Design of a Single Stage Gas Gun

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Abstract

I new range of laboratory equipment is required in the impact and ballistics laboratory within the School of Engineering and Information Technology, University of New South Wales – Canberra Campus. The design of one item of this equipment, a single stage gas gun, is the subject of this report. This is prototype design which is to meet all relevant Australian Standards preferably without the requirement for external certification and inspection. The most challenging part of this design is the manufacture of the barrel. The school's workshop can manufacture most of the items for this gun with the exception of the 3m long barrel with a 20mm hole bored through the centre and the vacuum vessel that will be used as the target chamber. This report includes the development of an analytical model for the gas dynamics of the gas gun to enable the prediction of the performance of the gun with various projectiles. The gas gun requirements and model have been included in this summary report.

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Nomenclature

a_{proj}	≡ Projectile acceleration	∂U	≡ Change in internal energy
P_{proj}	≡ Pressure on Projectile	∂W	≡ Work done by system
d_b	≡ Diameter of the Bore	∂Q	≡ Heat to/from surroundings
A_b	≡ Area of the Bore	ρ	≡ Density
t_b	≡ wall thickness of the barrel	$P_{0,X}$	≡ Stagnation Pressure at X
m_{proj}	≡ Mass of the Projectile	P_X	≡ Static Pressure at X
m_{rec}	≡ Recoiling mass	V_0	≡ Initial Volume
v_{proj}	≡ Velocity of the Projectile	V_X	≡ Volume at X
v_{rec}	≡ Velocity of the Recoiling mass	M	≡ Mach Number
E_{rec}	≡ Recoiling energy	γ	≡ Heat Capacity Ratio of Air

I. Introduction

The University of New South Wales – Canberra Campus (UNSW-Canberra) is embarking on a new field of research in the area of impact dynamics and ballistics. In order to conduct research in this field, the university requires several pieces of laboratory equipment. One of these pieces is a single-staged, 20mm bore gas gun. The purpose of the piece of equipment is to provide a repeatable method to conduct low to medium velocity (250 to 600 m/s) impact and ