be pulled in the catch box to improve the projectile muzzle velocities. This will evacuate the barrel removing effects of air resistance. Simulations in Co-Project 82 also showed that an optimum barrel length existed for the highest velocity after which it decreased, this is most likely due to the effects of atmospheric pressure on the muzzle side of the projectile. therefore an evacuated barrel will allow for the gas gun to effectively use the longer barrels.
- A method for determining the second stage temperature can be looked into as this is valuable information. The method of placing substances of known combustion temperatures can be looked into further and potentially implemented as an initial approximation.
- The suggested second stage pressure measurement of using a Hopkinson bar should also be looked into.
- The double boiler set-up should be completed to make the moulding of wax billets possible.
- A cross piece can be brazed onto the barrels to make it easier to tighten and loosen as this proved to be one of the time consuming aspects of use. The barrel also needs to be turned many times to fully tighten due to the need for a labyrinth seal, therefore something to grip on would make this task much easier.
- A pressure regulator should be added to the gas gun setup to allow for safer pressurising of the reservoir.
- The deformation of the piston cap should be recorded after each shot to estimate teh final volume in the transition piece.

Bibliography

[1] M. Denny, "Gas gun dynamics," *European Journal of Physics*, vol. 34, no. 5, pp. 1327–1336, 2013.

[2] T. J. Cloete, "Ideal Gas Dynamics for Shock Waves and Gas Guns Speed of Sound in an Ideal Gas," 2008.

[3] A. E. Seigel, *The Theory of High Speed Guns*, 1965, no. May.

[4] S. Division, *SANS 347 : 2012 SOUTH AFRICAN NATIONAL STANDARD Categorization and conformity assessment criteria for all pressure equipment*, 2012.

[5] C. Rahner, H. A. Al-Qureshi, D. Stainer, D. Hotza, and M. C. Fredel, "Numerical evaluation of a light-gas gun facility for impact test," *Modelling and Simulation in Engineering*, vol. 2014, pp. 0–6, 2014.

[6] A. B. Sawaoka, *Akira.pdf*, A. B. Sawaoka, Ed. Japan: KTK Scientific Publishers/Terra Scientific Publishing Company (TERRAPUB). [Online]. Available: https://www.terrapub.co.jp/e-library/sawaoka/pdf/023.pdf

[7] R. J. Rynearson and J. L. Rand, "No Title," no. August 1972, 2019.

[8] S. L. Milora, S. K. Combs, M. J. Gouge, and R. Kincaid, "Quickgun: An Algorithm for Estimating the Performance of Two-Stage Light Gas Guns," 1990.

[9] White Frank M., "Fluid Mechanics."

A. Appendices

A.1 Appendix A Gantt Chart

A.2 Appendix B Initial Risk Identification

Department of Mechanical Engineering **Rev 1.1**

Initial Risk Identification Form

- **Completion of this Risk Identification Form is required before any detail design or manufacturing is started.**
- **The purpose is to identify special safety requirements upfront, and to ensure that the necessary safety knowledge have been acquired, or specialist have been contracted.**
- **Failure to complete this form properly may result in refusal to perform your actual test / run your equipment.**
- **This form is incomplete without the attached supporting documentation as required for certain conditions.**

Student Name	Viveshan Govender
Supervisor	Mr T Cloete
Project title and number	80:REDESIGN, MODIFY AND TEST A SMALL TWO-STAGE GAS GUN

Section A: Vessels under pressure

1. Does your design/apparatus have an operating pressure above 50 kPa(g), and holds gas or two-phase fluid heated to above atmospheric saturation conditions? *If YES, then complete the remaining section.*	YES	NO
2. Study the South African classification of pressure equipment (SANS 347:2007). Note that a container made up of welded pipes is considered a pressure vessel.	Sign initials VG	
3. Does your pressure vessel fall within the Standard Engineering Practice (category 0)? *Attach a brief report showing the calculations performed and steps followed to arrive at the classification.*	YES	NO
4. If **YES** to Question 3, you acknowledge the following: • Your final design will make use of appropriate pressure vessel calculations, and will be properly documented and verified by your supervisor. • You will complete a hydraulic test of 1.25 times the design pressure using water before actual testing or operation. This test will be witnessed by your supervisor and a photo of the pressure gauge reading will be included in your report. • Alternatively a pneumatic test may be performed in an enclosed environment. • If your setup is a refrigeration system, you will study the requirements of SANS 10147, and include in your final report the key aspects applicable to your design.	Sign initials VG	
5. if **NO** to Question 3, you acknowledge the following: • A suitable certified pressure vessel design & manufacturing company have been identified and has agreed to ensure all pressure regulations are met. *Proof of this must be attached.* • Your final report will contain a detail pressure vessel design pack, including a test certificate and certificate of compliance by the consulting company.	Sign initials	

Section B: Electrical installations

1. Does your design/apparatus make use of electricity above 50V where any element of the electrical design/manufacturing is done by yourself, i.e. not part of a bought-out component? *If YES, then complete the remaining section.*	YES	NO
2. Read the Machine Lab Safety Rulebook (on Vula), and then consult Mr Maysam Soltanian (Electrical Engineering Machines Lab) regarding specific requirements. *Attach a brief summary of discussion outcomes and requirements.*	Sign initials	
3. Have you been advised to contract an external electrician to assist?	YES	NO
4. if **YES** to Question 3, you acknowledge the following: • An electrician has been identified and he has agreed to assist. *Proof of this must be attached.* • You will include the electrical certificate in your final report.	Sign initials	
5. if **NO** to Question 3, you acknowledge the following: • You will generate proper electrical diagrams of your setup. • You will continue to consult Mr Soltanian w.r.t. wiring, equipment and testing. • You will have your Supervisor and/or Mr Soltanian witness the first power-on event.	Sign initials	

Section C: Hazardous chemicals and fuels

NO PROJECTS INVOLVING THE STORAGE OF HEATED FUEL MAY BE DONE

1. Does your design/apparatus make use of materials (chemicals, gasses, etc.) which may be hazardous to health, or the environment? **OR** Does your setup involve the use of flammable fuel, including LP Gas? *If YES, then complete the remaining section.*	YES	NO
2. Consult with Mrs Penny Louw (CME lab) or Prof Genevieve Langdon (BISRU) or Mr Sa-aadat Parker (Composites) regarding the specific requirements in terms of handling, storage, record keeping etc. *Attach a brief summary of discussion outcomes and requirements.*	Sign initials	
3. Attach the Material Safety Declaration Sheet (MSDS) for any hazardous material to be used.	Sign initials	

I have read all attached documentation and is satisfied that the necessary safety considerations will be adhered to during the physical execution of the project.	**Supervisor Signature**	**Date**
		2019/05/13

A.3 Appendix C Risk Assessment Forms

Department of Mechanical Engineering rev 1.0
Risk Assessment Form

- **Risk Assessments are not required for simple workshop activities covered by the Safety Declaration. However permission must be obtained from the Workshop Manager before commencing any activity in the Workshop.**
- **A new Risk Assessment form needs to be completed for each major activity within your project.**
- **You are required to include this document (signed) in your bound project submission and mount a copy next to any rig / apparatus you are using.**

Your Name	Viveshan Govender
Your Supervisor	Mr T Cloete
Project title and number	80: REDESIGN, MODIFY AND TEST A SMALL TWO-STAGE GAS GUN
Area Safety Warden	

This Section to be completed by the student (Must be typed and the declaration signed)			
Location where the activity will be done	BISRU Lab		
Describe the activity (use attachment with diagrams if needed)	Firing a 2 stage gas gun and pressurising a reservoir to 10 bar. A small projectile is to be launched from the gas guns barrel into a catch box at supersonic speeds.		
Names of persons involved in this activity	Viveshan Govender, Matt Barry, Kenilwe Kekane		
Describe in detail the risks you (and others) will face during this activity and the potential consequences of your activities	The gas supply line can potentially come loose, and this could come loose resulting in leakage and the pressure line swinging around (The gas being used is air therefore leakages are non-toxic). Potential hearing damage from firing projectiles at supersonic speeds. Injuries from lifting/dropping heavy objects.		
Does this activity involve the use of any materials (chemicals, gasses, etc.) which may be hazardous to health, or the environment	No	Yes	*If Yes list the chemicals / gasses to be used and attach the MSDS(s) for these materials.*
Does this activity involve any equipment / device designed or built by you which is to be plugged into mains electricity?	No	Yes	*If Yes please consult with Mr Richard Whittemore or* Mr Maysam Soltanian (Electrical Machines Lab) *before connecting to the mains / switching on.*
Does the activity involve any new equipment / devices designed by you which will be pressurized with a gas or volatile liquids?	No	Yes	*If Yes please check the relevant SANS Pressurised Equipment Regulations and consult with A/Prof Fuls before testing.*
What precautions are required to protect against the risks detailed above?	Only fire the gun in the catch box. Follow the SANS pressure vessel standards. Lifting heavy objects in the correct procedure whilst taking extra care not to drop heavy items. Wear the correct PPE. When firing is to take place ensure that everyone in the area is aware and has the correct PPE (ear protection). Use correct lifting procedure and take extra care not to drop heavy items.		
Describe the personal protective equipment (PPE) required during this activity – specify in detail.	Eye Protection - Safety Glasses Ear Protection – Ear Plugs		
Describe the shutdown procedure in detail.	Turn off the compressed air supply and bleed the release valve on the pneumatic circuit, the disconnect the circuit from the gun and finally remove the projectile from the barrel (if it is still there)		
Describe any relevant emergency procedures, e.g. spillage response etc.	Turn off the compressed air supply and notify the area warden.		

I declare that I am aware of the risks associated with this activity and will take all necessary steps to mitigate these risks.	**Student Signature**	**Date**
	[signature]	20/09/2019

I am aware of the student's intended activity, and have provided the necessary guidance, inputs, and oversight.	**Supervisor Signature**	**Date**
	[signature]	2019/09/20

This section to be completed by the Area Safety Warden		
Level of supervision required (Please tick relevant block)	A = work may not take place without supervisor/warden present.	
	B = work may not take place without a 2nd party present.	✓
	C = no specific extra supervision requirements.	
I am satisfied that the student is aware of the risks associated with this activity and grant approval for it to proceed.	**Signature**	**Date**
	[signature]	2019-09-26

Appendix C Risk Assessment Forms

Department of Mechanical Engineering — rev 1.0

Risk Assessment Form

- **Risk Assessments are not required for simple workshop activities covered by the Safety Declaration. However permission must be obtained from the Workshop Manager before commencing any activity in the Workshop.**
- **A new Risk Assessment form needs to be completed for each major activity within your project.**
- **You are required to include this document (signed) in your bound project submission and mount a copy next to any rig / apparatus you are using.**

Your Name	Viveshan Govender
Your Supervisor	Mr T Cloete
Project title and number	80: REDESIGN, MODIFY AND TEST A SMALL TWO-STAGE GAS GUN
Area Safety Warden	

This Section to be completed by the student (Must be typed and the declaration signed)			
Location where the activity will be done	BISRU Lab		
Describe the activity (use attachment with diagrams if needed)	A small two stage gas will be pressure tested in the blast chamber at 1.25 times the design pressure.		
Names of persons involved in this activity	Mr Trevor Cloete, Viveshan Govender, Matt Barry, Kenilwe Kekane		
Describe in detail the risks you (and others) will face during this activity and the potential consequences of your activities	The gas gun assembly is heavy and can result in injury if dropped. Loud Noises from compressed air. Potential failure due to overpressure		
Does this activity involve the use of any materials (chemicals, gasses, etc.) which may be hazardous to health, or the environment	No	Yes	*If Yes list the chemicals / gasses to be used and attach the MSDS(s) for these materials.*
Does this activity involve any equipment / device designed or built by you which is to be plugged into mains electricity?	No	Yes	*If Yes please consult with Mr Richard Whittemore or* Mr Maysam Soltanian (Electrical Machines Lab) *before connecting to the mains / switching on.*
Does the activity involve any new equipment / devices designed by you which will be pressurized with a gas or volatile liquids?	No	Yes	*If Yes please check the relevant SANS Pressurised Equipment Regulations and consult with A/Prof Fuls before testing.*
What precautions are required to protect against the risks detailed above?	Wear correct PPE and have assistance when moving the assembly to the blast chamber		
Describe the personal protective equipment (PPE) required during this activity – specify in detail.	Eye Protection – Safety glasses Ear Protection – Ear Plugs Closed Shoes		
Describe the shutdown procedure in detail.	Turn off compressed air supply and bleed the release valve,		
Describe any relevant emergency procedures, e.g. spillage response etc.	Turn off compressed air supply as soon as possible and notify the area warden.		

I declare that I am aware of the risks associated with this activity and will take all necessary steps to mitigate these risks.	**Student Signature**	**Date**
		20/09/2019

I am aware of the student's intended activity, and have provided the necessary guidance, inputs, and oversight.	**Supervisor Signature**	**Date**
		2019/09/20

This section to be completed by the Area Safety Warden		
Level of supervision required (Please tick relevant block)	A = work may not take place without supervisor/warden present.	✓
	B = work may not take place without a 2^{nd} party present.	
	C = no specific extra supervision requirements.	
I am satisfied that the student is aware of the risks associated with this activity and grant approval for it to proceed.	**Signature**	**Date**
		2019-09-26

Appendix C Risk Assessment Forms

Department of Mechanical Engineering
Risk Assessment Form

rev 1.0

- **Risk Assessments are not required for simple workshop activities covered by the Safety Declaration. However permission must be obtained from the Workshop Manager before commencing any activity in the Workshop.**
- **A new Risk Assessment form needs to be completed for each major activity within your project.**
- **You are required to include this document (signed) in your bound project submission and mount a copy next to any rig / apparatus you are using.**

Your Name	Viveshan Govender
Your Supervisor	Mr Trevor Cloete
Project title and number	Project 80: Redesign, Modify and Test a small two-stage gas gun
Area Safety Warden	

This Section to be completed by the student (Must be typed and the declaration signed)			
Location where the activity will be done	BISRU		
Describe the activity (use attachment with diagrams if needed)	Assembly of the 2 stage gas gun and general lab work activities related to the assembly.		
Names of persons involved in this activity	Viveshan Govender, Matt Barry, Kenilwe Kekane		
Describe in detail the risks you (and others) will face during this activity and the potential consequences of your activities	Potential injury during assembly such as dropping heavy, minor injuries when tightening the nuts (if the spanner slips). There is also a potential for injury from lifting heavy objects in the incorrect procedure		
Does this activity involve the use of any materials (chemicals, gasses, etc.) which may be hazardous to health, or the environment	No	Yes	*If Yes list the chemicals / gasses to be used and attach the MSDS(s) for these materials.*
Does this activity involve any equipment / device designed or built by you which is to be plugged into mains electricity?	No	Yes	*If Yes please consult with Mr Richard Whittemore or* Mr Maysam Soltanian (Electrical Machines Lab) *before connecting to the mains / switching on.*
Does the activity involve any new equipment / devices designed by you which will be pressurized with a gas or volatile liquids?	No	Yes	*If Yes please check the relevant SANS Pressurised Equipment Regulations and consult with A/Prof Fuls before testing.*
What precautions are required to protect against the risks detailed above?	Closed shoes are to be worn in the lab to reduce the injury of falling parts – this risk will also be reduced by having assistance in the assembly process. Use the correct lifting procedure when lifting heavy objects.		
Describe the personal protective equipment (PPE) required during this activity – specify in detail.	Eye Protection -Safety Glasses Closed shoes Lab coat		
Describe the shutdown procedure in detail.	Turn off the compressed air supply and bleed the release valve on the pneumatic circuit, the disconnect the circuit from the gun and finally remove the projectile from the barrel (if it is still there)		
Describe any relevant emergency procedures, e.g. spillage response etc.	Turn off the compressed air supply and notify the area warden.		

I declare that I am aware of the risks associated with this activity and will take all necessary steps to mitigate these risks.	**Student Signature**	**Date**
		20/09/2019

I am aware of the student's intended activity, and have provided the necessary guidance, inputs, and oversight.	**Supervisor Signature**	**Date**
		2019/09/20

This section to be completed by the Area Safety Warden		
Level of supervision required (Please tick relevant block)	A = work may not take place without supervisor/warden present.	
	B = work may not take place without a 2nd party present.	✓
	C = no specific extra supervision requirements.	
I am satisfied that the student is aware of the risks associated with this activity and grant approval for it to proceed.	**Signature**	**Date**
		2019-09-26

Appendix C Risk Assessment Forms

Department of Mechanical Engineering
Risk Assessment Form

rev 1.0

- **Risk Assessments are not required for simple workshop activities covered by the Safety Declaration. However permission must be obtained from the Workshop Manager before commencing any activity in the Workshop.**
- **A new Risk Assessment form needs to be completed for each major activity within your project.**
- **You are required to include this document (signed) in your bound project submission and mount a copy next to any rig / apparatus you are using.**

Your Name	Viveshan Govender
Your Supervisor	Mr T Cloete
Project title and number	80: REDESIGN, MODIFY AND TEST A SMALL TWO-STAGE GAS GUN
Area Safety Warden	

This Section to be completed by the student (Must be typed and the declaration signed)			
Location where the activity will be done	BISRU Lab		
Describe the activity (use attachment with diagrams if needed)	Leak Test the two stage gas gun by applying a low pressure to the reservoir and check if the applied soap bubbles to indicate leakage.		
Names of persons involved in this activity	Viveshan Govender, Matt Barry, Kenilwe Kekane 1-3 bar gauge		
Describe in detail the risks you (and others) will face during this activity and the potential consequences of your activities	The two stage gas gun will be connected to a low pressure air supply to test if the gun has any leaks. The pressure line could come loose and swing around and potentially hit someone. The gas gun assembly could fall on someone if and since it is a heavy assembly (between 15kg to 20kg), it could result in injury SLIP HAZARD		
Does this activity involve the use of any materials (chemicals, gasses, etc.) which may be hazardous to health, or the environment	No	Yes	*If Yes list the chemicals / gasses to be used and attach the MSDS(s) for these materials.*
Does this activity involve any equipment / device designed or built by you which is to be plugged into mains electricity?	No	Yes	*If Yes please consult with Mr Richard Whittemore or* Mr Maysam Soltanian (Electrical Machines Lab) *before connecting to the mains / switching on.*
Does the activity involve any new equipment / devices designed by you which will be pressurized with a gas or volatile liquids?	Yes	Yes	*If Yes please check the relevant SANS Pressurised Equipment Regulations and consult with A/Prof Fuls before testing.*
What precautions are required to protect against the risks detailed above?	Wear the correct PPE (Closed Shoes, Eye Protection, Ear Plugs) CHECK ALL FASTENERS + PRESSURE FITTINGS		
Describe the personal protective equipment (PPE) required during this activity – specify in detail.	Closed Shoes Eye Protection Earplugs Lab coat		
Describe the shutdown procedure in detail.	Turn of the main air supply and bleed the relief valve on the pneumatic circuit then disconnect the pressure line from the gun		
Describe any relevant emergency procedures, e.g. spillage response etc.	Turn off the main air supply.		

I declare that I am aware of the risks associated with this activity and will take all necessary steps to mitigate these risks.	**Student Signature** VGovender	**Date** 30/09/2019

I am aware of the student's intended activity, and have provided the necessary guidance, inputs, and oversight.	**Supervisor Signature**	**Date** 2019/09/30

This section to be completed by the Area Safety Warden		
Level of supervision required (Please tick relevant block)	A = work may not take place without supervisor/warden present.	✓
	B = work may not take place without a 2nd party present.	
	C = no specific extra supervision requirements.	
I am satisfied that the student is aware of the risks associated with this activity and grant approval for it to proceed.	**Signature**	**Date** 2019-9-30

SUPERVISOR PRESENT FOR LEAK / PRESSURE TEST

A.4 Appendix D Impact of Engineering Activity

University of Cape Town · iYunivesithi yaseKapa · Universiteit van Kaapstad

SPES BONA

Department of Mechanical Engineering

MEC4110W – Final-Year Project

Impact of Engineering Activity

Rev4

By completing this assessment, you will help to demonstrate that you have met the requirement of ECSA's Exit Level Outcome 7: Impact of Engineering activity. If it is determined that you have not successfully completed this task, you will be required to rework and resubmit this document. Should this still not be considered acceptable, you will not pass MEC4110W.

You are required to include this document in your Interim Report as an appendix. Your supervisor will read it and then sign as the reviewer.

In the space provided below, please write up to 300 words on how the technology in your project impacts on society. You can consider "society" in three spheres: 1) your fellow students and other staff members, 2) the institution more generally, and/or 3) the broader society. You may need to consider the "downstream" impact of the technology in your project if you are undertaking a focused research-based project.

Fellow students and staff members:
This project will impact on fellow students and staff by allowing for further research to be carried out in this field as well as add to the current knowledge of the field. The new design which is aimed to be more user-friendly will allow for easier and more frequent and routine testing – which can aid in research pertaining to projectile impacts. This particular project has been an ongoing project which will likely have future iterations, the design choices and findings will hopefully aid in the future redesigns and improvements. If successfully completed this project will provide a means for students and staff to fire projectiles at various targets at supersonic speeds in a safe and easy manner to aid in potential research/projects. Further improvement and research on this type of gas gun will also allow for a better understanding of the underlying gas dynamics which can in conjunction with testing be used to characterise the performance of the 2 stage gas gun to allow for more accurate simulations.

Institution more generally:
This project will also impact on the institution (UCT) in a positive way as it can potentially allow for various other research fields to be explored. The university or more specifically BISRU could potentially focus more resources on this field. Depending on the success of this project BISRU will have a 2 stage gas gun that can be used for routine testing of supersonic projectile impacts safely. The continuation of this project could result in UCT investing in a large scale 2 stage gas gun which will allow for a whole new realm of research opportunities to be explored.

Broader Society:
The impact on the broader society involves research than can improve the design of protective equipment from IED's and other high velocity impacts. This potentially save lives of those who depend on such protective equipment. This also benefits the industry which is involved in the design and manufacture of protective equipment.

Signed	Date
Boven	13/05/2019

Reviewer's comments:

Reviewer's signature: Date: 2019/05/13

A.5 Appendix E Assessment of Ethics In Research Project

Application for Approval of Ethics in Research (EiR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

APPLICATION FORM

Please Note:
Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data. The objective of submitting this application *prior* to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook** (available from the UCT EBE, Research Ethics website) prior to completing this application form: http://www.ebe.uct.ac.za/ebe/research/ethics1

APPLICANT'S DETAILS		
Name of principal researcher, student or external applicant		Viveshan Govender
Department		Mechanical Engineering
Preferred email address of applicant:		GVNVIV009@myuct.ac.za
If Student	Your Degree: e.g., MSc, PhD, etc.	BSc Mechanical Engineering
	Credit Value of Research: e.g., 60/120/180/360 etc.	46
	Name of Supervisor (if supervised):	Mr T J Cloete
If this is a researchcontract, indicate the source of funding/sponsorship		
Project Title		REDESIGN, MODIFY AND TEST A SMALL TWO-STAGE GAS GUN

I hereby undertake to carry out my research in such a way that:

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

SIGNED BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	Viveshan Govender	VGovender	**05 May 2019**

APPLICATION APPROVED BY	Full name	Signature	Date
Supervisor (where applicable)	Trevor John Cloete	TJCloete	2019 05/06
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section1; and for all Undergraduateresearch (Including Honours).	George Vicatos		9/5/19
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.			

Page **1** of **1**

A.6 Appendix F Analytical Solution

Calculating the number of steps required for the Analytical Model

$P_{atm} := 101.325kPa$

$L_{pt} := 0.7m$ Pump tube length

$x_0 := 2.5m$ Initial Equivalent Length

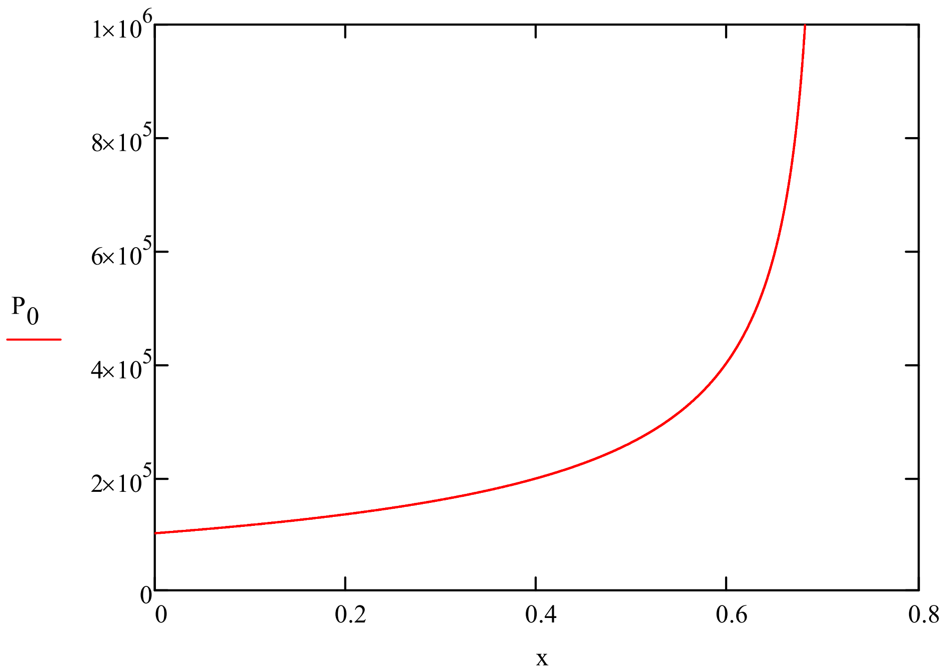
$\gamma := 1.4$ Specific heat ratio

Incrimenting the piston position in the first stage to determine what the final length has to be such that the initial reservoir pressure is 10 bar

$i := 1..68107$ number of steps

$x_{i-1} := 0.00001m \cdot i$

$$P_0 := -P_{atm} \cdot \frac{L_{pt}}{x_0} \left[\frac{1 - \left(\frac{L_{pt} - x}{L_{pt}} \right)^{1-\gamma}}{1 - \left(\frac{x_0 + x}{x_0} \right)^{1-\gamma}} \right]$$



It was found that 68107 steps were needed with a 0.00001m incriment to ensure that the pressure is 10 bar in the initial stage.

This is used in the python Analytical model of the two stage gas gun.

A.7 Appendix G Numerical Solution

$$m_{piston}\ddot{x}_{piston} = P_1 A_{pump-tube} - P_2 A_{pump-tube} \tag{A.1}$$

$$m_{projectile}\ddot{x}_{projectile} = P_2 A_{barrel} - P_{atm} A_{barrel} \tag{A.2}$$

$$P_1 = P_0 \left(\frac{V_0}{V_0 + A_{pump-tube} x_{piston}} \right)^{\gamma} \tag{A.3}$$

$$P_2 = P_{atm} \left(\frac{V_{20}}{V_{20} + A_{barrel} x_{projectile} - A_{pump-tube} x_{piston}} \right)^{\gamma} \tag{A.4}$$

Taking a Taylor expansion about x_{n+1}

$$x_{n+1} = x_n + \delta t \dot{x}_n + \frac{\delta t^2}{2}\ddot{x}_n + ... \tag{A.5}$$

Taking a Taylor expansion about x_{n-1}

$$x_{n-1} = x_n - \delta t \dot{x}_n + \frac{\delta t^2}{2}\ddot{x}_n + ... \tag{A.6}$$

Subtracting the taylor expansions results in the following

$$x_{n-1} - x_{n+1} = \tag{A.7}$$

A.8 Appendix H Derivations

A.9 Pressure-Work Relationship for Ideal Gas

Pressure-Work Relationship for Ideal Gas Pressure is not constant with expansion. If we assume isentropic (No heat transfer into/out of the gas and constant entropy/reversible), The following relationship applies.

$$P_0 V_0^\gamma = P\left(x\right) V^\gamma \tag{A.8}$$

If we also treat the gas as ideal then the ideal gas equation can be used

$$PV = nRT \tag{A.9}$$

If we consider a piston doing work on a gas with an initial volume V_0 and Pressure P_0. The initial volume is the reservoir volume and the final volume is the sum of reservoir + barrel volume

$$\mathrm{d}W = F\mathrm{d}x \tag{A.10}$$

$$\mathrm{d}W = PA\mathrm{d}x \tag{A.11}$$

$$A\mathrm{d}x = \mathrm{d}V \tag{A.12}$$

$$\mathrm{d}W = P\mathrm{d}V \tag{A.13}$$

$$P_0 V_0^\gamma = PV^\gamma \tag{A.14}$$

$$W = \int_{V_0}^{V} \frac{P_0 V_0^\gamma}{V^\gamma}\,\mathrm{d}V \tag{A.15}$$

$$W = P_0 V_0^\gamma \int_{V_0}^{V} \frac{1}{V^\gamma}\,\mathrm{d}V \tag{A.16}$$

$$W = P_0 V_0^\gamma \left[\frac{V^{1-\gamma}}{1-\gamma}\right]_{V_0}^{V} \tag{A.17}$$

$$W = \frac{P_0 V_0^\gamma}{1-\gamma}\left[V^{1-\gamma} - V_0^{1-\gamma}\right] \tag{A.18}$$

$$W = \frac{P_0 V_0^\gamma V_0^{1-\gamma}}{1-\gamma}\left[\frac{V^{1-\gamma}}{V_0^{1-\gamma}} - 1\right] \tag{A.19}$$

$$W = \frac{P_0 V_0^{\gamma+1-\gamma}}{1-\gamma}\left[\frac{V^{1-\gamma}}{V_0^{1-\gamma}} - 1\right] \tag{A.20}$$

$$W = \frac{P_0 V_0}{\gamma-1}\left[1 - \left(\frac{V}{V_0}\right)^{1-\gamma}\right] \tag{A.21}$$

If we assume no losses then all the work is converted to kinetic energy, then we have

$$T = \frac{1}{2}mv^2 \tag{A.22}$$

$$W = T \tag{A.23}$$

$$\frac{P_0V_0}{\gamma - 1}\left[1 - \left(\frac{V}{V_0}\right)^{1-\gamma}\right] = \frac{1}{2}mv^2 \tag{A.24}$$

$$v = \sqrt{\frac{2P_0V_0}{m\left(\gamma - 1\right)}\left[1 - \left(\frac{V}{V_0}\right)^{1-\gamma}\right]} \tag{A.25}$$

If we assume that the gas can expand infinitely and all Work is converted to kinetic energy, then the maximum theoretical velocity can be found as,

$$V \to \infty \tag{A.26}$$

$$\gamma > 1 \tag{A.27}$$

$$\frac{V}{V_0} \to \infty \tag{A.28}$$

$$\left(\frac{V}{V_0}\right)^{1-\gamma} \to 0 \tag{A.29}$$

$$W \to \frac{P_0V_0}{\gamma - 1} \tag{A.30}$$

$$v_{max} = \sqrt{\frac{2P_0V_0}{m\left(\gamma - 1\right)}} \tag{A.31}$$

If we however take into account gas dynamics the maximum attainable velocity is given by

$$c = \sqrt{\gamma RT} \tag{A.32}$$

$$v_{max} = \frac{2}{\gamma - 1}\sqrt{\gamma RT} \tag{A.33}$$

Assuming the Area of the reservoir and barrel are the same. The velocity can be expressed as follows

$$v = \sqrt{\frac{2P_0V_0}{m\left(\gamma - 1\right)}\left[1 - \left(\frac{AL}{AL_0}\right)^{1-\gamma}\right]} \tag{A.34}$$

$$v = \sqrt{\frac{2P_0V_0}{m\left(\gamma - 1\right)}\left[1 - \left(\frac{L}{L_0}\right)^{1-\gamma}\right]} \tag{A.35}$$

$$L > L_0 \tag{A.36}$$

$$\gamma > 1 \tag{A.37}$$

$$\left(\frac{L}{L_0}\right)^{1-\gamma} \to 0 \text{ as } L \to \infty \tag{A.38}$$

$$\text{therefore} \tag{A.39}$$

$$v \to v_{max} \text{ as } L \to \infty \tag{A.40}$$

A.10 Effect of mass of gas on the piston Velocity

Assuming that the velocity distribution in the gas is linear

$$
\begin{aligned}
T &= \frac{1}{2}mv_p^2 + \int_{\mathrm{V}} \frac{1}{2}\mathrm{d}mv^2 \\
\mathrm{d}m &= \rho A\mathrm{dx} \\
v_x &= v\frac{x}{x_p} \\
T &= \frac{1}{2}mv_p^2 + \int_{\mathrm{V}} \frac{1}{2}\mathrm{d}mv^2 \\
T &= \frac{1}{2}mv_p^2 + \int_{\mathrm{V}} \frac{1}{2}\rho A\mathrm{dx}(v\frac{x}{x_p})^2 \\
T &= \frac{1}{2}mv_p^2 + \frac{1}{2}\rho A \int_0^{x_p} (\frac{v}{x_p})^2 x^2\mathrm{dx} \\
T &= \frac{1}{2}mv_p^2 + \frac{1}{2}\rho A(\frac{v}{x_p})^2[\frac{1}{3}x^3]|_0^{x_p} \\
T &= \frac{1}{2}mv_p^2 + \frac{1}{2}\rho A(\frac{v}{x_p})^2[\frac{1}{3}x^3 - 0] \\
T &= \frac{1}{2}mv_p^2 + \frac{1}{2}(\frac{1}{3}\rho A x_p)v^2 \\
T &= \frac{1}{2}mv_p^2 + \frac{1}{2}(\frac{1}{3}m_g)v^2
\end{aligned}
$$

The net gas mass effect on the kinetic energy is therefore 1/3 of the mass of the gas.

The density of the gas changes after compression and can be determined as follows.

$$\rho_2 = \rho_1 \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}}$$

The mass of the piston and gas are calculated below to show the comparison between the two.

$$
\begin{aligned}
m_{piston} &= 2800(\frac{\pi}{4}0.015^2 \times 0.08) = 440g \\
\rho_2 = 1.2\left(\frac{10}{1}\right)^{\frac{1}{1.4}} &= 6.21 \\
m_{gass} = 6.21 \times \frac{\pi}{4} \times 0.5^2 \times 0.3 &= 3.6g
\end{aligned}
$$

The gas mass is therefore insignificant in comparison to the piston mass.

A.10.1 Air Leakage derivation

A.11 Appendix I Pressure Vessel Calculations

The following calculations were done in Mathcad 15

Reservoir Failure Analysis

$V_{res} := 0.0042m^3$	Reservoir Volume
$\sigma_y := 276MPa$	Yield Stress of Aluminum
$t := 3.18mm$	Vessel Wall thickness
$D := 101.6mm$	Inner Diameter of Reservoir
$P := 10bar$	Internal Pressure
$\frac{D}{t} = 31.95$	Inner Diameter to thickness ratio
$\frac{D}{t} > 20$	therefore thin wall asumption is valid

Conditions For Distortion Energy

$$(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 \le 2\sigma_y^2 \qquad \sigma_e = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma 1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}{2}} = \frac{\sigma_y}{SF}$$

$$\sigma_{hoop} := \frac{P \cdot D}{2t} = 15.975\,MPa$$

$$\sigma_{Longitudinal} := P \cdot \frac{D}{4t} = 7.987\,MPa$$

$$\sigma_{radial} := 0MPa$$

$$\sigma_1 := \sigma_{hoop}$$

$$\sigma_2 := \sigma_{Longitudinal}$$

$$\sigma_3 := \sigma_{radial}$$

Solving for Saftey Factor on Yield under distortion energy failure theory

$$SF := \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}{2}} = \frac{\sigma_y}{SF} \text{ solve}, SF \rightarrow \frac{276.0 \cdot MPa}{\sqrt{1.913967010798624075e14 \cdot Pa^2}}$$

$SF = 19.95$ Saftey Factor

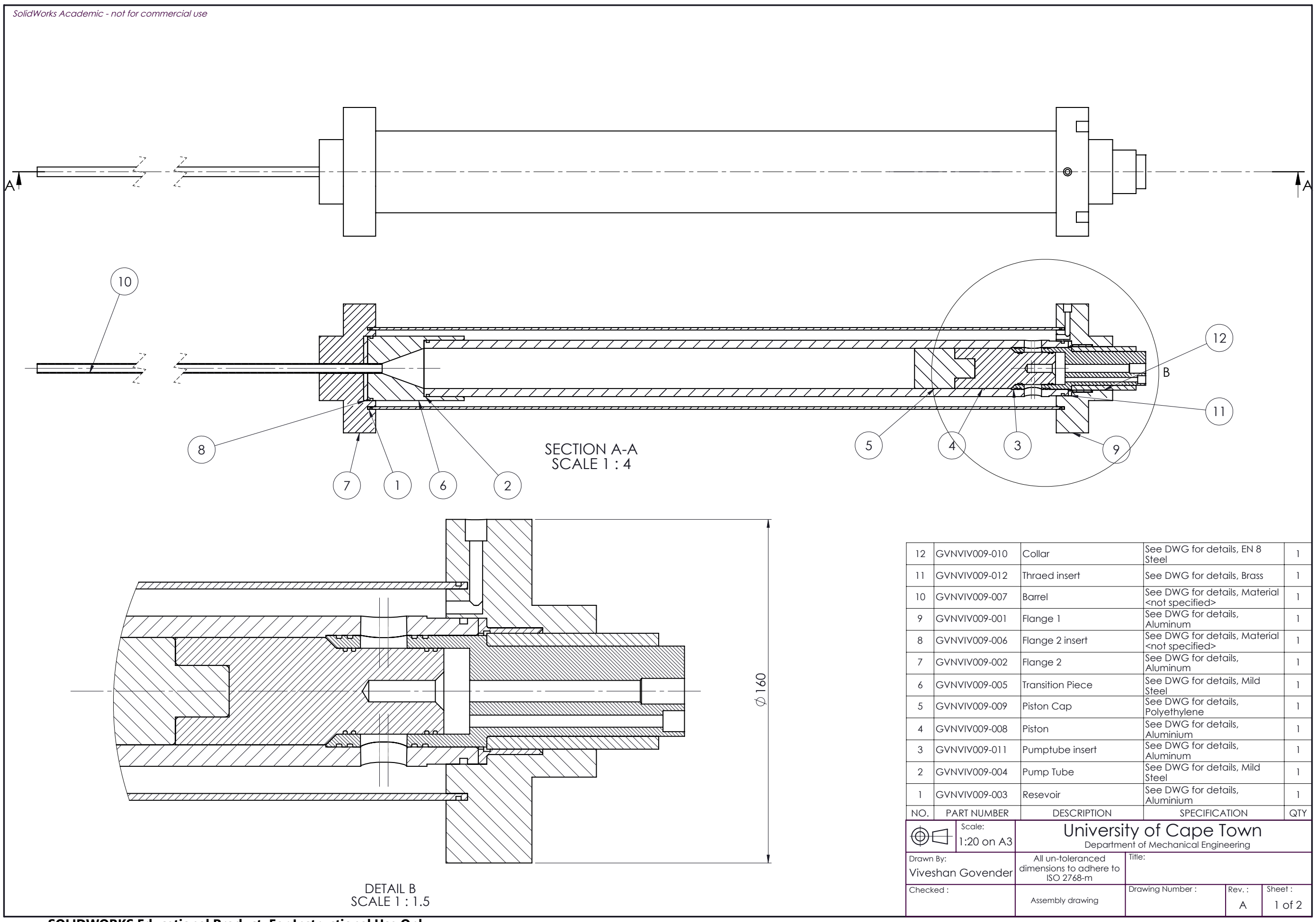
$$\sigma_e := (\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 = 382.793\,MPa^2$$

$$2\sigma_y^2 = 152352\,MPa^2$$

$$\sigma_e < 2\sigma_y^2$$

Therefore vessel should not fail under the internal pressure of 10 bar with a saftey factor of 19.95

A.12 Appendix I Part Drawings

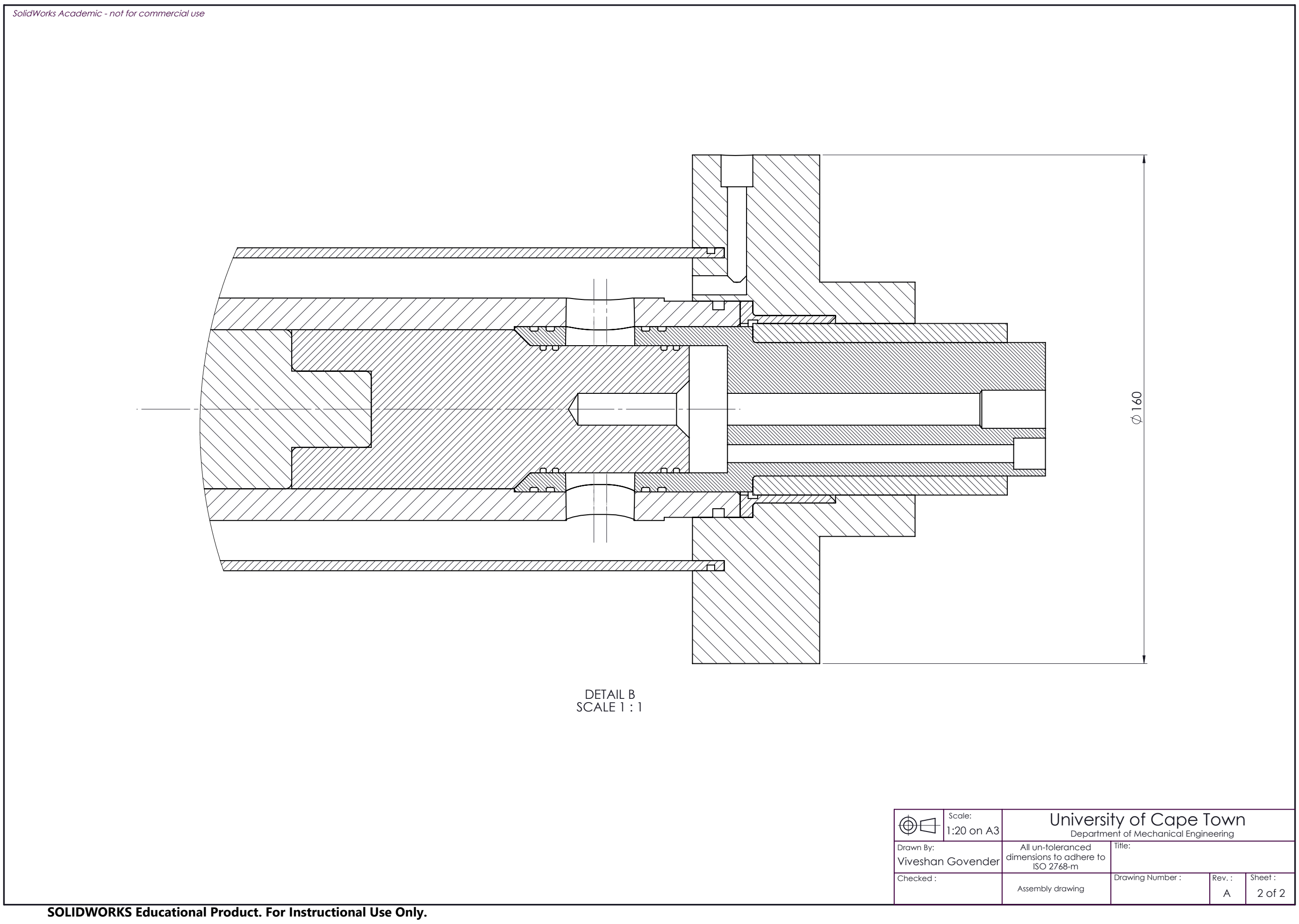


NO.	PART NUMBER	DESCRIPTION	SPECIFICATION	QTY
12	GVNVIV009-010	Collar	See DWG for details, EN 8 Steel	1
11	GVNVIV009-012	Thraed insert	See DWG for details, Brass	1
10	GVNVIV009-007	Barrel	See DWG for details, Material <not specified>	1
9	GVNVIV009-001	Flange 1	See DWG for details, Aluminum	1
8	GVNVIV009-006	Flange 2 insert	See DWG for details, Material <not specified>	1
7	GVNVIV009-002	Flange 2	See DWG for details, Aluminum	1
6	GVNVIV009-005	Transition Piece	See DWG for details, Mild Steel	1
5	GVNVIV009-009	Piston Cap	See DWG for details, Polyethylene	1
4	GVNVIV009-008	Piston	See DWG for details, Aluminium	1
3	GVNVIV009-011	Pumptube insert	See DWG for details, Aluminum	1
2	GVNVIV009-004	Pump Tube	See DWG for details, Mild Steel	1
1	GVNVIV009-003	Resevoir	See DWG for details, Aluminium	1

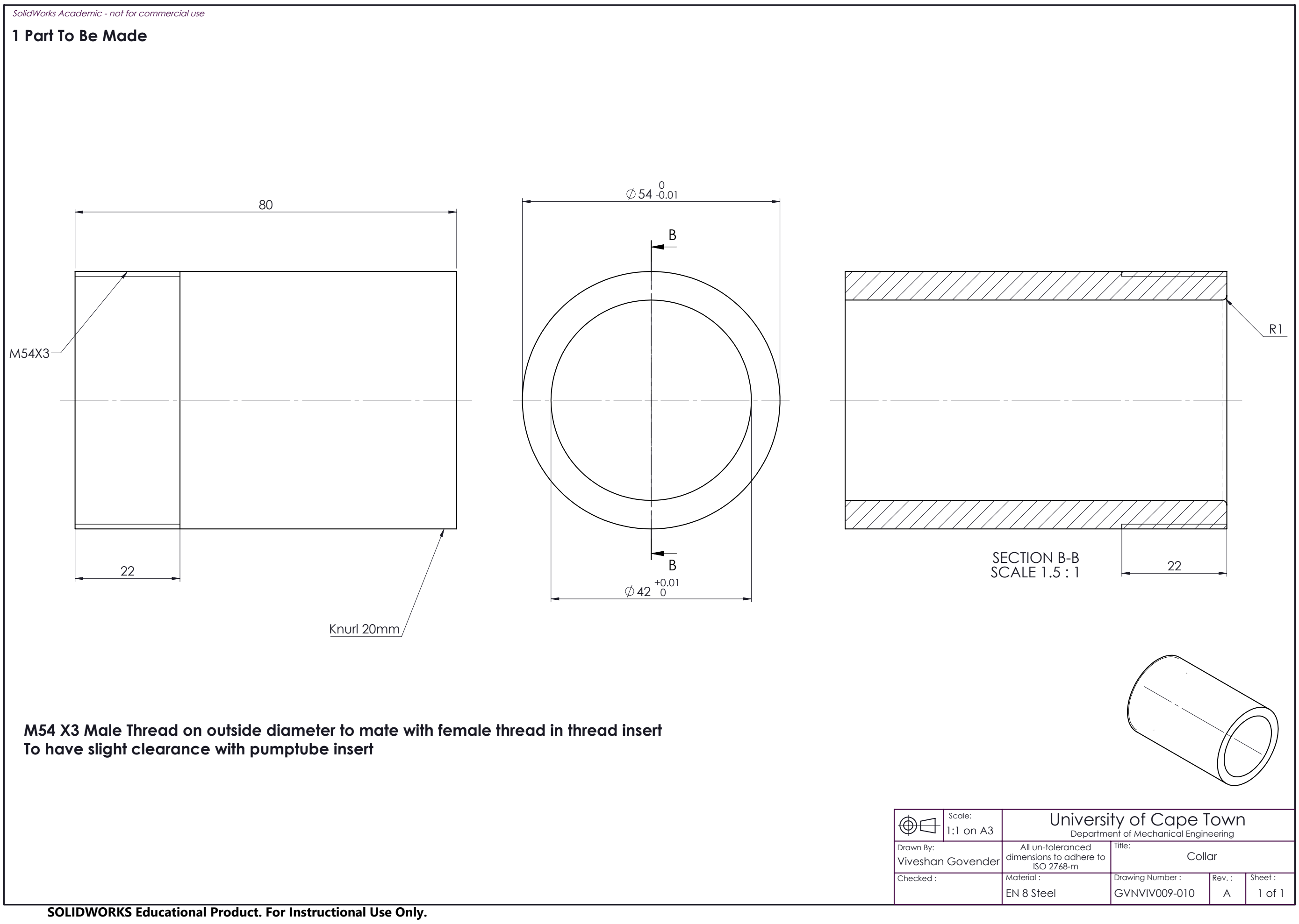
Scale: 1:20 on A3	University of Cape Town Department of Mechanical Engineering	
Drawn By: Viveshan Govender	All un-toleranced dimensions to adhere to ISO 2768-m	Title:
Checked :	Assembly drawing	Drawing Number : / Rev. : A / Sheet : 1 of 2

SOLIDWORKS Educational Product. For Instructional Use Only.

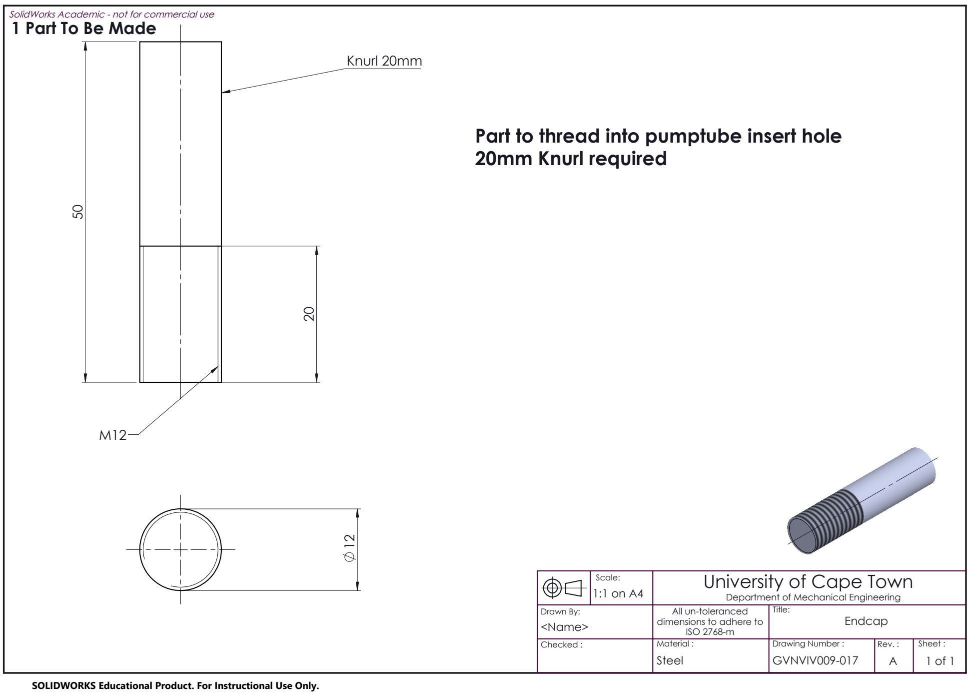
A.13 Appendix I Part Drawings



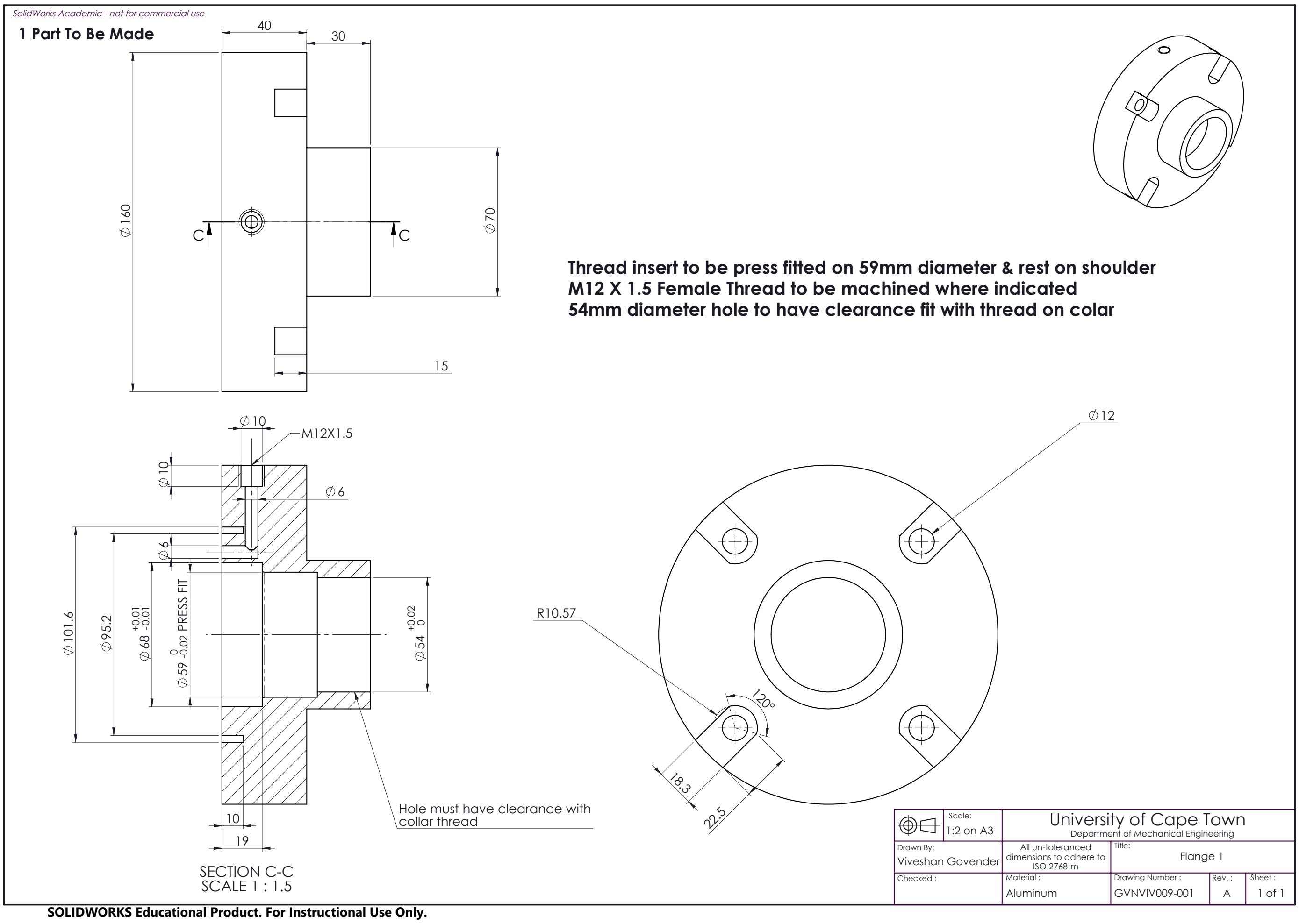
A.14 Appendix I Part Drawings



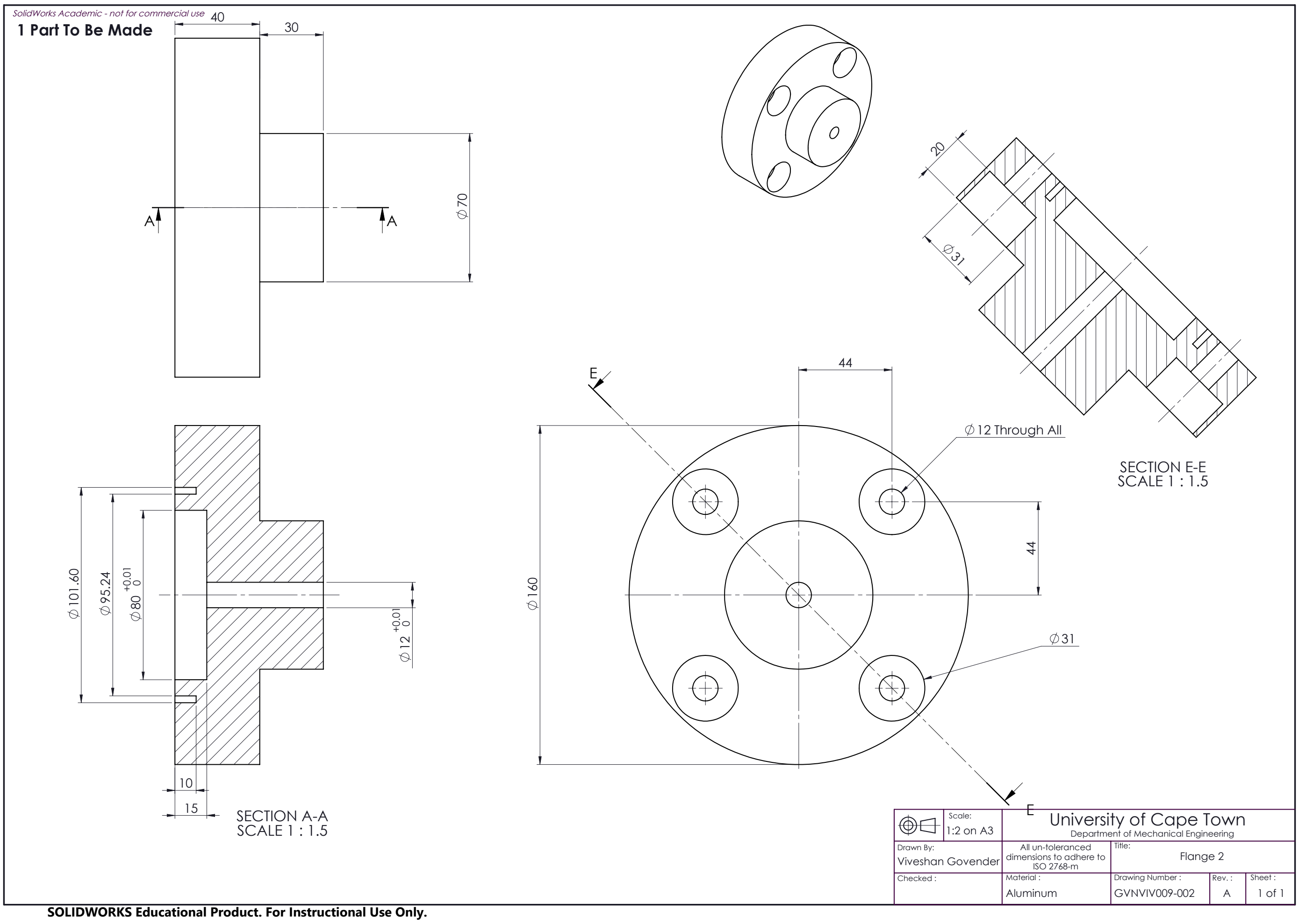
A.15 Appendix I Part Drawings



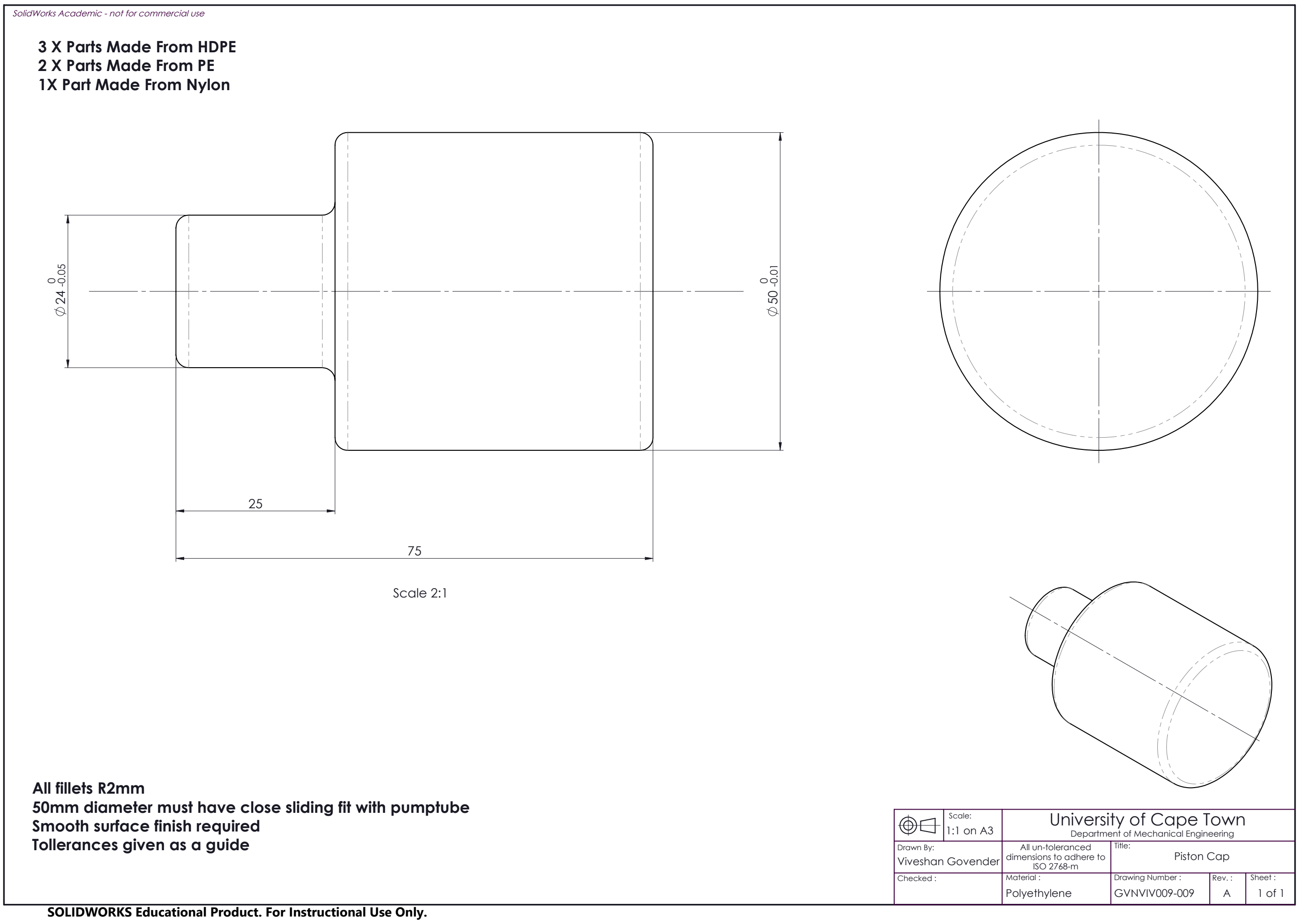
A.16 Appendix I Part Drawings



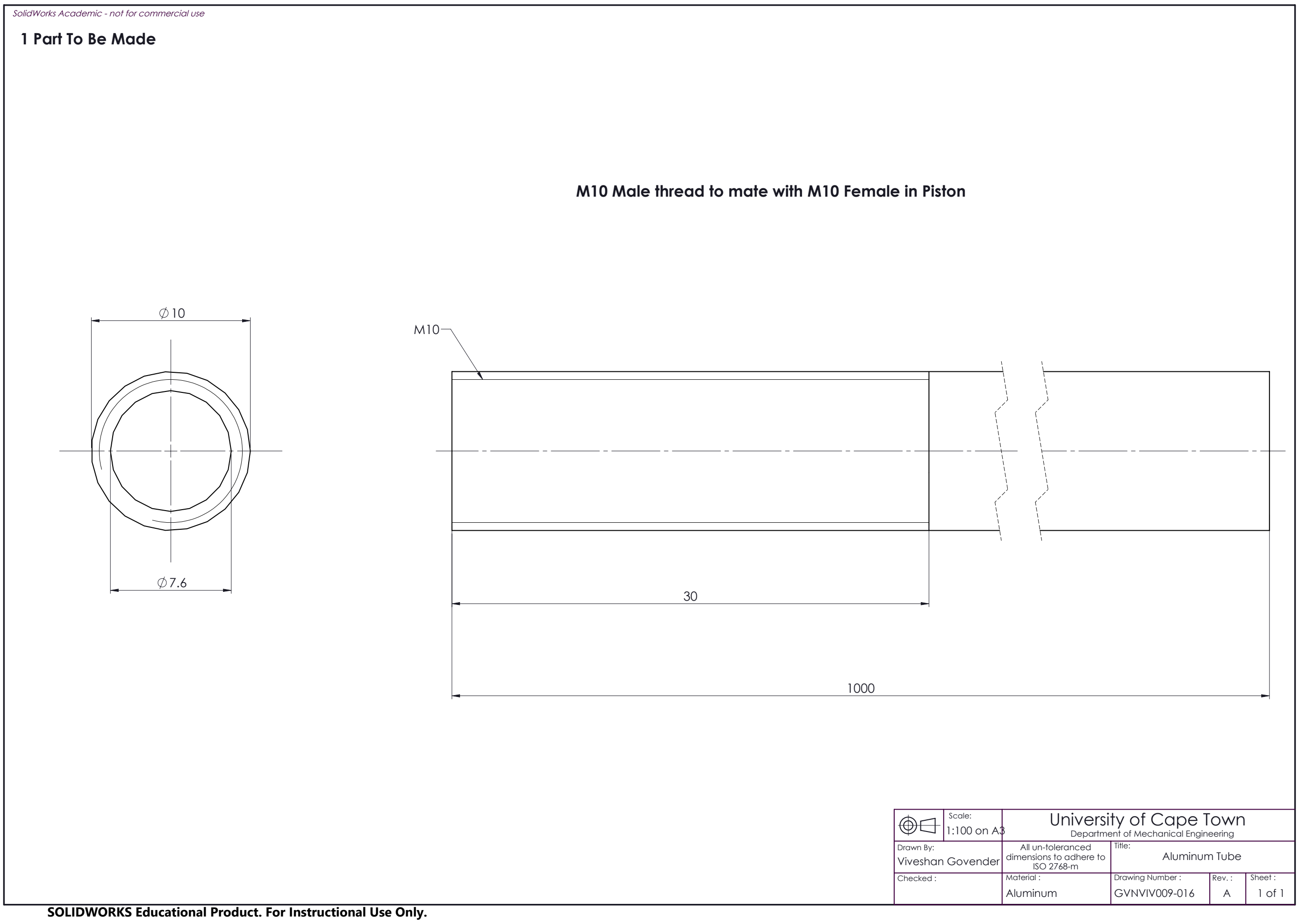
A.17 Appendix I Part Drawings



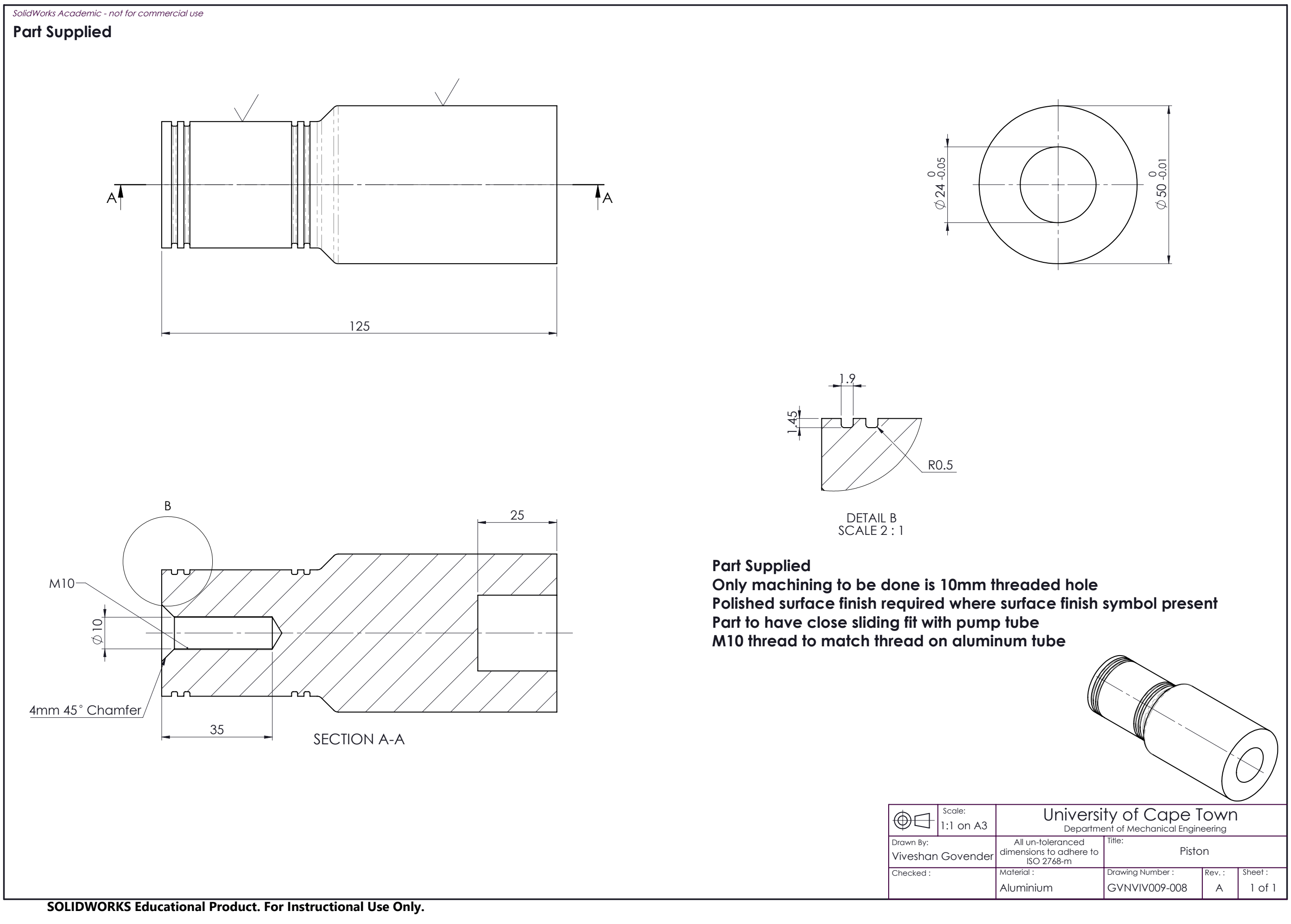
A.18 Appendix I Part Drawings



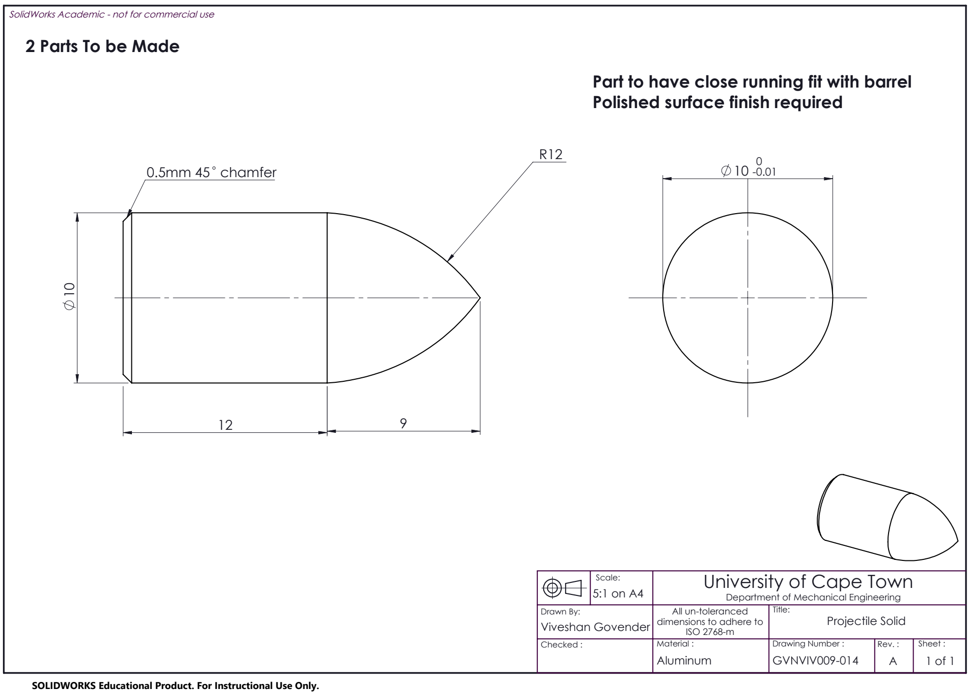
A.19 Appendix I Part Drawings



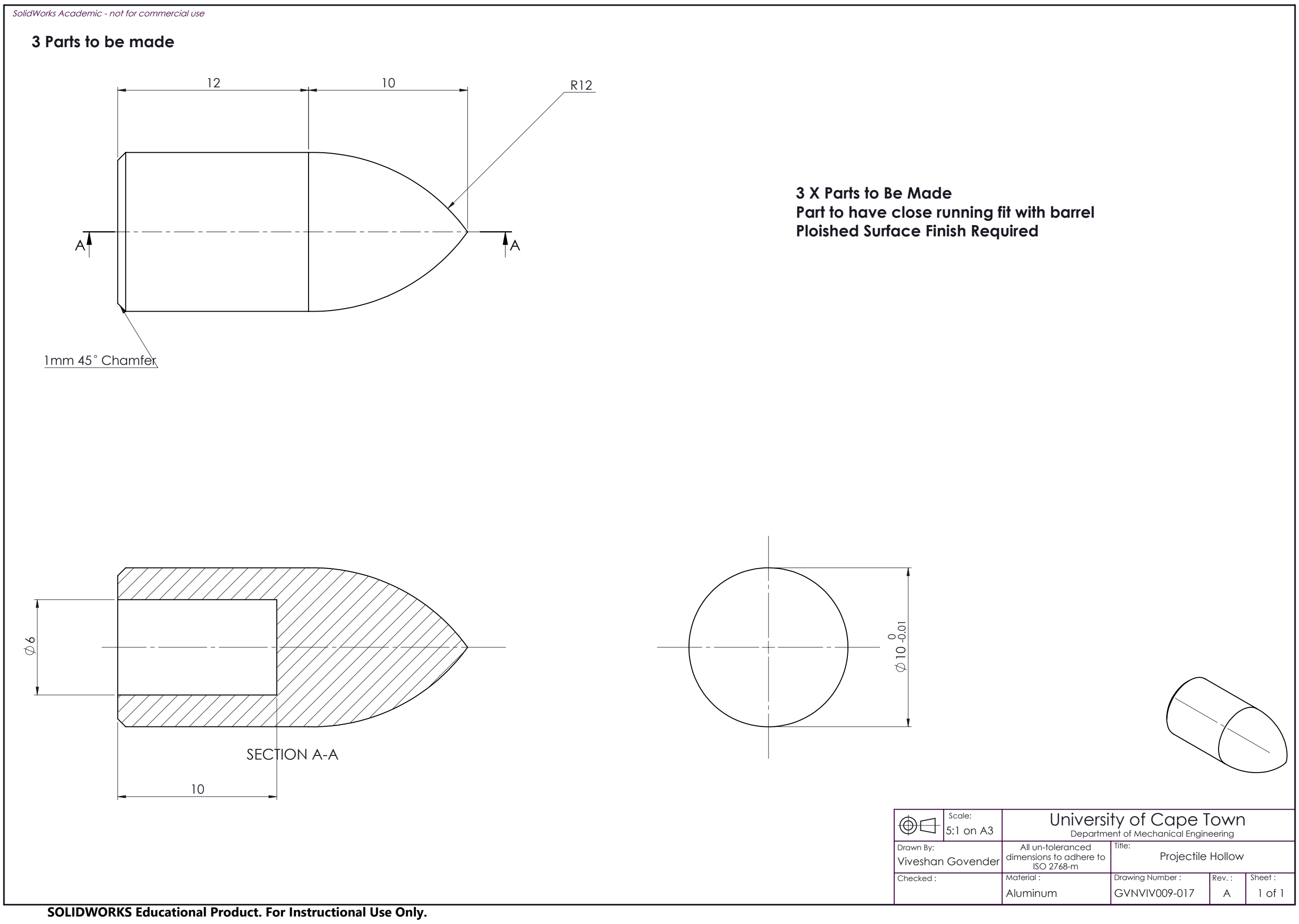
A.20 Appendix I Part Drawings



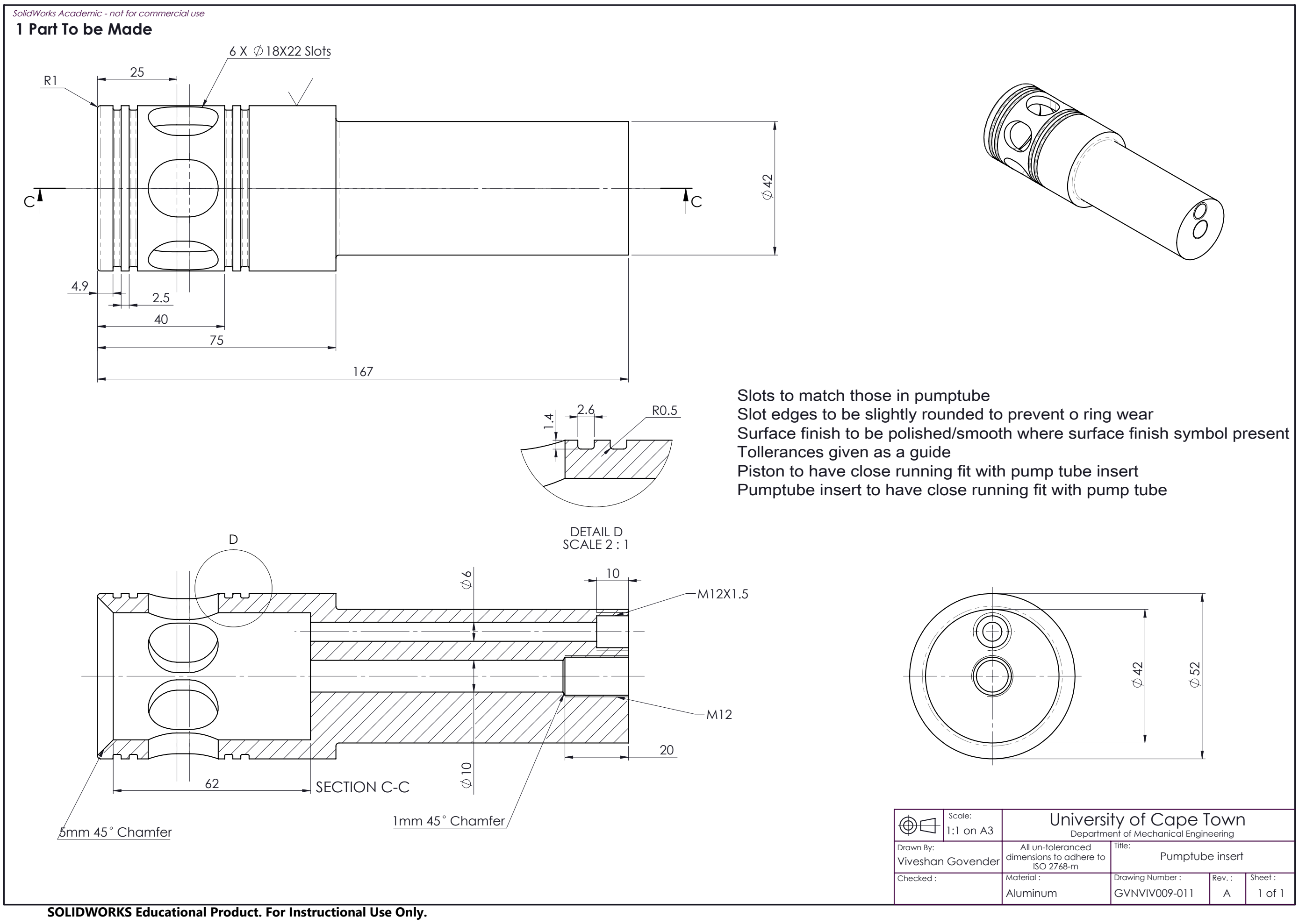
A.21 Appendix I Part Drawings



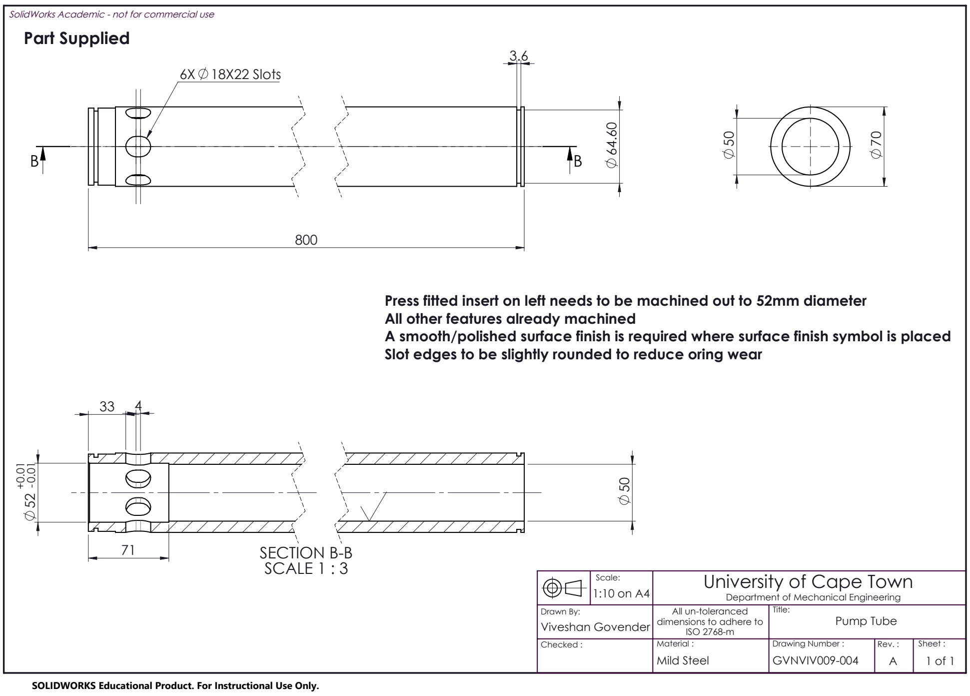
A.22 Appendix I Part Drawings



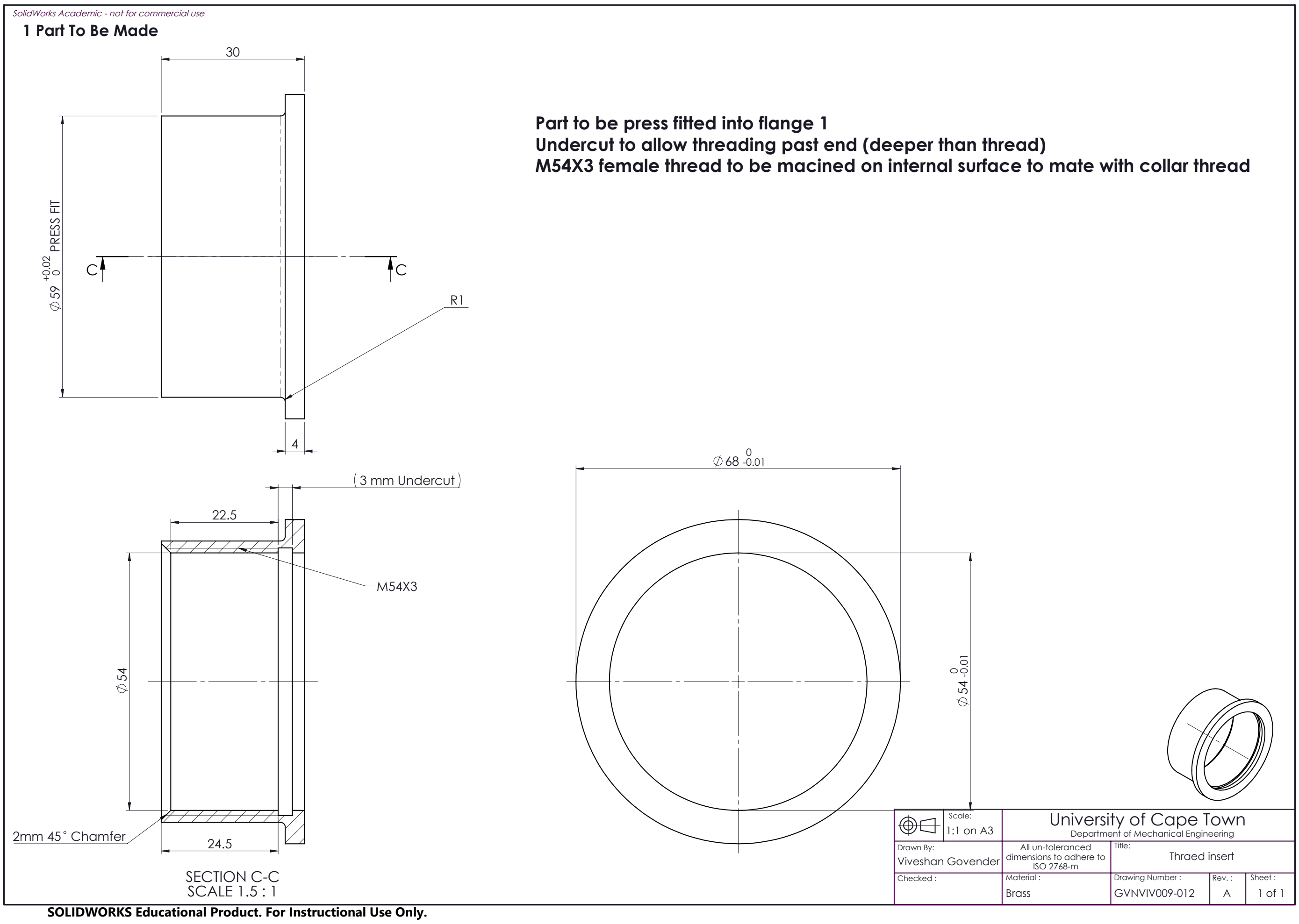
A.23 Appendix I Part Drawings



A.24 Appendix I Part Drawings



A.25 Appendix I Part Drawings



A.26 Appendix J Invoices and Quotes

DEPARTMENT OF MECHANICAL ENGINEERING
MEC4110W ORDER REQUISITION

*In order to facilitate efficient purchasing, please ensure that **all** the information requested on this form is supplied and hand the form in to Ms B Glass (Room 203.1). Where possible, please attach a quote for the goods requested. This form must be used for **ALL** purchases – including cash purchases made through the workshop.*
Please be aware that an order will not be processed without your supervisor's signature.

STUDENT DETAILS		
DATE: 12/08/19	STUDENT'S NAME: Viveshan Govender	STUDENT NUMBER: GVNVIV009
SUPERVISOR NAME: Mr Trevor Cloete	SUPERVISOR SIGNATURE:	PROJECT NUMBER: 80
VENDOR DETAILS		
NAME OF VENDOR:	DONSTEEL & FORGINGS (Vendor Number:202623)	
FULL POSTAL ADRESS:	12 Willow Rd	
	Stikland	
	Bellville	POSTAL CODE: 7530
TELEPHONE NUMBER: 021 949 7550	CONTACT PERSON (IF KNOWN): Niven	FAX NUMBER: +27 21 949 7520

ITEMS TO BE PURCHASED

FULL DESCRIPTION OF ITEM/S:	Quantity	Unit Price (excl VAT)
55mm diameter X 170mm length EN8 Steel Billet (EN3B055D 55mm DIA BMS (1 X 170mm LONG)) – Quoted (See Attached)	1	96.35
60mm diameter X 90mm length EN8 Steel Billet EN3B015D 60mm DIA BMS (1 X 90mm LONG) – Quoted (See Attached)	1	62.22
15mm diameter X 60mm length EN8 Steel Billet/solid r0d EN3B015D 15mm DIA BMS (1 X 1000mm LONG) – Quoted (See Attached)	1	40.54

Important Information

1. Check the UCT vendor list http://www.staff.uct.ac.za/staff/finance/procurement/uct-vendors/preferred
2. Obtain a quote for the goods that you require.
3. Please check and discuss the timelines with your supervisor when ordering items from other countries. In some cases, items were delivered after the project deadline, please try to source your items from within RSA.
4. If you are submitting claims for reimbursements, please ensure that the original invoice/proof of payment is attached on a separate A4 paper.
5. Obtain your supervisor's signature
6. Hand in form to Ms Glass for processing

Rev_Feb2019

Appendix J Invoices and Quotes

DONSTEEL & FORGINGS
A Division of Hudaco Trading (Pty) Ltd

12 Willow Road
Stikland
Bellville
7530

Quotation Only

Date & Time	2019/08/08 03:07:08 PM
Page	1
Document No	QU102412

COD - NIVEN

Deliver To
SALOSHNEE

Account	Your Reference	Tax Exempt	Tax Reference	Sales Code	
CASNB1	1	Y		N	Exclusive

Code	Description	Disc%	Tax	PIECES	Nett Price
EN3B055D	55 DIA BMS	0	15.00%	1	96.35
'	1X170			0	
EN3B060D	60 DIA BMS	0	15.00%	1	62.22
'	1X90MM			0	
EN3B015D	15 DIA BMS	0	15.00%	1	40.54
'	1X1000MM			0	

Banking Details :
Standard Bank
Branch - Germiston - Code - 011642
Current Acc Nr - 301 147 779

Sub Total		199.11
Discount @	0.00%	0.00
Amount Excl Tax		199.11
Tax		29.86
Total		228.97

Appendix J Invoices and Quotes

DEPARTMENT OF MECHANICAL ENGINEERING
MEC4110W ORDER REQUISITION

*In order to facilitate efficient purchasing, please ensure that **all** the information requested on this form is supplied and hand the form in to Ms B Glass (Room 203.1). Where possible, please attach a quote for the goods requested. This form must be used for **ALL** purchases – including cash purchases made through the workshop.*
Please be aware that an order will not be processed without your supervisor's signature.

STUDENT DETAILS		
DATE: 12/08/19	STUDENT'S NAME: Viveshan Govender	STUDENT NUMBER: GVNVIV009
SUPERVISOR NAME: Mr Trevor Cloete	SUPERVISOR SIGNATURE:	PROJECT NUMBER:80
VENDOR DETAILS		
NAME OF VENDOR:	Non Ferrous Metal Works SA (Vendor Number: 200361)	
FULL POSTAL ADRESS:	114 Voortrekker Road	
	Salt River	POSTAL CODE: 7995
	Cape Town	
TELEPHONE NUMBER:021 511 0286	CONTACT PERSON (IF KNOWN): Ismail	FAX NUMBER:021 511 7538

ITEMS TO BE PURCHASED

FULL DESCRIPTION OF ITEM/S:	Quantity	Unit Price (excl VAT)
160mm diameter X 70mm length Aluminium billet Aluminium Round Bar – 6082T6 – 165mm X 3000mm Length (2 X 70mm LONG) – Quoted (See Attached)	2	300
70mm diameter X 35mm length Brass billet Brass Round Bar – 385 – Half Hard 70mm X STD (1 X 35mm LONG) – Quoted (See Attached)	1	126
10mm OD X 1.2mm WT X 1m length Aluminium tube Aluminium Extruded Tube – 6063T6 – 10mm OD X 1.22mm WT – 6000mm Length (1 X 6 METRE LENGTH) – Quoted (See Attached)	1	54

Important Information

1. Check the UCT vendor list http://www.staff.uct.ac.za/staff/finance/procurement/uct-vendors/preferred
2. Obtain a quote for the goods that you require.
3. Please check and discuss the timelines with your supervisor when ordering items from other countries. In some cases, items were delivered after the project deadline, please try to source your items from within RSA.
4. If you are submitting claims for reimbursements, please ensure that the original invoice/proof of payment is attached on a separate A4 paper.
5. Obtain your supervisor's signature
6. Hand in form to Ms Glass for processing

Rev_Feb2019

Appendix J Invoices and Quotes

Non-Ferrous Metal Works (SA) (Pty) Ltd
114 Voortrekker Road
Salt River
CAPE TOWN
Western Cape
7995
South Africa

Branch Telephone 021 511 0286
Branch Fax 021 511 7538

NON-FERROUS METAL WORKS SA (Pty) Ltd

Head Office Telephone	(031) 480 7388
Head Office Fax	(031) 468 6934
Web	www.nfm.co.za
Reg. No.	1951/000559/07
Vat number	4370108260

Ship to:
VIVESHAN GOVENDER
COLLECTION
South Africa

Quotation

Page	1 of 1
Number	SQ00028683-1
Date	2019/08/08
Requisition	
Your ref.	VIVESHAN
Our ref.	ISMAIL
Quotation deadline	2019/08/15
Payment	Cash on Delivery

Item number	Description	Ship date	Quantity	Unit	Sales price	Amount
ARB6082T6IMP	Aluminium Round Bar - 6082T6 - 165mm X 3000mm Length 2 X 70MM LONG	2019/08/09	2.00	Pcs	300.00	600.00
BRB385HH	Brass Round Bar - 385 - Half Hard 70mm X STD 1 X 35MM LONG	2019/08/09	0.04	Mtr	3,600.00	126.00
ATT6063T6	Ali Extr Tube - 6063T6 - 10mm OD X 1.22mm WT - 6000mm Length 1 X 6 METRE LEN CT/IS REFER////// VIVESHAN	2019/08/09	1.00	Len	54.00	54.00

Currency	Sales subtotal amount	Total discount	Charges	Net amount	VAT	Round-off	Total
ZAR	780.00	0.00	0.00	780.00	117.00	0.00	897.00

Banking Details:
Account
Branch Code
Account Number

Please refer to our website for our Standard Terms and Conditions of Sales

A.27 Appendix K Numerical Code

```
#Viveshan Govender
#GVNVIV009
#2019

import numpy as np
import matplotlib.pyplot as plt
import openpyxl
from openpyxl import Workbook
import os


gamma=1.4
P_atm=101325
rho_piston=8050 #piston density
rho_piston_h=970 #piston cap density
rho_projectile=2800 #Aluminum projectile density
L_10=0.001 #Section 1 initial length
L_piston=0.125 #Piston Lenght
L_piston_h=0.05 #Piston Cap length
L_projectile=0.0217 #Projectile length
d_1=0.05 #d pump tube
d_2=0.012 #d barrel
P0=1000000+P_atm# 10 bar in pump tube and atmospheric in initial section
P20=P_atm #atmospheric pressure in second stage initially
T20=296 #initial temp stage 2
L_pump_tube=0.8
L_barrel=2.9
V_resevoir=0.005 #reservoir volume excl internal comps



A_piston,A_piston_head,A_pump_tube=np.pi*d_1**2/4,np.pi*d_1**2/4,np.pi*
    d_1**2/4
A_barrel=np.pi*d_2**2/4
V_piston=A_piston*L_piston
V_piston_head=A_piston_head*L_piston_h
V_projectile=A_barrel*L_projectile
V0=V_resevoir+A_pump_tube*L_10
V20=A_pump_tube*L_pump_tube-(A_pump_tube*L_10+V_piston+V_piston_head)
    +5.33*(10**-5) # initial volume stage 2 incl conical

#Not a good approximation
#m_piston_tot=V_piston*rho_piston+V_piston_head*rho_piston_h #assuming
    both are solid cylinders
#m_projectile=V_projectile*rho_projectile

#Use these values instead closer to actual
m_piston_tot=0.5
m_projectile=0.002


x_1_max=L_pump_tube-(L_piston+L_piston_h+L_10)
V_total=A_pump_tube*L_pump_tube+A_barrel*L_barrel


n_steps=6400
t = np.linspace(0, 0.3, n_steps+1)  # time vector
dt=t[1]-t[0]
```

```
print(dt)

#empty vectors to store solutions
x1 = np.zeros(n_steps+2)
v1 = np.zeros(n_steps+2)
a1 = np.zeros(n_steps+2)
x2 = np.zeros(n_steps+2)
v2 = np.zeros(n_steps+2)
a2 = np.zeros(n_steps+2)
P_1 = np.zeros(n_steps+2)
P_2 = np.zeros(n_steps+2)
V_1 = np.zeros(n_steps+2)
V_2 = np.zeros(n_steps+2)
T_2 = np.zeros(n_steps+2)


#set intial conditions in arrays
x1[1]=0
v1[1]=0
a1[1]=P0*A_piston/m_piston_tot #EOM
x2[1]=0
v2[1]=0
a2[1]=0 #EOM
P_1[1]=P0/100000 # conv to bar
P_2[1]=P20/100000 # conv to bar
V_1[1]=V0
V_2[1]=V20
T_2[1]=T20

#ficticous initial conditions for Central diff method
x1[0]=x1[1]-dt*v1[1]+a1[1]*(dt**2)/2
x2[0]=x2[1]-dt*v2[1]+a2[1]*(dt**2)/2


def PVT(V0,A_pump_tube,V20,A_barrel,P0,P20,T20,gamma,i):
    V1 = V0 + A_pump_tube*x1[i]
    V2 = V20 - A_pump_tube*x1[i] + A_barrel*x2[i]
    P1 = P0*(V0/V1)**gamma
    P2 = P20*(V20/V2)**gamma
    T2 = T20/((P20/P2)**((gamma-1)/gamma))
    return V1,V2,P1,P2,T2


Exit_barrel=False
Piston_End=False
while Exit_barrel==False:
    for i in range(1,n_steps+1):
        V1,V2,P1,P2,T2=PVT(V0,A_pump_tube,V20,A_barrel,P0,P20,T20,gamma,
    i)
        if x2[i]>=L_barrel:
            if Exit_barrel==False:
                exitbarrel=i
            Exit_barrel=True
            x2[i]=L_barrel
        x1[i+1] = 2*x1[i] - x1[i-1] + (dt**2)/m_piston_tot*(P1*
    A_pump_tube-P2*A_pump_tube)
        if x1[i+1]>=x_1_max:
            if Piston_End==False:
                pistonend=i
            Piston_End=True
```

```
                x1[i+1]=x_1_max
            if Piston_End==True:
                x1[i+1]=x_1_max
            v1[i] = (x1[i+1] - x1[i-1])/(2*dt)
            a1[i] = (x1[i+1] - 2*x1[i] + x1[i-1])/(dt**2)
            x2[i+1] = 2*x2[i] - x2[i-1] + (dt**2)/m_projectile*(P2*A_barrel-
        P20*A_barrel)
            v2[i] = (x2[i+1] - x2[i-1])/(2*dt)
            a2[i] = (x2[i+1] - 2*x2[i] + x2[i-1])/(dt**2)
            P_1[i] = P1/100000
            P_2[i] = P2/100000
            V_1[i] = V1
            V_2[i] = V2
            T_2[i] = T2

########################################
cwd = os.getcwd()
filepath=str(cwd)+"/convergence.xlsx"
try:
    wb = openpyxl.load_workbook(filepath)
except:
    wb = Workbook()

wb.create_sheet("100 steps")
wb.create_sheet("200 steps")
wb.create_sheet("400 steps")
wb.create_sheet("800 steps")
wb.create_sheet("1600 steps")
wb.create_sheet("3200 steps")
wb.create_sheet("6400 steps")
wb.active=6 #0 for 1st sheet, 1 for 2nd sheet
sheet = wb.active
sheet.cell(row=1,column=1).value="Time"
sheet.cell(row=1,column=2).value="Piston Position"
sheet.cell(row=1,column=3).value="Piston Velocity"
sheet.cell(row=1,column=4).value="Piston Acceleration"
sheet.cell(row=1,column=5).value="Projectile Position"
sheet.cell(row=1,column=6).value="Projectile Velocity"
sheet.cell(row=1,column=7).value="Projectile Acceleration"
sheet.cell(row=1,column=8).value="Stage 1 Volume"
sheet.cell(row=1,column=9).value="Stage 2 Volume"
sheet.cell(row=1,column=10).value="Stage 1 Pressure"
sheet.cell(row=1,column=11).value="Stage 2 Pressure"
sheet.cell(row=1,column=12).value="Stage 2 Temperature"
for i in range(len(t[0:exitbarrel])):
        sheet.cell(row=i+2, column=1).value = t[i]
for i in range(len(x1[0:exitbarrel])):
        sheet.cell(row=i+2, column=2).value = x1[i]
for i in range(len(v1[0:exitbarrel])):
        sheet.cell(row=i+2, column=3).value = v1[i]
for i in range(len(a1[0:exitbarrel])):
        sheet.cell(row=i+2, column=4).value = a1[i]
for i in range(len(x2[0:exitbarrel])):
        sheet.cell(row=i+2, column=5).value = x2[i]
for i in range(len(v2[0:exitbarrel])):
        sheet.cell(row=i+2, column=6).value = v2[i]
for i in range(len(a2[0:exitbarrel])):
        sheet.cell(row=i+2, column=7).value = a2[i]
for i in range(len(V_1[0:exitbarrel])):
        sheet.cell(row=i+2, column=8).value = V_1[i]
```

```
for i in range(len(V_2[0:exitbarrel])):
        sheet.cell(row=i+2, column=9).value = V_2[i]
for i in range(len(P_1[0:exitbarrel])):
        sheet.cell(row=i+2, column=10).value = P_1[i]
for i in range(len(P_2[0:exitbarrel])):
        sheet.cell(row=i+2, column=11).value = P_2[i]
for i in range(len(T_2[0:exitbarrel])):
        sheet.cell(row=i+2, column=12).value = T_2[i]


wb.save(str(filepath))
######################################
#############################################################
##############SANS########################
vol1=np.array([0.1,1,5,10,100,1000,10000,10000])
d1=np.array([50,50,50,50,50,50,50,50])
vol2=np.array([0.1,1,5,10,100,1000,2000,2000])
d2=np.array([100000,100000,20000,10000,1000,100,50,50])
vol3=np.array([0.1,1,5,10,100,750,1000,10000])
d3=np.array([300000,300000,60000,30000,3000,400,400,400])
vol4=np.array([1,5,10,100,400,400,400,400])
d4=np.array([20000,4000,2000,200,50,50,50,50])
vol5=np.array([1,5,10,100,100,100,100,100])
d5=np.array([5000,1000,500,50,50,50,50,50])
vol6=np.array([1,1,1,1,1,1,1,1])
d6=np.array([100000,10000,5000,5000,5000,5000,5000,5000])


vol_1=np.zeros(n_steps+1)
vol_2=np.zeros(n_steps+1)
vol_3=np.zeros(n_steps+1)
vol_4=np.zeros(n_steps+1)
vol_5=np.zeros(n_steps+1)
vol_6=np.zeros(n_steps+1)
d_1=np.zeros(n_steps+1)
d_2=np.zeros(n_steps+1)
d_3=np.zeros(n_steps+1)
d_4=np.zeros(n_steps+1)
d_5=np.zeros(n_steps+1)
d_6=np.zeros(n_steps+1)


for i in range(8):
    vol_1[i]=vol1[i]
    vol_2[i]=vol2[i]
    vol_3[i]=vol3[i]
    vol_4[i]=vol4[i]
    vol_5[i]=vol5[i]
    vol_6[i]=vol6[i]
    d_1[i]=d1[i]
    d_2[i]=d2[i]
    d_3[i]=d3[i]
    d_4[i]=d4[i]
    d_5[i]=d5[i]
    d_6[i]=d6[i]


for i in range(n_steps-7):
    vol_1[i+8]=vol1[7]
    vol_2[i+8]=vol2[7]
```

```
    vol_3[i+8]=vol3[7]
    vol_4[i+8]=vol4[7]
    vol_5[i+8]=vol5[7]
    vol_6[i+8]=vol6[7]
    d_1[i+8]=d1[7]
    d_2[i+8]=d2[7]
    d_3[i+8]=d3[7]
    d_4[i+8]=d4[7]
    d_5[i+8]=d5[7]
    d_6[i+8]=d6[7]

##########################################
#
    ########################################################################

plt.figure(1)
plt.plot(t[0:exitbarrel-1],x1[1:exitbarrel], 'g',t[0:exitbarrel-1],x2[1:
    exitbarrel], 'b',lw=1)
plt.xlabel('Time - $t (s)$')
plt.ylabel('Displacement - $x_1 (m)$, $x_2 (m)$')
plt.plot([t[pistonend],t[pistonend]] , [ min(min(x1),min(x2)), max(max(
    x1),max(x2))], '--k',lw=1)
plt.plot([t[exitbarrel],t[exitbarrel]] , [ min(min(x1),min(x2)), max(max
    (x1),max(x2))], '--r',lw=1)
plt.title('Displacement vs Time of piston and projectile - 2 Stage Gas
    Gun')
plt.legend(['Piston','Projectile'])
plt.tight_layout()  # make room for axis labels
plt.grid()
plt.axhline(y=0, color='black',lw=0.6)
plt.axvline(x=0, color='black',lw=0.6)
plt.box(False)

plt.figure(2)
plt.plot(t[0:exitbarrel-1],v1[1:exitbarrel], 'g',t[0:exitbarrel-1],v2[1:
    exitbarrel], 'b',lw=1)
plt.xlabel('Time - $t (s)$')
plt.ylabel('Velocity - $v_1 (m/s)$, $v_2 (m/s)$')
plt.plot([t[pistonend],t[pistonend]] , [ min(min(v1),min(v2)), max(max(
    v1),max(v2))], '--k',lw=1)
plt.plot([t[exitbarrel],t[exitbarrel]] , [ min(min(v1),min(v2)), max(max
    (v1),max(v2))], '--r',lw=1)
plt.title('Velocity vs Time for piston and projectile - 2 Stage Gas Gun'
    )
plt.legend(['Piston','Projectile'])
plt.tight_layout()  # make room for axis labels
plt.grid()
plt.axhline(y=0, color='black',lw=0.6)
plt.axvline(x=0, color='black',lw=0.6)
plt.box(False)

plt.figure(3)
plt.plot(t[0:exitbarrel-1],V_1[1:exitbarrel], 'g',t[0:exitbarrel-1],V_2
    [1:exitbarrel], 'b',lw=1)
plt.xlabel('Time - $t (s)$')
plt.ylabel('Volume - $v (m^3)$')
plt.plot([t[pistonend],t[pistonend]] , [ min(min(V_1),min(V_2)), max(max
    (V_1),max(V_2))], '--k',lw=1)
```

```
plt.plot([t[exitbarrel],t[exitbarrel]] , [ min(min(V_1),min(V_2)), max(
    max(V_1),max(V_2))], '--r',lw=1)
plt.title('Volume vs time for two stage Gas Gun')
plt.legend(['Stage 1','Stage 2'])
plt.tight_layout()  # make room for axis labels
plt.grid()
plt.axhline(y=0, color='black',lw=0.6)
plt.axvline(x=0, color='black',lw=0.6)
plt.box(False)

plt.figure(4)
plt.plot(t[0:exitbarrel-1],T_2[1:exitbarrel], 'b',lw=1)
plt.xlabel('Time - $t (s)$')
plt.ylabel('Temperature - $Kelvin (K)$')
plt.plot([t[pistonend],t[pistonend]] , [ min(T_2), max(T_2)], '--k',lw
    =1)
plt.plot([t[exitbarrel],t[exitbarrel]] , [ min(T_2), max(T_2)], '--r',lw
    =1)
plt.title('Second Stage temperature vs time 2 stage Gas Gun')
plt.legend(['Temperature in Stage 2'])
plt.tight_layout()  # make room for axis labels
plt.grid()
plt.axhline(y=0, color='black',lw=0.6)
plt.axvline(x=0, color='black',lw=0.6)
plt.box(False)

##################################################################

V1SANS=(V_1[1:exitbarrel])*1000
P1SANS=(P_1[1:exitbarrel])*100-101.325
V2SANS=(V_2[1:exitbarrel])*1000
P2SANS=(P_2[1:exitbarrel])*100-101.325

plt.figure(5)
plt.loglog(vol_1,d_1,'k',vol_2,d_2,'k',vol_3,d_3,'k',vol_4,d_4,'k',vol_5
    ,d_5,'k',vol_6,d_6,'k',label='_nolegend_')
plt.plot(V1SANS,P1SANS,'b',V2SANS,P2SANS,'m')
plt.plot([5,0] , [1000,5], '--g',lw=1)
plt.plot([5,5] , [1000,0], '--g',lw=1)
plt.xlabel('Volume - $l$')
plt.ylabel('Design Pressure $kPa-gauge$')
plt.title('SANS Pressure Vessel Standards Non dangerous gasses')
plt.legend(['Stage 1 Volume','Stage 2 Volume','Resevoir'])
plt.tight_layout()  # make room for axis labels
plt.grid(which='both')
plt.axhline(y=0, color='black',lw=0.6)
plt.axvline(x=0, color='black',lw=0.6)
plt.box(False)
plt.xlim((0.1,10**4))
plt.ylim((0.1,500000))
plt.fill_between((0.1,1),(10**5,10**5),(50,50),color='r',alpha=0.2)
plt.fill_between(vol_5,d_5,d_1,color='r',alpha=0.2)
plt.fill_between((0.1,10**4),(50,50),color='y',alpha=0.1)
plt.text(0.5*(0.1+5),100,'SEP')
plt.text(0.5*(0.1+15),2,'Unregulated')
plt.text(120,60,'I')
plt.text(700,60,'II')
plt.text(5000,60,'III')
plt.text(5000,10000,'IV')
plt.text(0.15,300100,'PS=300000')
```

```
plt.text(0.15,100100,'PS=100000')
plt.text(0.75,20000,'V=1',rotation=90)
plt.text(20,14300,'PS*V=300000',rotation=328)
plt.text(19,6000,'PS*V=100000',rotation=330.5)
plt.text(14,1500,'PS*V=20000',rotation=330.5)
plt.text(10,550,'PS*V=5000',rotation=330)
plt.text(2000,400,'PS=400')

plt.show()
```

A.28 Appendix K Analytical Code

```
#Viveshan Govender
#GVNVIV009
#2019

import numpy as np
import matplotlib.pyplot as plt


P_atm=101325
L_pt=0.7
A_0=0.00196
x_0=2.5
y=1.4
T_0=293

V_pt=np.pi/4*0.05**2
V_tp=4.416*10**(-5)

n_steps=68107
x_1=np.zeros(n_steps)
P_0=np.zeros(n_steps)
x_2=np.zeros(n_steps)
P_2=np.zeros(n_steps)
T_2=np.zeros(n_steps)
V_2=np.zeros(n_steps)


for i in range(1,n_steps):
  x_1[i]=i*0.00001

for i in range(n_steps):
  P_0[i]=-P_atm*(L_pt/x_0)*((1-((L_pt-x_1[i])/L_pt)**(1-y))/(1-((x_0+x_1
    [i])/x_0)**(1-y)))

for i in range(n_steps):
  x_2[i]=L_pt-x_1[i]
  #P_2[i]=P_atm*((L_pt)/(x_2[i]))**y
  P_2[i]=P_atm*((V_pt+V_tp)/(V_tp+A_0*(L_pt-x_1[i])))**y
  T_2[i]=T_0*((P_2[i]/(P_atm))**(1-1/y))
  V_2[i]=A_0*x_2[i]
P_0=P_0/100000
P_2=P_2/100000

plt.figure(1)
plt.plot(x_2,P_0,lw=1)
plt.xlabel('Piston Position $m$')
plt.ylabel('Pressure $bar$')
plt.title('Length of pumptube covered by Piston for 10 bar 1st Stage
```

```
    pressure')
plt.legend(['1st Stage Pressure'])
plt.tight_layout()  # make room for axis labels
plt.grid()
plt.axhline(y=0, color='black',lw=0.6)
plt.axvline(x=0, color='black',lw=0.6)
plt.box(False)

plt.figure(2)
plt.plot(x_1,P_2,lw=1)
plt.xlabel('Piston Position')
plt.ylabel('Pressure $bar$')
plt.title('Piston Position vs 2nd stage Pressure')
plt.legend(['2nd Stage Pressure'])
plt.tight_layout()  # make room for axis labels
plt.grid()
plt.axhline(y=0, color='black',lw=0.6)
plt.axvline(x=0, color='black',lw=0.6)
plt.box(False)

plt.figure(3)
plt.plot(x_1,T_2,lw=1)
plt.xlabel('Piston Position')
plt.ylabel('Tmperature $K$')
plt.title('Sencond Stage Temperature')
plt.legend(['2nd Stage Temperature'])
plt.tight_layout()  # make room for axis labels
plt.grid()
plt.axhline(y=0, color='black',lw=0.6)
plt.axvline(x=0, color='black',lw=0.6)
plt.box(False)



###################2 Stage#############################
P_0=P_0*100000
P_2=P_2*100000
n_steps=20000
V0=min(V_2)
P0=max(P_2)
A0=np.pi/4*0.01**2
L0=V0/A0
m_projectile=0.0015
L_barrel=np.zeros(n_steps)

for i in range(1,n_steps):
  L_barrel[i]=i*0.001

v_p_IG=np.zeros(n_steps)

C_1=(2*P0*V0)/(m_projectile*(y-1))

for i in range(n_steps):
  v_p_IG[i]=np.sqrt(C_1*(1-(((L_barrel[i]+L0))/L0)**(1-y)))

R=287
v_max=2/(y-1)*np.sqrt(y*R*T_0)
a_max=P0*A0/m_projectile

v=np.linspace(0,824,n_steps)
```

```
L_GD=np.zeros(n_steps)

C1=v_max**2/a_max
C2=(y-1)/2
C3=2/(y+1)
C4=-((y+1)/(y-1))

C5=(y-1)/(y+1)

for i in range(n_steps):
  L_GD[i]=C1*C2*C3*((1-v[i]/v_max)**C4-1)-C1*C2*(1-v[i]/v_max)**(C4*C3)+
    C1*C2


plt.figure(4)
plt.plot(L_barrel,v_p_IG,L_GD,v,lw=1)
plt.xlabel('Barrel Length $m$')
plt.ylabel('Velocity $m/s$')
plt.title('Barrel Length vs velocity - 2 Stage Gas Gun')
plt.legend(['Ideal Gas','Gas Dynamics'])
plt.tight_layout()  # make room for axis labels
plt.grid()
plt.axhline(y=0, color='black',lw=0.6)
plt.axvline(x=0, color='black',lw=0.6)
plt.box(False)



plt.show()
```

A.29 Appendix K Single Stage Gas Gun Code

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

P0=1000000
V0=0.005
d_barrel=0.01
d_projectile=0.01
L_projectile=0.02
rho_al=7800
gamma_air=1.4

m_projectile=2800*np.pi*d_projectile**2/4*L_projectile #approximating
    projectile as cylinder
m_projectile=0.00408
print(m_projectile)
L0=V0/(np.pi*d_barrel**2/4)
n_steps=1000
L=np.linspace(0,20,n_steps+1,endpoint=True)

v1=np.zeros(n_steps+1)

C_1=(2*P0*V0)/(m_projectile*(gamma_air-1))
for i in range(n_steps+1):
  v1[i]=np.sqrt(C_1*(1-((L[i]+L0)/L0)**(1-gamma_air)))


####GAS DYNAMICS ##############################
gamma_air=1.4
```

```
R=287
T=293
P0=1000000
A0=np.pi*0.01**2/4
m_projectile=5/1000


v_max=2/(gamma_air-1)*np.sqrt(gamma_air*R*T)
a_max=P0*A0/m_projectile

v=np.linspace(0,410,n_steps+1)


C1=v_max**2/a_max
C2=(gamma_air-1)/2
C3=2/(gamma_air+1)
C4=-((gamma_air+1)/(gamma_air-1))

C5=(gamma_air-1)/(gamma_air+1)

for i in range(n_steps+1):
  L[i]=C1*C2*C3*((1-v[i]/v_max)**C4-1)-C1*C2*(1-v[i]/v_max)**(C4*C3)+C1*C2
  #L[i]=C1*(C2*(C5+C3*(1-v[i]/v_max)**(C4)-(1-v[i]/v_max)**(-2/(gamma_air-1))))


plt.figure(1)
plt.plot(L, v1, 'g',L,v)
plt.xlabel('Barel Length - $L (m)$')
plt.ylabel('Velocity - $v (m/s)$')
plt.title('Velocity vs Barrel Length for single stage Gas Gun \n using gas dynamics and Ideal Gas')
plt.legend(['Ideal Gas','Gas Dynamics'])
plt.tight_layout()  # make room for axis labels

plt.show()
```

Appendix L Interim Report Marked

UNIVERSITY OF CAPE TOWN

Department of Mechanical Engineering

RONDEBOSCH, CAPE TOWN
SOUTH AFRICA

INTERIM REPORT

PROJECT No:

80

REDESIGN, MODIFY AND TEST A SMALL TWO-STAGE GAS GUN

Viveshan Govender

Student Number!

To improve the design ofprotective equipment against improvised explosive devices (IEDs), it is important to have detailed knowledge of the way structures respond to projectile impact events. To do this, laboratory scale projectile launchers are required that are capable of safely launching large projectiles at high subsonic speeds and small projectile at supersonic speeds. To attain supersonic speeds, a driving gas at high initial pressure and temperature is required. 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.

Recently, a small two-stage gas guns has been developed at the Blast Impact and Survivability Research Unit (BISRU) that is able to launch a small projectile at 400 m/s using 5 L of compressed air at a pressure of 1 bar. The aim of this project is to redesign, 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. The project will primarily focus on converting the current prototype to functional apparatus for routine testing and conducting extensive testing to map out the performance.

Words in Body: 3900

SUPERVISOR:

Mr Trevor Cloete

Appendix L Interim Report Marked

Plagerism Decleration

1. I know that plagiarism is wrong. Plagiarism is to use another's work and pretend that itis o1ne's own.
2. Each significant contribution to, and quotation in, this assignment from the work(s) ofother people has been attributed and has been cited and referenced.
3. This assignment is my own work.
4. I have not allowed and will not allow anyone to copy my work with the intention ofpassing it off as his or her own work.

Surname	Initials	Student Number	Signature
GOVENDER	V	GVNVIV009	

Date 14/05/2019

Appendix L Interim Report Marked

Abstract

This report aims to redesign a small two-stage gas gun that is capable of firing small projectiles at supersonic speeds and bigger projectiles at high subsonic speeds while making it more routine and user friendly.

The main goal of this project is to redesign the 2018 prototype with the aim of improving its usability and making it more routine by improving reload and piston replacement times.

Once the basic theory is reviewed numerical modelling of the gun will be created and used to check the parameters that affect the efficiency and performance of the gas gun. A basic concept is then generated.

abstract must have conclusions.

Appendix L Interim Report Marked

Contents

Appendix L Interim Report Marked

1 Introduction

how different from "abstract"?

The aim of this final year project is to re-design, build and test a small prototype twostage gas gun for use in the Blast Impact and Survivability Unit at the University of Cape Town.

A two-stage gas gun is a device that is used to launch small projectiles to supersonic velocities. This is achieved by using a relatively low pressure gas in the first stage to drive a free piston that compresses a light gas in another chamber(second stage) to high pressures and temperatures that launches the projectile.

The main consideration in redesigning the gun is to make it more user-friendly so that it can be effectively and efficiently used for routine testing and experimentation. The current design requires the gun to be disassembled to replace the piston cap and projectile, which is a cumbersome and time consuming process.

1.1 Project Limitations, Scope and Goals

1.1.1 Project Constraints and Limitations

The following constraints and limitations must be considered throughout the design process.

- The is a overall length constraint on the gas gun and the space available on the new I beam needs to be considered. ✓
- The first stage(supply) pressure is limited to 10 bar (1 MPa). ✓
- The reservoir Volume is limited to 5 litres. ✓
- Air is to be used in both stages. ✓ ~~why?~~ ~~other possibilities~~?
- Other gasses are an option provided that they are non volatile, non-toxic and fi~~ts~~ within the budget.
- The reload process needs to be short (< 5 minutes) to ensure that repeated firing is possible with minimal effort. ✓

The gun needs to be safe to operate and assemble. All the relevant regulations surrounding pressure vessels need to be adhered to (SANS). The pressure and volume in the first stage chamber are constrained to ensure that the vessel does not have to be certified - this will be verified in the report. ✓

Appendix L Interim Report Marked

1.1.2 Scope and Goals

The scope of this project is to redesign the current two-stage gas gun such that it is more user-friendly. The gun needs to reach at least Mach 1 as well as have a short (< 5min) and easy reload process. The light trap that is currently being used to measure the projectile speed needs to be improved in terms of accuracy. An extended (time permitting) goal of this project is to create a vacuum in the catch chamber and barrel.

Another long term goal of this project is to gather data from the gun to better understand gas dynamics.

All 'stretch' goals

2 Literature Review

General comment: You may want to start with a more general history / overview before getting into the operating principles.

The literature that will be reviewed below will mainly focus on gas gun designs so that the important aspects for the success of the gun can be determined and used in the design of this prototype. Literature on the working principals and theory behind single stage gas guns, and its limitations will be reviewed. The theory and principals applicable to 2 stage gas guns are then examined and the differences between single and two stage gas guns are discussed. Finally the detailed working principals and design of 2 stage gas guns are explored.

2.1 Operating principals of single stage gas guns

A single stage gas gun operates by using pressurised gas to drive a projectile down a barrel. Figure 2.1 shows a schematic of a single stage gas gun, where P_0, V_0, A, a, m are the initial pressure, initial volume, reservoir cross sectional area, barrel cross sectional area and projectile mass respectively.[1]

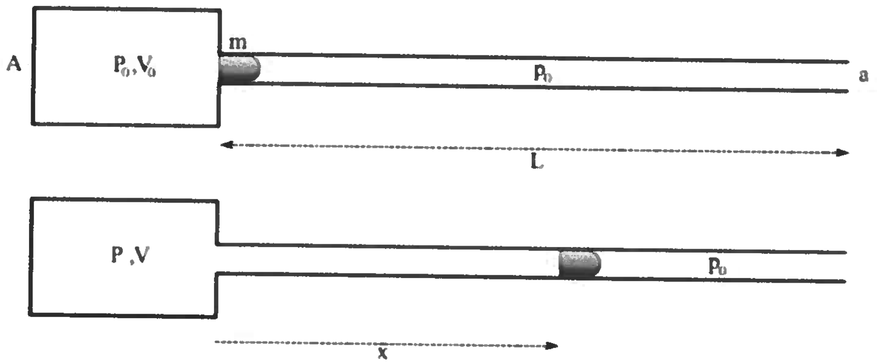


Figure 2.1: Single stage gas gun schematic[1]

Not sudden P_0 ? what is this?

? A single stage gas gun can operate under two conditions the first being a sudden high initial pressure P_0 applied to the reservoir which will rapidly accelerate the projectile down the barrel or the chamber can be pressurised to the required pressure and separated from the projectile by a diaphragm which bursts when the desired pressure is reached and accelerates the projectile down the barrel as the gas expands. To achieve significantly high velocities with this set up a high pressure vessel is required, either the gun reservoir or the gas cylinder used to supply the pressure. Furthermore to achieve high supersonic velocities high static pressure is required which is not safe, it will also be shown that in addition to this excessively long barrels are required.

...iaphragm usually ...n shock tube or valve.

Your sentences are too long.

Knowing that pressure is not constant with expansion due to an increase in volume and assuming isentropic expansion(there is no heat transfer into/out-of the gas as the expansion occurs in a fraction of a second and it is a constant entropy and internally reversible process) of an ideal gas. An expression for the projectile velocity can now be determined as follows.[2]

You state many things upfront without first creating context ... patience!

Appendix L Interim Report Marked

The pressure-volume and pressure temperature relationships are as follows, where P_0, V_0 are the initial pressure and volume.

why not in-line?

looks like scans/cut & paste ?

$$P_0 V_0^{\gamma} = P V^{\gamma} \qquad \text{(2.1) (2.2)}$$

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

The work done on the projectile can be found by integrating the pressure over the volume.

$$W = \int_{V_0}^{V(x)} \frac{P_0 V_0^{\gamma}}{V(x)^{\gamma}} \mathrm{d}V(x) = \frac{P_0 V_0}{\gamma - 1}\left[1 - \left(\frac{V(x)}{V_0}\right)^{1-\gamma}\right] \qquad (2.3)$$

You need to write the equations yourself or you must give a reference with every equation :: or this is plagiarism!

If we assume no losses then all the work is converted to kinetic energy and a theoretical expression for the projectile velocity can now be found.

... and ... ?

... pressure is the same everywhere i.e. speed of sound >> projectile velocity.

$$\frac{P_0 V_0}{\gamma - 1}\left[1 - \left(\frac{V(x)}{V_0}\right)^{1-\gamma}\right] = \frac{1}{2} m v^2 \qquad (2.4)$$

$$v = \sqrt{\frac{2 P_0 V_0}{m(\gamma - 1)}\left[1 - \left(\frac{V(x)}{V_0}\right)^{1-\gamma}\right]} \qquad (2.5)$$

If we make the assumption of a constant diameter gas gun the velocity can be expressed follows, where x is the projectile position along the barrel and x_0 is the initial length of the barrel such that it has the same volume as V_0.

"hypothetical" / "equivalent"

$$v = \sqrt{\frac{2 P_0 V_0}{m(\gamma - 1)}\left[1 - \left(\frac{x}{x_0}\right)^{1-\gamma}\right]} \qquad (2.6)$$

where do you plot/discuss results? give a reference.

2.1.1 Limitations of single stage gas gun

If we assume that the gas can expand infinitely and all work is converted to kinetic energy, then the maximum theoretical velocity can be found from Equation ??,

$$v_{max} = \sqrt{\frac{2 P_0 V_0}{m(\gamma - 1)}} \qquad (2.7)$$

If we, however, consider the effects of gas dynamics the maximum attainable exit velocity for the projectile is only a function of the specific heat ratio, ideal gas constant and temperature. It is independent of the initial pressure and volume, which means that one cannot simply keep increasing the driving pressure to reach higher velocities. The governing equations are given below [3].

not the same setup. You need to introduce the setup.

Oh, I see what you mean ?

Not really. The initial volume is infinite!

$$c = \sqrt{\gamma R T} \qquad (2.8)$$

$$v_{max} = \frac{2}{\gamma - 1}\sqrt{\gamma R T} \qquad](2.9)$$

The following was derived in [3] to show a relationship between barrel length and projectile exit velocity considering the effects of gas dynamics.

general note: You jump around a bit, i.e. your topics are not clearly delimited. We need to chat.

Appendix L Interim Report Marked

$$L = \frac{u_{max}^2}{\dot{u}_{max}} \frac{\gamma - 1}{2} \left[\frac{2}{\gamma + 1} \left[\left[1 - \frac{u}{u_{max}} \right]^{-\frac{\gamma+1}{\gamma-1}} - 1 \right] - \left[1 - \frac{u}{u_{max}} \right]^{-\frac{\gamma+1}{\gamma-1}\frac{2}{\gamma+1}} \right] \tag{2.10}$$

where,

same as V_{max}? use ~~conti~~ consistent notation.

u_{max} = maximum projectile velocity

$u^{\cdot}_{max}$ = maximum projectile acceleration — definition? $\dot{u}_{max}$ = ?

u = Exit Velocity L = Barrel length

Figure 2.2 shows the attainable velocity for a given barrel length. It was also shown in this paper that beyond a barrel length of $5m$ the results in terms of velocity had diminishing returns. This also shows that the barrel length for nitrogen at 25bar and a barrel diameter of 12mm requires a barrel length greater than $5m$ to reach the speed of sound. [3] ← ... for a 10g projectile!

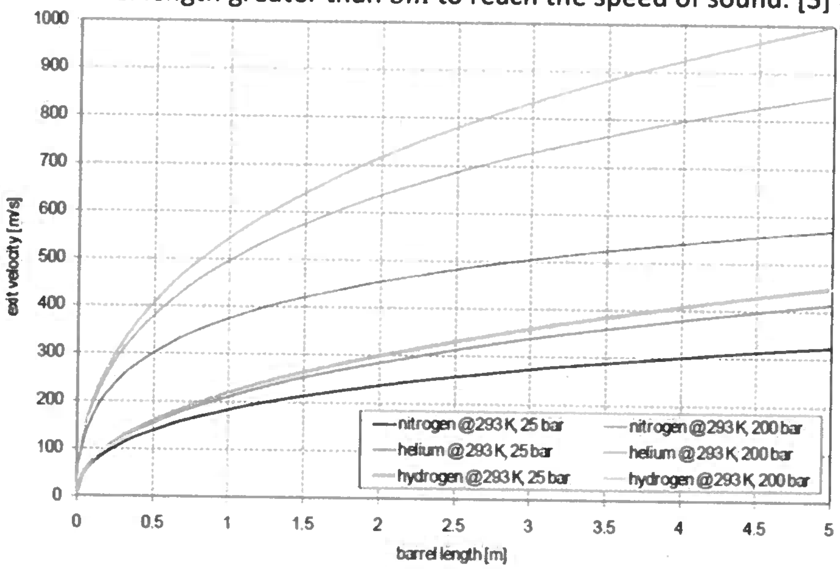


Figure 2.2: Exit velocity for an ideal constant diameter gas gun with a 12 mm bore and 10 g projectile [3]

correct conclusion, but you need to refine your argument.

It is therefore beneficial to explore 2 stage gas guns when space is a constraint and high static pressures are not an option. ✓ 2 stage beneficial ∵ achieve high temp/Press which allow ↑ velocity

How can this be true? I know what you mean, but it's ~~tru~~ not 100% true.

2.2 Single vs Two Stage Gas Guns

A two stage gas gun is based on the design ? and operating principals of a single stage gas gun. The main structural difference between a single and two stage gas gun is that a two stage gas gun has 2 reservoirs typically separated by a free piston whereas a single stage gas gun has only a high pressure reservoir. Not really 2 reservoirs (Pump tube NOT reservoir)

A two stage gas gun relies on the low pressure gas in stage 1 to accelerate the free piston that is used to rapidly compress the second stage gas to high pressures and temperatures. This allows for much higher projectile velocities as it is not possible/safe to achieve these high static pressures.

ok. why? ... ?

Appendix L Interim Report Marked

2.3 Operating principals of two-stage gas gun

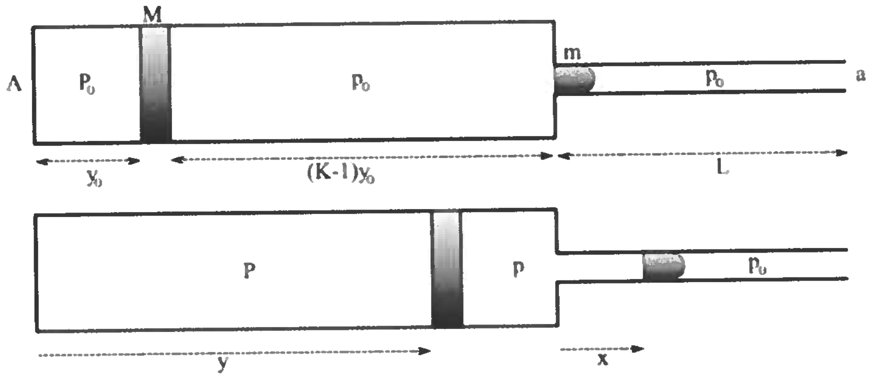


Figure 2.3: Two stage gas gun schematic [1]

elaborate, why is this a reasonable assumption?

The thermodynamic properties in the first stage of the gas gun can be calculated from the zero dimensional(the pressure equilibrates instantaneosly) expressions for mass and energy if the assumption of ideal gas and adiabatic expansion are assumed [4]. The equation of motion can be determined for the piston by applying newtons second law to it where the force is caused by the pressure imbalance between the two stages. By using a low pressure in the second stage (generally atmospheric pressure) very high compression ratios can be achieved which results in very high final pressures and temperatures. This allows for much higher projectile velocities. The final pressure in second stage is found on the basis that the kinetic energy of the piston is ideally converted to work in the second stage under the ideal gas assumption[4].

ok. why?

?

This is all a bit vague - where do you do this? Why mention it here?

An analytical solution for the projectile velocity can be found by assuming the compression in the first stage is isentropic and the piston reaches the end of its stroke before the projectile moves. A control volume in the transition piece (Figure 2.4) can be taken to apply the energy conversion to the projectile [2]. This is sufficinet for a first order approximation, however, in reality this is better aproximated by an 1D model [4].

what kind of 'model'? numerical? They've all 10 models!

2.4 Pressure Disturbances

As the projectile moves within the barrel a rarefaction disturbance is transmitted into the gas at the speed of sound in the opposite direction of the projectile. If one were to consider an infinitesimal layer of gas behind the projectile at every instant in time, there exists an infinitesimal rarefaction disturbance in this layer resulting in an infinitesimal pressure drop in the layer of gas behind it. As the projectile moves along the barrel it leaves a low pressure region directly behind the projectile which the layer of gas directly behind fills and drops in pressure. As the projectile moves along the barrel all these infinitesimal pressure drops add up and have a finite effect, the figure below shows this. A qualitative analysis shows that

Appendix L Interim Report Marked

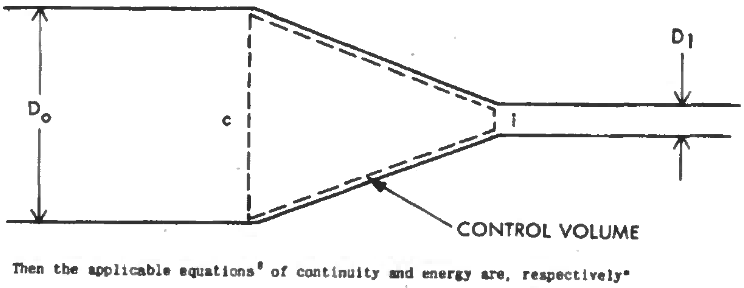


Figure 2.4: Control Volume transition piece [2]

the faster the layer of gas behind the projectile moves to fill the evacuated space behind the projectile the lower the effect of rarefaction will be. This indicates that a driving gas with low inertia and therefore low mass will be beneficial. It should also be noted that this effect is more noticeable at higher velocities.[2] ✓

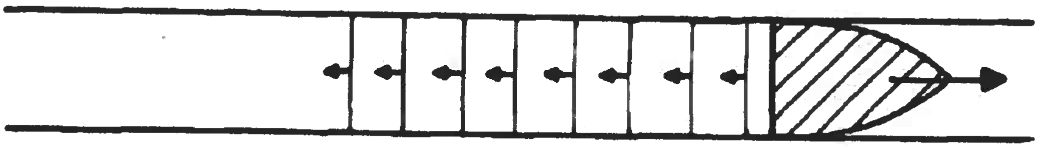


Figure 2.5: Rarefaction Pressure disturbances [2]

2.5 Pressure vessel theory

This project involves the use of a pressure vessel, therefore all the necessary standards and regulations surrounding pressure vessels need to be considered. A pressure vessel is defined as a housing/container that holds a fluid or gas at a static pressure of greater than or equal to 50 kPa. This project will follow the SANS 347 pressure vessel standards[5]. The maximum static pressure held in the reservoir for this project is 10 bar ($1000KPa$), the following graph can be used to determine the maximum volume for the reservoir such that it remain in the Sound Engineering Practice (SEP) region of the graph. The reason for needing to remain in the SEP region is to avoid the need to have the pressure vessel certified which is an unnecessary additional cost as well as to make the design *safer*. For the given pressure of 10 bar($1000KPa$) the maximum allowable volume to remain in the SEP region is $5l$.

how? Good design leads to safety, not certification ~~also~~ avoidance.

The standards are only applied to the reservoir of the gas gun as this is where the static pressure will be held. The second stage of the gas gun only holds the high pressure for a fraction of a second so the standards do not need to be applied to it. The vessel strength will be calculated to ensure that the wall thickness is enough to support the pressure. The design will also be fail safe in nature as it will be designed to leak if the pressure is held for too long - ensuring that static pressure cannot be stored in this section.

You sure you want to say this in a report? - You need a better argument than that!

Look again, The high pressure region is also < 1L so can go up to 100 kPa = 1000 bar! ... so may ~~certi~~ SEP is still good enough!

Appendix L Interim Report Marked

Plot Pump tube
Graph to
Show always
in SEP

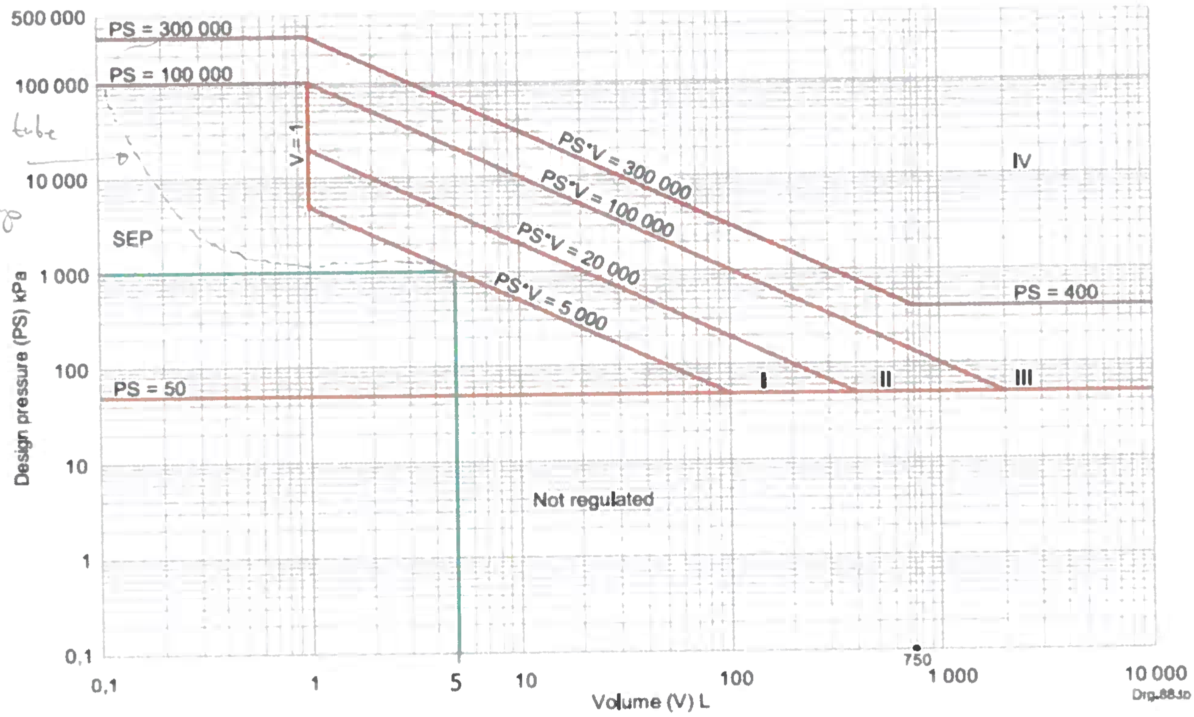


Figure 2.6: Graph for pressure vessels — Non-dangerous gas [5]

3 Theory

5g? based on what?
give a motivation.
(How got 5g) material and volume..

3.1 Single stage Gas gun Performance

Using the initial conditions prescribed in this project and assuming a projectile mass of $5g$ and air as the driving gas, the maximum attainable velocity of a single stage gas gun is found using Equation 2.7:

$V_0 = 5l = 0.05m^3$

$P_0 = 10bar = 1MPa$

$T_0 = 293K$

$\gamma = 1.4$ for air

$m = 5g$

$$v_{max} = \sqrt{\frac{2P_0V_0}{m(\gamma-1)}} = \sqrt{\frac{2\times 1\times 10^6\times 0.05}{0.05\times(1.4-1)}} = 2236m/s$$

The above shows that for the given initial conditions the maximum attainable exit velocity for a projectile driven by air(treated as an ideal gas) is $2236m/s$.

Considering gas dynamics it can be shown that for the same initial conditions a maximum velocity is actually $1715m/s$ according to Equation 2.9. This is then the limiting case for the

Appendix L Interim Report Marked

maximum velocity of a single stage gas gun. This will, however, further be reduced if other effects such a pressure disturbances and frictional losses are included.

$$v_{max} = \frac{2}{\gamma - 1}\sqrt{\gamma RT} = \frac{2}{1.4 - 1}\sqrt{1.4 \times 287 \times 293} = 1715m/s \quad (3.1)$$

Figure 3.1 shows a plot of barrel length against velocity for a single stage gas gun under the isentropic assumption using Equation 2.5. This is ignoring all resistive forces such as friction and air resistance. One can see that excessively long barrel lengths are required to attain the speed of sound. For the initial conditions specified in this project an initial barrel length of 3.9m is required, this is excluding the length of the reservoir/pump tube. ✓

Furthermore looking at Figure 3.2 one can see that barrel lengths in excess of 2000m are required to approach the maximum attainable velocity. This graph also shows how after a certain point an increase in the barrel length does not show significant increase in velocity.

Plotting a graph (Figure 3.3) for Equation2.10 for the initial conditions of this project it can be shown that a barrel length of 11 m is required to reach the speed of sound when taking into account the effects of gas dynamics. This shows that the effects of gas dynamics further reduces the achievable velocity. This confirms that a single stage gas gun will not achieve supersonic speeds for the initial conditions of this project. ✓

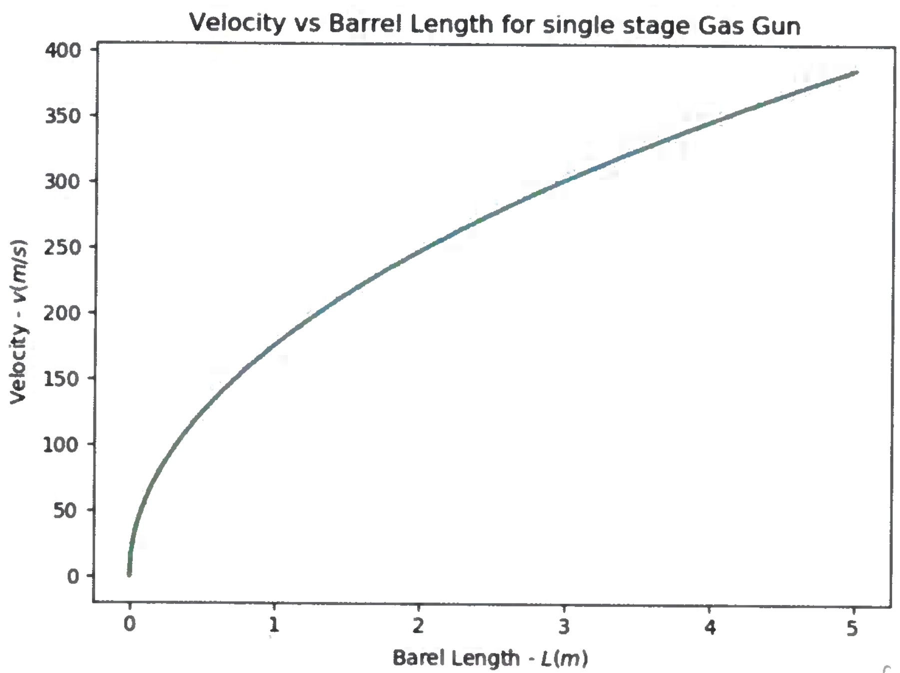


Figure 3.1: Velocity vs Barrel Length (Energy Conversion)

Ideal Gas

which theory is this?

Appendix L Interim Report Marked

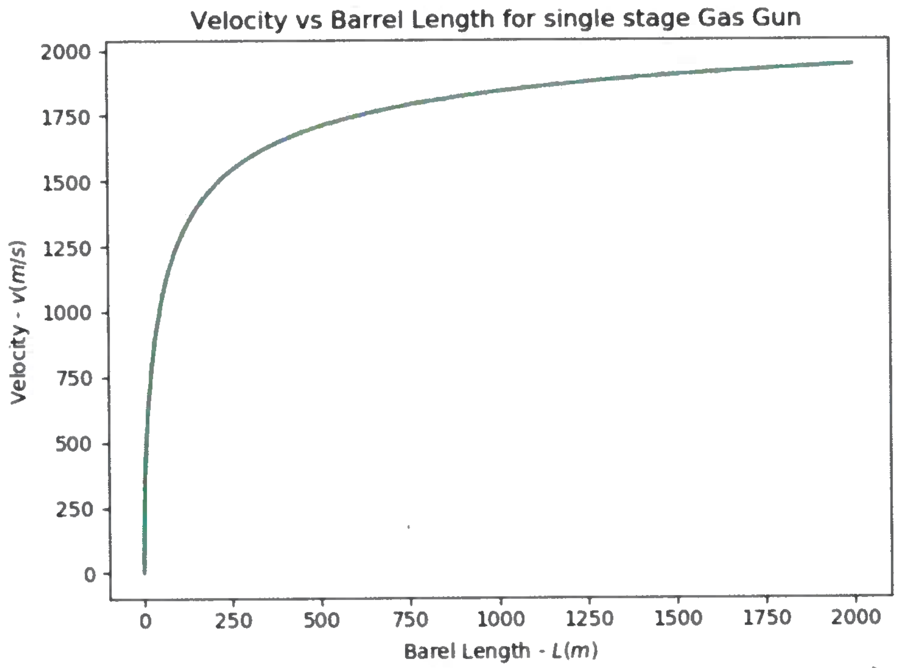


Figure 3.2: Velocity vs Barrel Length (Energy Conversion)

Could be a single graph and up to 20m should be sufficient to show the fundamental problem.

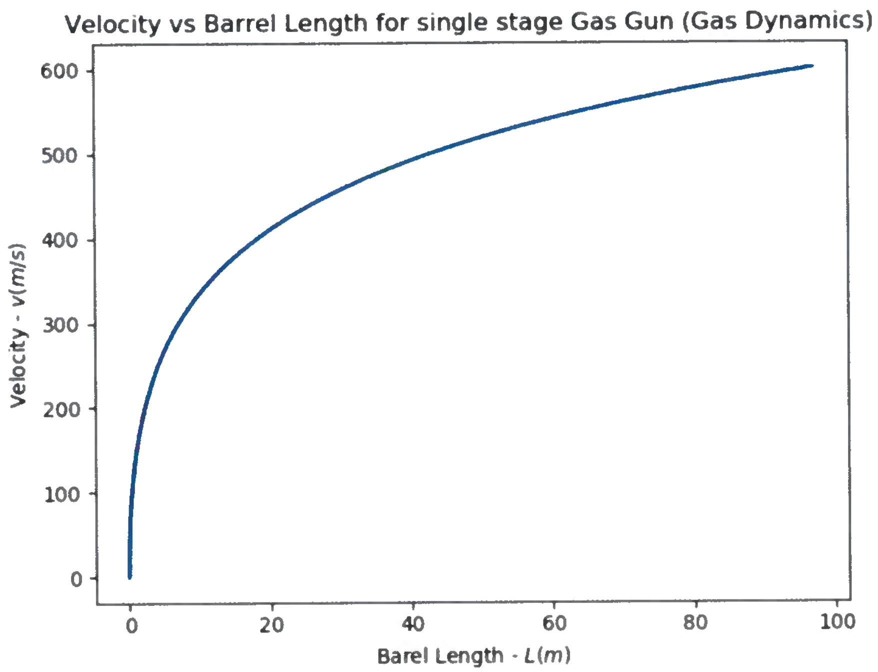


Figure 3.3: Velocity vs Barrel Length (Gas Dynamics)

Appendix L Interim Report Marked

4 Analytical Solution for... ?

4.1 Energy Approach

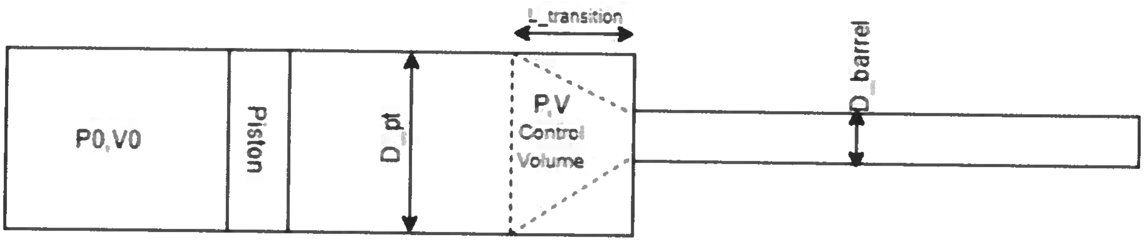


Figure 4.1: 2 stage schematic

? what?

This approach assumes that the projectile remains stationary up until the piston reaches the end of its stroke. The Pressure behind the projectile can be found by considering the control volume indicated in Figure 4.1 Insentropic compression is assumed so Equation2.1 can be used.

$$P = \frac{P_0 V_0^{\gamma}}{V^{\gamma}}$$

The control volume is given as the volume of a truncated cone:

$$V = \frac{1}{3}\pi R_{pt}^2 \left(l_{transition} + \frac{l_{transition} R_{Barrel}}{R_{pt} - R_{Barrel}} \right) - \frac{1}{3}\pi R_{barrel}^2 \frac{l_{transition} R_{barrel}}{R_{pt} - R_{Barrel}} \qquad (4.1)$$

need to explain more clearly.

At this point the pressure in the control volume is essentially the initial pressure that drives the projectile and the single stage velocity expression derived in Equation 2.6 can be used as shown bellow. Where x is the position of the projectile in the barrel and x_0 is the initial length so that the the volume remains the same as the area is reduced.

$$v = \sqrt{\frac{2PV}{m(\gamma - 1)} \left[1 - \left(\frac{x}{x_0} \right)^{1-\gamma} \right]}$$

is this still valid given (4.1)?

$$x_0 = \frac{V}{\frac{\pi}{4} d_{barrel}^2}$$

For the initial conditions of this project (10bar,5l) and assuming a projectile mass of $5g$ the maximum obtainable velocity for a $2.9m$ long $12mm$ diameter barrel is $427.6m/s$ and the absolute maximum is $575.8m/s$. Reducing the projectile mass to $2g$ results in a maximum velocity for a $2.9m$ long barrel of $910.4m/s$.

Show details.
This is important.

5 Numerical Model

This is not quite correct. Let's chat.

A basic central difference numerical model was modified from the 2018 project[6]. The reason for using central difference over other schemes is that central difference assumes equilibrium at the n^{th} time step and therefore requires the forces at the n^{th} time step. This is useful as we only know what the forces are at the current (n^{th}) time step as they are dependent on the positions of the piston and projectile. The equations of motion for both the piston and projectile were determined as follows. Where P_1 and P_2 are the pressures behind the piston and behind the projectile respectively. V_0 and V_{20} are the initial volumes in the first and second stages of the gas gun respectively.

$$m_{piston}\ddot{x}_{piston} = P_1 A_{pump-tube} - P_2 A_{pump-tube} \tag{5.1}$$

$$m_{projectile}\ddot{x}_{projectile} = P_2 A_{barrel} - P_{atm} A_{barrel} \tag{5.2}$$

$$P_1 = P_0 \left(\frac{V_0}{V_0 + A_{pump-tube} x_{piston}} \right)^{\gamma} \tag{5.3}$$

$$P_2 = P_{atm} \left(\frac{V_{20}}{V_{20} + A_{barrel} x_{projectile} - A_{pump-tube} x_{piston}} \right)^{\gamma} \tag{5.4}$$

One can see that it is not feasible to solve the above analytically as it is a 2 degree of freedom problem therefore a central difference numerical integration scheme is employed to integrate and solve the above equations of motion. The updating variables used in the scheme are given bellow.

need to explain this in more detail.

$$V_1 = V_0 + A_{pump-tube} x_{pist(i)} \tag{5.5}$$

$$V_2 = V_{20} - A_{pump-tube} x_{pist(i)} + A_{barrel} x_{proj(i)} \tag{5.6}$$

$$P_1 = P_0 \left(\frac{V_0}{V_1} \right)^{\gamma} \tag{5.7}$$

$$P_2 = P_{atm} \left(\frac{V_{20}}{V_2} \right)^{\gamma} \tag{5.8}$$

$$T_2 = T_{20} \frac{1}{\left(\frac{P_{20}}{P_2} \right)^{\frac{\gamma-1}{\gamma}}} \tag{5.9}$$

$$x_{pist(i+1)} = 2x_{pist(i)} - x_{pist(i-1)} + \frac{dt^2}{m_{piston}} \left(P_1 - P_2 \right) A_{pump-tube} \tag{5.10}$$

$$\dot{x}_{pist(i)} = \frac{1}{2dt} \left(x_{pist(i+1)} - x_{pist(i-1)} \right) \tag{5.11}$$

$$\ddot{x}_{pist(i)} = \frac{1}{dt^2} \left(x_{pist(i+1)} - 2x_{pist(i)} + x_{pist(i-1)} \right) \tag{5.12}$$

$$x_{proj(i+1)} = 2x_{proj(i)} - x_{proj(i-1)} + \frac{dt^2}{m_{proj}} \left(P_2 - P_{atm} \right) A_{barrel} \tag{5.13}$$

$$\dot{x}_{proj(i)} = \frac{1}{2dt} \left(x_{proj(i+1)} - x_{proj(i-1)} \right) \tag{5.14}$$

$$\ddot{x}_{proj(i)} = \frac{1}{dt^2} \left(x_{proj(i+1)} - 2x_{proj(i)} + x_{proj(i-1)} \right) \tag{5.15}$$

Appendix L Interim Report Marked

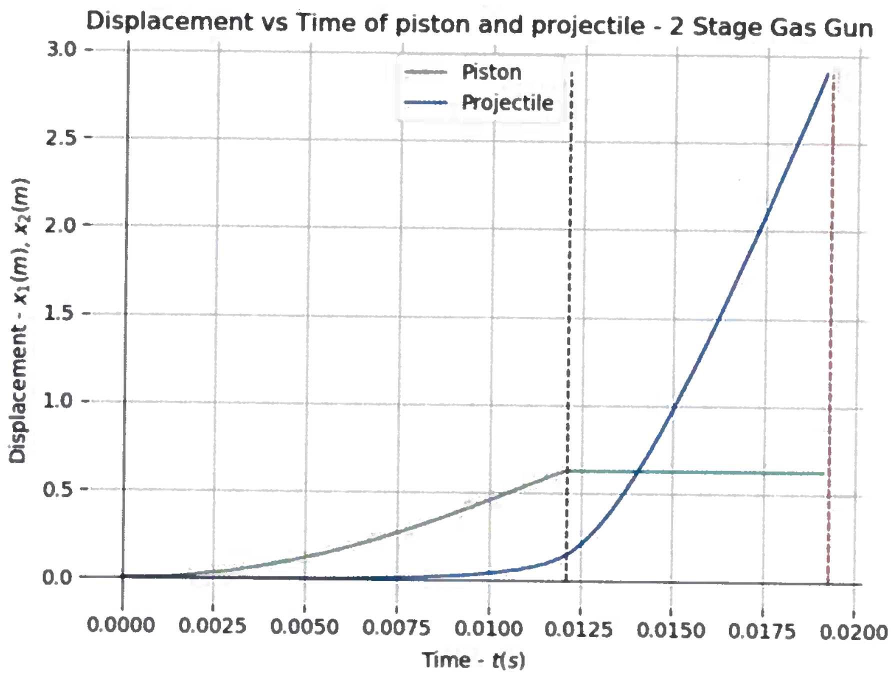
The results of this numerical model are given below for the initial conditions of 10 bar and 5l shown in the accompanying table.

Table 5.1: Numerial Results

projectile mass	piston mass	max temperature	max velocity	max pressure
0.004kg	0.2kg	948K	504m/s	59bar
0.005kg	0.4kg	843K	461m/s	40bar
0.002kg	0.5kg	750K	580m/s	26bar

The results for the first entry in Table5 showed the most promising results in terms of projectile motion before the piston ends it stroke, i.e. it moved very little in comparison to the others. However, a higher maximum velocity is obtained with a projectile mass of $2g$ and piston mass of $500g$.

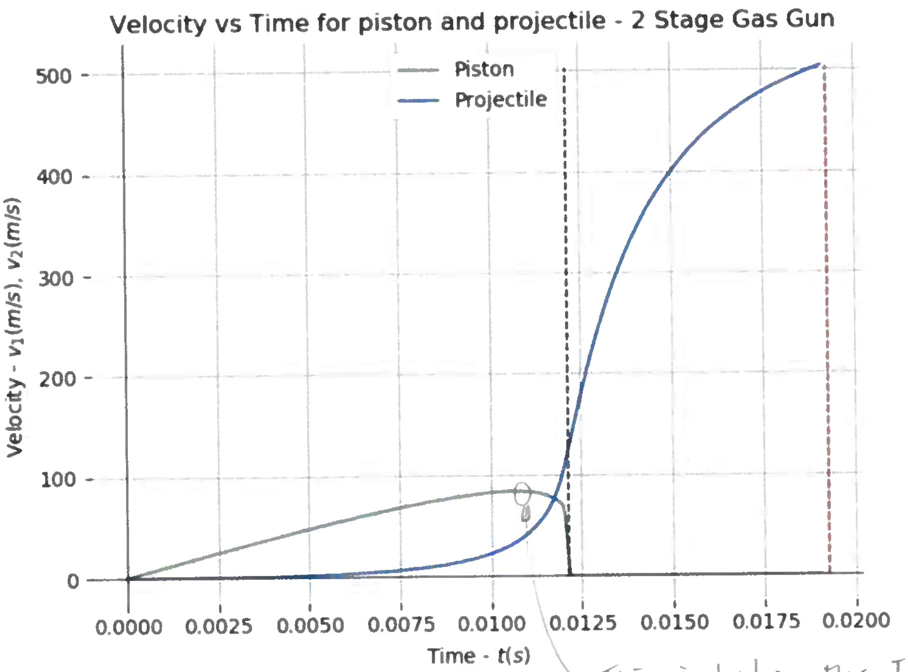
The graphs below are for the projectile mass of $4g$ and $200g$ to illustrate the numerical model.



nice!

Figure 5.1: Displacement vs. Time for piston and Projectile

Appendix L Interim Report Marked



This is higher than I'd expect!

Figure 5.2: Velocity vs. Time for piston and Projectile

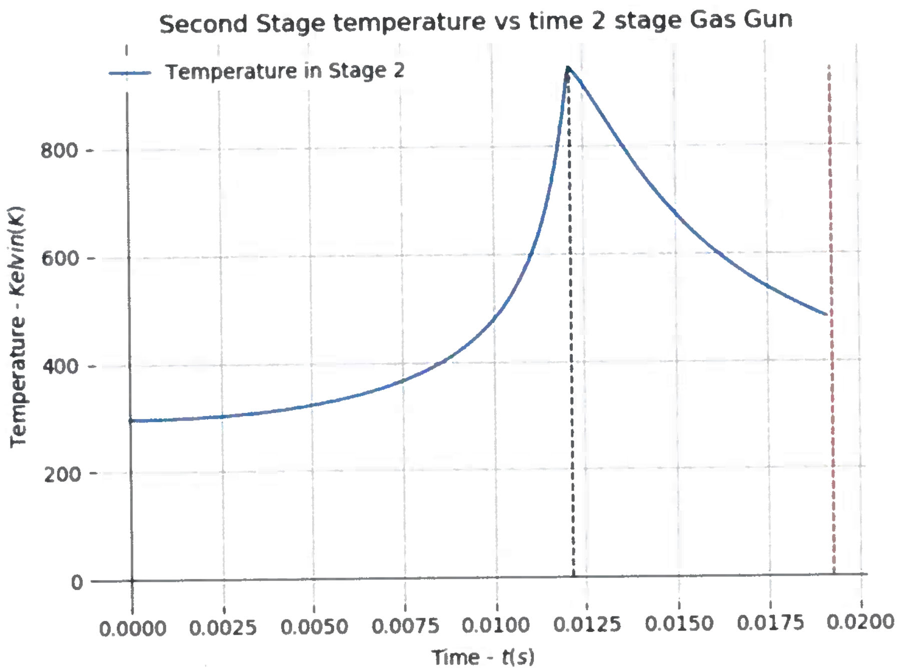
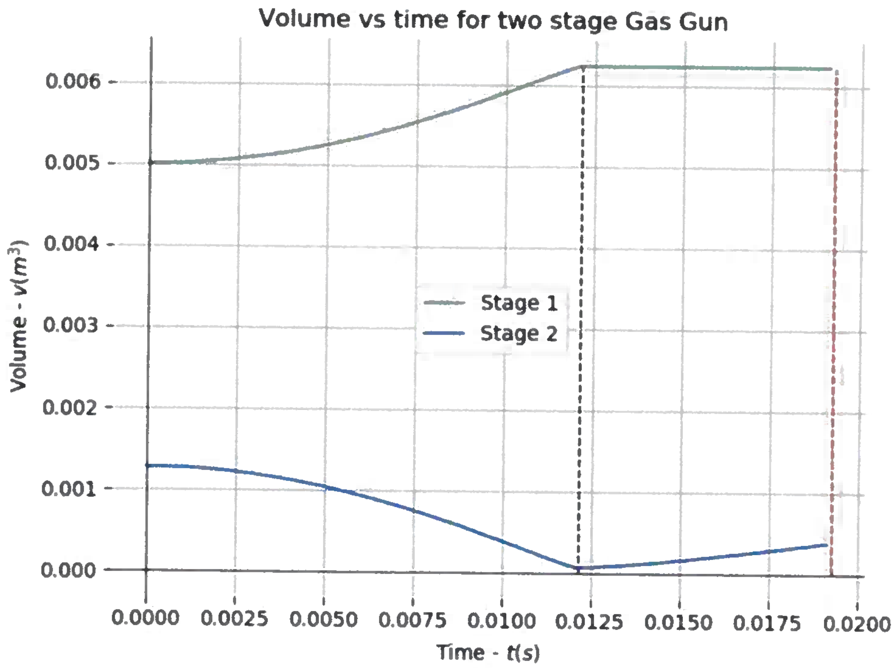


Figure 5.3: Temperature vs. Time for Second stage

Appendix L Interim Report Marked



not a useful plot?

Figure 5.4: Volume vs. Time

6 Planning

6.1 Detailed Design Considerations

The following design considerations will be included in the finial submission:

- Wall thickness calculations of the Reservoir.
- Improvement of the Light trap to measure the projectile speed.
- Shear stress calculations on the threads of the endcap.
- ? Hydraulic trigger system.
- look into materials for the deformable part of the piston ?

6.2 Project time-line and progress

The project has several milestones that span its duration as indicated on the Gannt chart in the appendices. The theory surrounding gas guns has been completed in this report and most of the calculations have been completed at this stage. The numerical model has been modified, however, effects of air resistance and friction are still to be included. The basic concept design has been completed. A closer inspection of the design needs to be done to properly determine its feasibility so that the detail design process can commence and parts can be drawn up to submit to the workshop by the first week of second semester.

can you include this?

Appendix L Interim Report Marked

The time allocated for the build and testing includes a buffer to allow for any delays from the workshop or any unforeseen hurdles. This should ensure that the project is successfully completed by the submission date.

A more detailed discussion required next time.

7 Conclusion

In conclusion, all the relevant theory has been reviewed and the project goals have been clearly defined. The project is behind schedule, however, the Gannt chart has been adjusted to accommodate for this and all the milestones can still be met within the given time-frame. The current concept needs to be thoroughly reviewed to ensure that it is feasible and if further concepts need to be generated. Once this is done the detailed design can be completed and drawings generated to submit for manufacturing. The analytical solution for the 2 stage gas gun has been completed, however it still needs to be reviewed to ensure that it is correct. The results do seem to be reasonable. The numerical model has also be included, however effects such as air resistance and frictional losses are still to be included in it. The detail design phase can now begin and the numerical model used to estimate performance

Appendix L Interim Report Marked

Bibliography

why use this and not the books I refer to?

[1] M. Denny, "Gas gun dynamics," *European Journal of Physics*, vol. 34, no. 5, pp. 1327– 1336, 2013. ✓

[2] A. E. Seigel, *The Theory of High Speed Guns*, 1965, no. May. – publisher?

[3] T. J. Cloete, "Ideal Gas Dynamics for Shock Waves and Gas Guns Speed of Sound in an Ideal Gas," 2008. – publisher?

[4] S. L. Milora, S. K. Combs, M. J. Gouge, and R. Kincaid, "Quickgun: An Algorithm for Estimating the Performance of Two-Stage Light Gas Guns," 1990. publisher ✓

[5] S. Division, *SANS 347 : 2012 SOUTH AFRICAN NATIONAL STANDARD Categorization and conformity assessment criteria for all pressure equipment*, 2012.

[6] Katherine Edwards, "Design, build and test a smallprototype two-stage gas gun," University of Cape Town, Cape Town, Tech. Rep., 2018.

~~Find the~~

Project Report

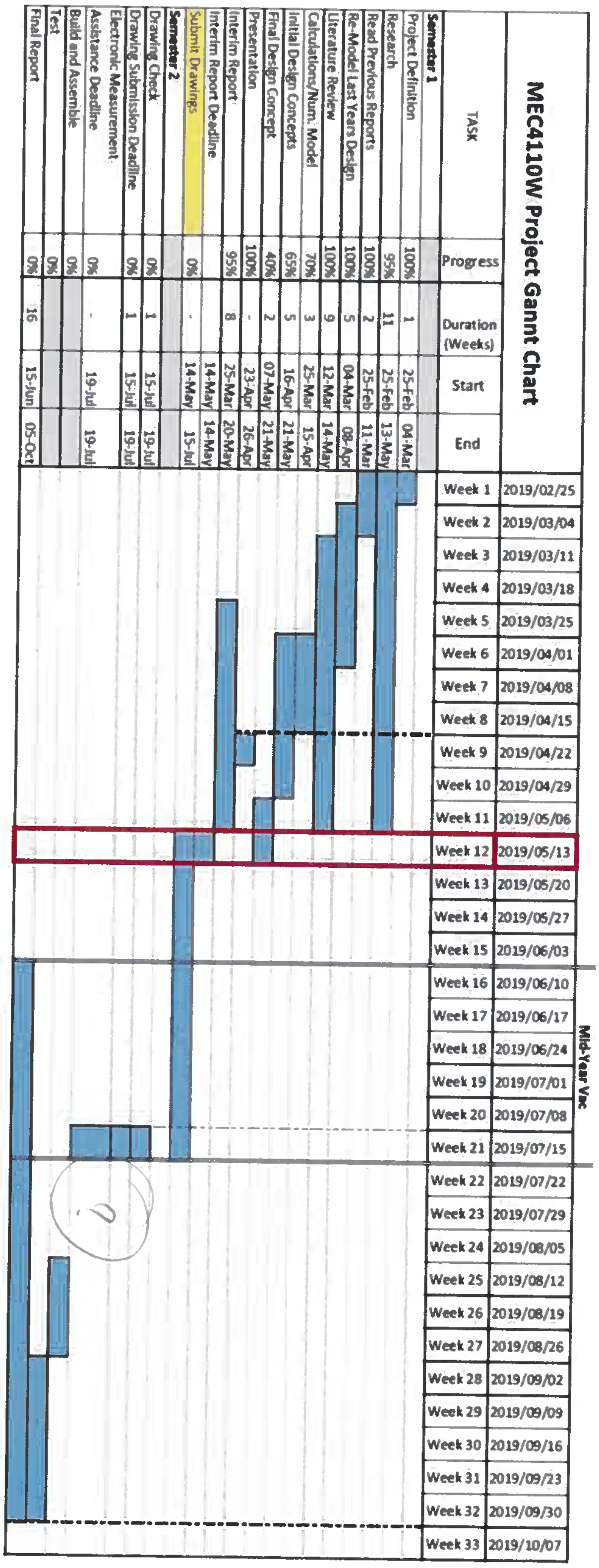
These references are incomplete.

Appendix L Interim Report Marked

Appendices

Appendix L Interim Report Marked

A.1 Appendix A Gannt Chart



Rotate

Figure A.1: Final Gannt Chart

Appendix L Interim Report Marked

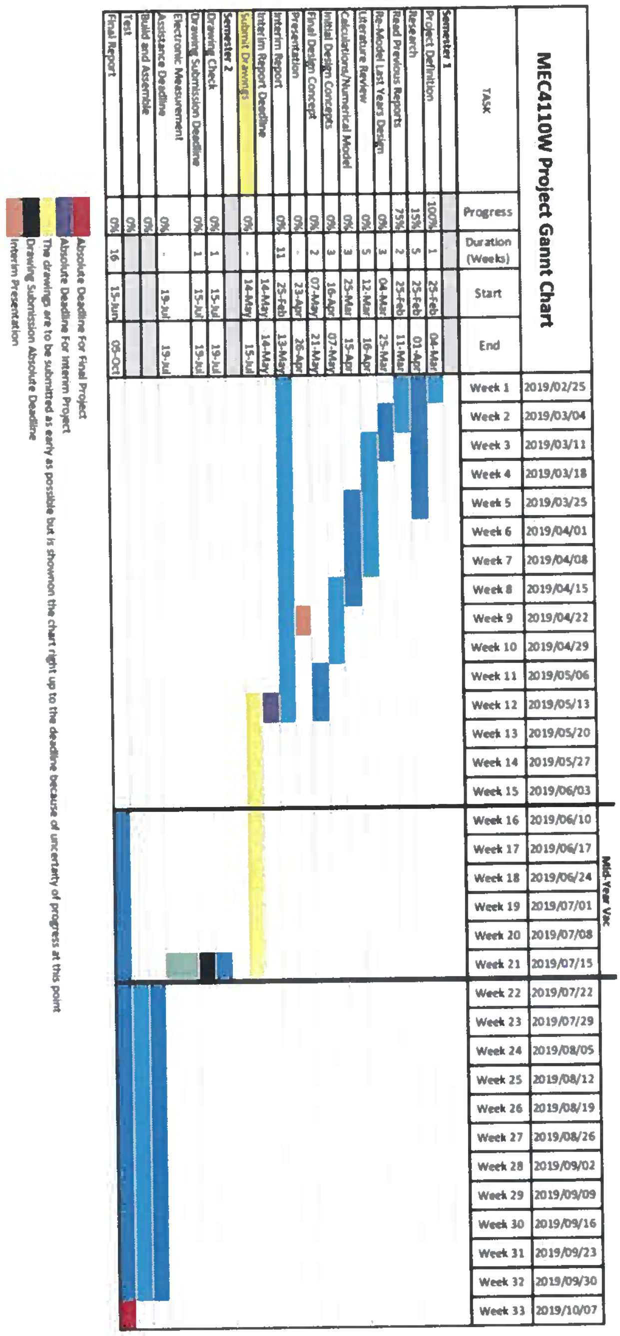


Figure A.2: Initial Gannt Chart The initial Gannt chart milestone completion dates were adjusted throughout the semester as they were not initially appropriately timed. The expected completion time was underestimated for most of the milestones. Another factor that resulted in the changes was due to in sufficient time being spent on the project throughout the semester. Going forward the gannt chart will be used more effectively to plan out the work structure to ensure that the work is completed on time. A work breakdown structure could also be generated to better lay out the tasks still to be completed.

Appendix L Interim Report Marked

A.2 Appendix B Initial Risk Identification

Department of Mechanical Engineering
Initial Risk Identification Form

Rev 1.1

- **Completion of this Risk Identification Form is required before any detail design or manufacturing is started.**
- **The purpose is to identify special safety requirements upfront, and to ensure that the necessary safety knowledge have been acquired, or specialist have been contracted.**
- **Failure to complete this form properly may result in refusal to perform your actual test / run your equipment.**
- **This form is incomplete without the attached supporting documentation as required for certain conditions.**

Student Name	Viveshan Govender
Supervisor	Mr T Cloete
Project title and number	80:REDESIGN, MODIFY AND TEST A SMALL TWO-STAGE GAS GUN

Section A: Vessels under pressure

1. Does your design/apparatus have an operating pressure above 50 kPa(g), and holds gas or two-phase fluid heated to above atmospheric saturation conditions? *If YES, then complete the remaining section.*	YES	NO
2. Study the South African classification of pressure equipment (SANS 347:2007). Note that a container made up of welded pipes is considered a pressure vessel.	Sign initials VG	
3. Does your pressure vessel fall within the Standard Engineering Practice (category 0)? *Attach a brief report showing the calculations performed and steps followed to arrive at the classification.*	YES	NO

4. If **YES** to Question 3, you acknowledge the following: • Your final design will make use of appropriate pressure vessel calculations, and will be properly documented and verified by your supervisor. • You will complete a hydraulic test of 1.25 times the design pressure using water before actual testing or operation. This test will be witnessed by your supervisor and a photo of the pressure gauge reading will be included in your report. • Alternatively a pneumatic test may be performed in an enclosed environment. • If your setup is a refrigeration system, you will study the requirements of SANS 10147, and include in your final report the key aspects applicable to your design.	Sign initials VG
5. If **NO** to Question 3, you acknowledge the following: • A suitable certified pressure vessel design & manufacturing company have been identified and has agreed to ensure all pressure regulations are met. *Proof of this must be attached.* • Your final report will contain a detail pressure vessel design pack, including a test certificate and certificate of compliance by the consulting company.	Sign initials

Section B: Electrical installations

1. Does your design/apparatus make use of electricity above 50V where any element of the electrical design/manufacturing is done by yourself, i.e. not part of a bought-out component? *If YES, then complete the remaining section.*	YES	NO
2. Read the Machine Lab Safety Rulebook (on Vula), and then consult Mr Maysam Soltanian (Electrical Engineering Machines Lab) regarding specific requirements. *Attach a brief summary of discussion outcomes and requirements.*	Sign initials	
3. Have you been advised to contract an external electrician to assist?	YES	NO
4. If **YES** to Question 3, you acknowledge the following: • An electrician has been identified and he has agreed to assist. *Proof of this must be attached.* • You will include the electrical certificate in your final report.	Sign initials	
5. If **NO** to Question 3, you acknowledge the following: • You will generate proper electrical diagrams of your setup. • You will continue to consult Mr Soltanian w.r.t. wiring, equipment and testing. • You will have your Supervisor and/or Mr Soltanian witness the first power-on event.	Sign initials	

Section C: Hazardous chemicals and fuels
NO PROJECTS INVOLVING THE STORAGE OF HEATED FUEL MAY BE DONE

1. Does your design/apparatus make use of materials (chemicals, gasses, etc.) which may be hazardous to health, or the environment? **OR** Does your setup involve the use of flammable fuel, including LP Gas? *If YES, then complete the remaining section.*	YES	NO
2. Consult with Mrs Penny Louw (CME lab) or Prof Genevieve Langdon (BISRU) or Mr Sa-aadat Parker (Composites) regarding the specific requirements in terms of handling, storage, record keeping etc. *Attach a brief summary of discussion outcomes and requirements.*	Sign initials	
3. Attach the Material Safety Declaration Sheet (MSDS) for any hazardous material to be used.	Sign initials	

I have read all attached documentation and is satisfied that the necessary safety considerations will be adhered to during the physical execution of the project.	**Supervisor Signature**	**Date**
		2019/05/13

Appendix L Interim Report Marked

A.3 Appendix C Impact of Engineering Activity

Department of Mechanical Engineering

MEC4110W – Final-Year Project

Impact of Engineering Activity Rev4

By completing this assessment, you will help to demonstrate that you have met the requirement of ECSA's Exit Level Outcome 7: Impact of Engineering activity. If it is determined that you have not successfully completed this task, you will be required to rework and resubmit this document. Should this still not be considered acceptable, you will not pass MEC4110W.

You are required to include this document in your Interim Report as an appendix. Your supervisor will read it and then sign as the reviewer.

In the space provided below, please write up to 300 words on how the technology in your project impacts on society. You can consider "society" in three spheres: 1) your fellow students and other staff members, 2) the institution more generally, and/or 3) the broader society. You may need to consider the "downstream" impact of the technology in your project if you are undertaking a focused research-based project.

Fellow students and staff members:
This project will impact on fellow students and staff by allowing for further research to be carried out in this field as well as add to the current knowledge of the field. The new design which is aimed to be more user-friendly will allow for easier and more frequent and routine testing – which can aid in research pertaining to projectile impacts. This particular project has been an ongoing project which will likely have future iterations, the design choices and findings will hopefully aid in the future redesigns and improvements. If successfully completed this project will provide a means for students and staff to fire projectiles at various targets at supersonic speeds in a safe and easy manner to aid in potential research/projects. Further improvement and research on this type of gas gun will also allow for a better understanding of the underlying gas dynamics which can in conjunction with testing be used to characterise the performance of the 2 stage gas gun to allow for more accurate simulations.

Institution more generally:
This project will also impact on the institution (UCT) in a positive way as it can potentially allow for various other research fields to be explored. The university or more specifically BISRU could potentially focus more resources on this field. Depending on the success of this project BISRU will have a 2 stage gas gun that can be used for routine testing of supersonic projectile impacts safely. The continuation of this project could result in UCT investing in a large scale 2 stage gas gun which will allow for a whole new realm of research opportunities to be explored.

Broader Society:
The impact on the broader society involves research than can improve the design of protective equipment from IED's and other high velocity impacts. This potentially save lives of those who depend on such protective equipment. This also benefits the industry which is involved in the design and manufacture of protective equipment.

Signed	Date
Bouw IL	13/05/2019

Reviewer's comments:

Reviewer's signature: Date: 2019/05/13

Appendix L Interim Report Marked

A.4 Appendix D Assessment of Ethics In Research Project

Application for Approval of Ethics in Research (EiR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

APPLICATION FORM

Please Note:
Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data. The objective of submitting this application *prior* to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook** (available from the UCT EBE, Research Ethics website) prior to completing this application form: http://www.ebe.uct.ac.za/ebe/research/ethics1

APPLICANT'S DETAILS		
Name of principal researcher, student or external applicant		Viveshan Govender
Department		Mechanical Engineering
Preferred email address of applicant:		GVNVIV009@myuct.ac.za
If Student	Your Degree: e.g., MSc, PhD, etc.	BSc Mechanical Engineering
	Credit Value of Research: e.g., 60/120/180/360 etc.	46
	Name of Supervisor (if supervised):	Mr T J Cloete
If this is a researchcontract, indicate the source of funding/sponsorship		
Project Title		REDESIGN, MODIFY AND TEST A SMALL TWO-STAGE GAS GUN

I hereby undertake to carry out my research in such a way that:

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

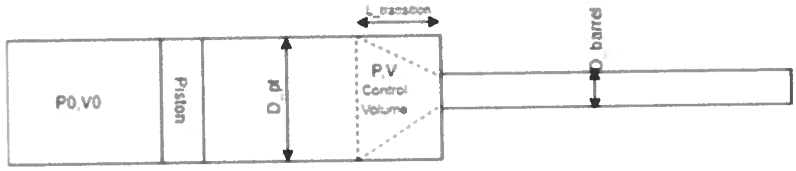
SIGNED BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	Viveshan Govender		**05 May 2019**

APPLICATION APPROVED BY	Full name	Signature	Date
Supervisor (where applicable)	Trevor John Cloete		2019 05/06
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section1; and for all Undergraduateresearch (including Honours).	George Vicatos		9/5/19
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.			

Page **1** of **1**

Appendix L Interim Report Marked

A.5 Appendix E Analytical Solution



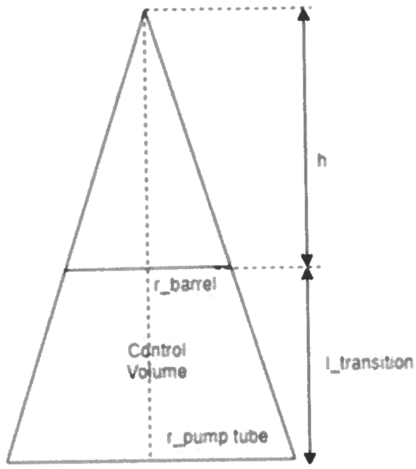
$d_{barrel} := 12mm \qquad d_{pumptube} := 50mm \qquad l_{transition} := 52mm \qquad V_0 := 5l \qquad P_0 := 10bar$

$m_{projectile} := 0.005kg \qquad \gamma := 1.4 \qquad x := 2.9m$

$$r_{pumptube} := \frac{d_{pumptube}}{2} \qquad r_{barrel} := \frac{d_{barrel}}{2}$$

$$\frac{h + l_{transition}}{r_{pumptube}} = \frac{h}{r_{barrel}} \qquad \frac{h + l_{transition}}{r_{pumptube}} - \frac{h}{r_{barrel}} = 0$$

$$h := \frac{h + l_{transition}}{r_{pumptube}} - \frac{h}{r_{barrel}} \text{ solve}, h \rightarrow \frac{312 \cdot mm}{19}$$



$$V_{control} := \left(\frac{\pi}{3}\right) \cdot r_{pumptube}^{\ 2} \cdot \left(l_{transition} + h\right) - \left(\frac{\pi}{3}\right) r_{barrel}^{\ 2} h = 0.044 L$$

$$P := P_0 \cdot \left(\frac{V_0}{V_{control}}\right)^{\gamma} = 7.507 \times 10^{8} \, Pa$$

$$V_{control} = \left(\frac{\pi}{4}\right) \cdot d_{barrel}^{\ 2} \cdot x_0$$

$$x_0 := \frac{V_{control}}{\left[\left(\frac{\pi}{4}\right) \cdot d_{barrel}^{\ 2}\right]} = 0.39 \, m$$

$$v := \sqrt{\left[\frac{2 \cdot P \cdot V_{control}}{m_{projectile} \cdot (\gamma - 1)}\right] \cdot \left[1 - \left(\frac{x}{x_0}\right)^{1-\gamma}\right]} = 4.276 \times 10^{3} \, \frac{m}{s}$$

$$v_{max} := \sqrt{\frac{2 \cdot P \cdot V_{control}}{m_{projectile} \cdot (\gamma - 1)}} = 5.758 \times 10^{3} \, \frac{m}{s}$$

Appendix L Interim Report Marked

A.6 Appendix F Numerical Solution

```
#Viveshan Govender
#GVNVIV009
#2019

import numpy as np
import matplotlib . pyplot as p l t

gamma=1.4
P atm=101325
rho piston =8050
rho piston _h =970
r h o⁻ p r o j e c t i l e =2800
L 10 =0.001
L piston =0.125
L piston _h =0.05
L _p r o j e c t i l e =0.0217
d 1 =0.05 #d pump tube
d 2 =0.012 #d b a r r e l
P0=1000000+P _atm# 10 bar in pump tube and atmospheric in i n i t i a l
  section
P20=P atm #atmospheric pressure in second stage i n i t i a l l y
T20=296 #i n i t i a l temp stage 2
L pump tube=0.8
L b a r r e l =2.9
V resevoir =0.005



A piston , A _piston head , A pump tube=np . pi *d _1 **2/4 ,np . pi *d _1 **2/4 ,np . pi *d _1 **2/4
A barrel=np . pi *d 2 **2/4
V piston=A piston * L piston
V piston head=A piston_head * L piston _h _
V p r o j e c t i l e=A barrel * L _ p r o j e c t i l e
V0=V resevoir+A pump tube*L 10 _
V20=A pump tube*L pump tube -(A pump tube*L 10+V piston+V _piston _head )
        +5.33*(10**-5) # i n i t i a l volume stage 2 i n c l conical

#Not a good approximation
#m piston _tot=V piston * rho _piston+V _piston _head * rho _piston _h #assuming both are s o l i d c y l
i n d e r s
#m p r o j e c t i l e=V p r o j e c t i l e * r h o _p r o j e c t i l e

#Use these values instead c l o s e r to actual
mpiston _tot =0.5
m _ p r o j e c t i l e =0.002


x 1 max=L pump tube -(L piston+L piston h+L 10 ) _ _
V total=A pump tube*L pump tube+A barrel * L b a r r e l _

```

```
n _steps =5000
t = np . l i n s p a c e (0,      0.3 ,     n _steps )          # time    vector
dt=t [1] − t [ 0 ]

#empty    vectors  to      store    s o l u t i o n s
x1 = np . zeros ( n _steps +1)
v1 = np . zeros (        _  nsteps +1)
a1 = np . zeros (        -  nsteps +1)
x2 = np . zeros (        -  nsteps +1)
v2 = np . zeros (        -  nsteps +1)
a2 = np . zeros (        -  nsteps +1)
    P1 = np .  _  zeros ( nsteps +1)
    P2 = np .  -  zeros ( nsteps +1)
    V1 = np .  -  zeros ( nsteps +1)
    V2 = np .  -  zeros ( nsteps +1)
    T2 = np .  -  zeros ( nsteps +1)


#set        i n t i a l conditions       in        arrays
x1 [1]=0
v1 [1]=0
a1 [1]=P0∗ A _piston / m _piston _tot #EOM
x2 [1]=0
v2 [1]=0
a2 [1]=0 #EOM
    P1 [1]=P0/100000 # conv  to       bar
    P2 [1]=P20/100000 # conv to       bar
    V1 [1]=V0
    V2 [1]=V20     T2 [1]=T20

#f i c t i c o u s i n i t i a l conditions for Central d i f f method x1 [0]= x1 [1] −
dt∗v1 [1]+ a1 [ 1 ] ∗ ( dt ∗∗2) /2
      x2 [0]= x2 [1] − dt∗v2 [1]+ a2 [ 1 ] ∗ ( dt ∗∗2) /2


      def PVT(V0 ,_A pump tube , V20 , A _barrel , P0 , P20 , T20 ,gamma, i ) :
      V1 = V0 + A pump tube∗x1 [ i ]
      V2 = V20 − A pump tube∗x1 [ i ] + A _barrel ∗x2 [ i ]
      P1 = P0∗(V0/V1) ∗∗gamma
      P2 = P20∗(V20/V2) ∗∗gamma
      T2 = T20/(( P20/P2) ∗∗((gamma−1)/gamma) )
      return V1 , V2 , P1 , P2 , T2


                   E x i t          b a r r e l=False
                   Piston End=False
                   while          E x i t    b a r r e l==False :
                   for   i          in       range (1 , n steps ) :
                   V1 , V2 , P1 , P2 ,T2=PVT(V0 , A pump tube , V20 , A _barrel , P0 , P20 , T20 ,gamma, i )
                   i f    x2 [ i ]>=L b a r r e l :
                   i f    E x i t    b a r r e l==False :
                   e x i t b a r r e l=i
```

Appendix L Interim Report Marked

```
                    Exit barrel=True
                    x2[i]=Lbarrel
                    x1[i+1] = 2*x1[i] - x1[i-1] + (dt**2)/m_piston_tot*(P1*A pump tube- P2*A
                    pump tube)
                    if  x1[i+1]>=x1max:
                    if  Piston End==False:
                    pistonend=i
                    Piston End=True   x1[i+1]=x1max
                if Piston End==True:
                x1[i+1]=x1max
                v1[i] = (x1[i+1] - x1[i-1]) /(2* dt)
                a1[i] = (x1[i+1] - 2*x1[i] + x1[i-1]) /(dt**2)
                x2[i+1] = 2*x2[i] - x2[i-1] + (dt**2)/m_projectile*(P2* A_barrel -P20 * A_barrel
                )
                v2[i] = (x2[i+1] - x2[i-1]) /(2* dt)
                    a2[i] = (x2[i+1] - 2*x2[i] + x2[i-1]) /(dt**2)  P1[i] = P1/100000
P2[i] =       P2/100000  V1[i] =
V1
      V2[i] =   V2
      T2[i] =   T2


   print(max( P_2 ))

plt.figure(1)
plt.plot(t[0:exitbarrel-1],x1[1:exitbarrel],  'g',t[0:exitbarrel-1],x2[1:
     exitbarrel],  'b',lw=1)
plt.xlabel('Time - $t  (s)$')
plt.ylabel(' Displacement - $x_1      (m)$,   $x_2    (m)$ ')
plt.plot([t[pistonend],t[pistonend]],[min(min(x1),min(x2)), max(max(x1), max(x2))],'--k',
lw=1)
plt.plot([t[exitbarrel],t[exitbarrel]],[min(min(x1),min(x2)), max(max(x1),max(x2))],
'--r', lw=1)
plt.title(' Displacement vs    Time   of    piston   and    projectile - 2     Stage
  Gas Gun '
     )
plt.legend([' Piston ',' Projectile '])
plt.tight_layout()  # make room    for    axis    labels
plt.grid()
plt.axhline(y=0, color=' black ', lw =0.6)  plt.axvline(x=0, color=' black ', lw =0.6)
 plt.box(False)

plt.figure(2)
plt.plot(t[0:exitbarrel-1],v1[1:exitbarrel],  'g',t[0:exitbarrel-1],v2[1:
     exitbarrel],  'b',lw=1)
plt.xlabel('Time - $t  (s)$')
plt.ylabel(' Velocity - $v_1    (m/s)$, $v_2    (m/s)$ ')
plt.plot([t[pistonend],t[pistonend]],[min(min(v1),min(v2)), max(max(v1), max(v2))],'--k',
lw=1)
plt.plot([t[exitbarrel],t[exitbarrel]],[min(min(v1),min(v2)), max(max(v1),max(v2))]
,'--r', lw=1)
plt.title(' Velocity    vs    Time    for    piston   and    projectile - 2     Stage
  Gas Gun ')
```

Appendix L Interim Report Marked

```
plt.legend(['Piston','Projectile'])
plt.tight_layout()  # make room for axis labels
plt.grid()
plt.axhline(y=0, color='black', lw=0.6)
plt.axvline(x=0, color='black', lw=0.6)
plt.box(False)

plt.figure(3)
plt.plot(t[0:exitbarrel-1],V_1[1:exitbarrel], 'g',t[0:exitbarrel-1],V_2[1:
    exitbarrel], 'b', lw=1)
plt.xlabel('Time - $t  (s)$')
plt.ylabel('Volume - $v  (m^3)$')
plt.plot([t[pistonend],t[pistonend]],[min(min(V1),min(V2)), max(max(V1),max(V2))],'--k'
    ,lw=1)
plt.plot([t[exitbarrel],t[exitbarrel]],[min(min(V1),min(V2)), max(max(V1),max(V2))
    ],'--r', lw=1)
plt.title('Volume vs time for two stage Gas Gun')
plt.legend(['Stage 1','Stage 2'])
plt.tight_layout()  # make room for axis labels
plt.grid()
plt.axhline(y=0, color='black', lw=0.6)
plt.axvline(x=0, color='black', lw=0.6)
plt.box(False)

plt.figure(4)
plt.plot(t[0:exitbarrel-1],T_2[1:exitbarrel], 'b', lw=1)
plt.xlabel('Time - $t  (s)$')
plt.ylabel('Temperature - $Kelvin  (K)$')
plt.plot([t[pistonend],t[pistonend]] , [ min(T2),max(T2)], '--k', lw=1)
plt.plot([t[exitbarrel],t[exitbarrel]] , [ min(T2),max(T2)], '--r',
    lw=1)
plt.title('Second Stage temperature vs time 2 stage Gas Gun')
plt.legend(['Temperature in Stage 2'])
plt.tight_layout()  # make room for axis labels
plt.grid()
plt.axhline(y=0, color='black', lw=0.6)
plt.axvline(x=0, color='black', lw=0.6)
plt.box(False)

plt.show()
```

Appendix L Interim Report Marked

A.7 Appendix G Derivations

Pressure-Work Relationship for Ideal Gas Pressure is not constant with expansion. If we assume isentropic (No heat transfer into/out of the gas and constant entropy/reversible), The following relationship applies.

$$P_0 V_0^{\gamma} = P(x)\, V^{\gamma} \tag{A.1}$$

If we also treat the gas as ideal then the ideal gas equation can be used

$$PV = nRT \tag{A.2}$$

If we consider a piston doing work on a gas with an initial volume V_0 and Pressure P_0. The initial volume is the reservoir volume and the final volume is the sum of reservoir + barrel volume

$$\mathrm{d}W = F\mathrm{d}x \tag{A.3}$$

$$\mathrm{d}W = PA\mathrm{d}x \tag{A.4}$$

$$A\mathrm{d}x = \mathrm{d}V \quad \text{(A.5)} \quad \mathrm{d}W = P\mathrm{d}V \quad \text{(A.6)}$$

$$P_0 V_0^{\gamma} = PV^{\gamma} \tag{A.7}$$

$$W = \int_{V_0}^{V} \frac{P_0 V_0^{\gamma}}{V^{\gamma}}\,\mathrm{d}V \tag{A.8}$$

$$W = P_0 V_0^{\gamma} \int_{V_0}^{V} \frac{1}{V^{\gamma}}\,\mathrm{d}V \tag{A.9}$$

$$W = P_0 V_0^{\gamma} \left[\frac{V^{1-\gamma}}{1-\gamma}\right]_{V_0}^{V} \tag{A.10}$$

$$W = \frac{P_0 V_0^{\gamma}}{1-\gamma}\left[V^{1-\gamma} - V_0^{1-\gamma}\right] \tag{A.11}$$

$$W = \frac{P_0 V_0^{\gamma} V_0^{1-\gamma}}{1-\gamma}\left[\frac{V^{1-\gamma}}{V_0^{1-\gamma}} - 1\right] \tag{A.12}$$

$$W = \frac{P_0 V_0^{\gamma+1-\gamma}}{1-\gamma}\left[\frac{V^{1-\gamma}}{V_0^{1-\gamma}} - 1\right] \tag{A.13}$$

$$W = \frac{P_0 V_0}{\gamma - 1}\left[1 - \left(\frac{V}{V_0}\right)^{1-\gamma}\right] \tag{A.14}$$

If we assume no losses then all the work is converted to kinetic energy, then we have

$$T = \frac{1}{2} m v^2 \tag{A.15}$$

$$W = T \tag{A.16}$$

$$\frac{P_0 V_0}{\gamma - 1}\left[1 - \left(\frac{V}{V_0}\right)^{1-\gamma}\right] = \frac{1}{2} m v^2 \tag{A.17}$$

$$v = \sqrt{\frac{2 P_0 V_0}{m(\gamma - 1)}\left[1 - \left(\frac{V}{V_0}\right)^{1-\gamma}\right]} \tag{A.18}$$

If we assume that the gas can expand infinitely and all Work is converted to kinetic energy, then the maximum theoretical velocity can be found as,

Appendix L Interim Report Marked

$$V \to \infty \quad \text{(A.19)}$$

$$\gamma > 1 \quad \text{(A.20)}$$

$$\frac{V}{V_0} \to \infty \quad \text{(A.21)}$$

$$\left(\frac{V}{V_0}\right)^{1-\gamma} \to 0 \quad \text{(A.22)}$$

$$W \to \frac{P_0 V_0}{\gamma - 1} \quad \text{(A.23)}$$

$$v_{max} = \sqrt{\frac{2P_0V_0}{m\left(\gamma - 1\right)}} \quad \text{(A.24)}$$

If we however take into account gas dynamics the maximum attainable velocity is given by

$$c = \sqrt{\gamma R T} \quad \text{(A.25)}$$

$$v_{max} = \frac{2}{\gamma - 1}\sqrt{\gamma R T} \quad \text{(A.26)}$$

Assuming the Area of the reservoir and barrel are the same. The velocity can be expressed as follows

$$v = \sqrt{\frac{2P_0V_0}{m\left(\gamma - 1\right)}\left[1 - \left(\frac{AL}{AL_0}\right)^{1-\gamma}\right]} \quad \text{(A.27)}$$

$$v = \sqrt{\frac{2P_0V_0}{m\left(\gamma - 1\right)}\left[1 - \left(\frac{L}{L_0}\right)^{1-\gamma}\right]} \quad \text{(A.28)}$$

$$L > L_0 \quad \text{(A.29)}$$

$$\gamma > 1 \quad \text{(A.30)}$$

$$\left(\frac{L}{L_0}\right)^{1-\gamma} \to 0 \text{ as } L \to \infty \quad \text{(A.31)}$$

therefore (A.32)

$$v \to v_{max} \text{ as } L \to \infty \quad \text{(A.33)}$$

Two Stage Gas Gun The Pressure behind the piston, assuming isentropic expansion, is

$$P(y) = \frac{P_0 V_0^{\gamma}}{V_y^{\gamma}} \quad \text{(A.34)}$$

$$P(y) = \frac{P_0\left(Ay_0\right)^{\gamma}}{\left(Ay\right)^{\gamma}} \quad \text{(A.35)}$$

$$P(y) = \frac{P_0\left(y_0\right)^{\gamma}}{\left(y\right)^{\gamma}} = P_0\left(\frac{y_0}{y}\right)^{\gamma} \quad \text{(A.36)}$$

The Pressure in front of the piston can be found as

$$V(x) = A_{res}(L_{res} - y) + A_{barrel}x \quad \text{(A.37)}$$

$$P(x) = \frac{P_0\left(\left(L_{res} - y_0\right)A_{res}\right)^{\gamma}}{\left(A_{res}(L_{res} - y) + A_{barrel}x\right)^{\gamma}} = P_0\left(\frac{\left(\left(L_{res} - y_0\right)A_{res}\right)}{\left(A_{res}(L_{res} - y) + A_{barrel}x\right)}\right)^{\gamma} \quad \text{(A.38)}$$

Appendix L Interim Report Marked

The equations of motion of the piston and projectile can then be expressed as follows

$m_{piston}\ddot{y} = (P(y) - P(x))A_{res}$ (A.39) $m_{projectile}\ddot{x} = (P(x) - P_0)A_{barrel}$ (A.40)

Effect of mass of gas on the piston Velocity Assuming that the velocity distribution in the gas is linear

$$T = \frac{1}{2}mv_p^2 + \int_V \frac{1}{2}\mathrm{d}mv^2 \quad \text{(A.41)}$$

$$\mathrm{d}m = \rho A\mathrm{d}x \quad \text{(A.42)}$$

$$v_x = v\frac{x}{x_p} \quad \text{(A.43)}$$

$$T = \frac{1}{2}mv_p^2 + \int_V \frac{1}{2}\mathrm{d}mv^2 \quad \text{(A.44)}$$

Appendix L Interim Report Marked

Appendix L Interim Report Marked

UNIVERSITY OF CAPE TOWN
MECHANICAL ENGINEERING DEPARTMENT

OCCUPATIONAL HEALTH AND SAFETY DECLARATION BY STUDENTS REQUIRING WORKSHOP ACCESS

I hereby undertake to ensure, as far as is reasonably practicable, that I will work safely and in a responsible manner.

I furthermore confirm that I will inform my supervisor and/or the Head of Department of any medication that I am taking, any medical condition or any other issue that may impair my ability to work on my final year thesis in a safe and competent manner.

I confirm that the Department of Mechanical Engineering at the University of Cape Town has given me General Safety Training and specific training on Workshop Safety Procedures, which I have understood, and that I will obtain the necessary training on the use of any other equipment or processes that are required for my particular thesis topic.

I further undertake to immediately inform my supervisor and the appropriate member of staff of any unsafe acts or conditions that I observe or encounter.

I am aware that:

1. The prescribed personal protective equipment shall be worn by me at all times.
2. I must wear closed shoes whilst in laboratories and workshops.
3. I will comply with safe work procedures and comply with all safety instructions.
4. No use shall be made of any of the University of Cape Town's machinery, plant, equipment or other items without prior approval.
5. I may not work at the University of Cape Town's premises whilst under the influence of alcohol or any other intoxicating substance.
6. I may not work at the University of Cape Town's premises after hours without the presence of a supervisor in the vicinity.

Signed at the University of Cape Town on the......9........of......MAY................20.19

WITNESS

STUDENT'S SIGNATURE

VIVESHAN GOVENDER (GVNVIV009)
NAME AND STUDENT NUMBER

Appendix L Interim Report Marked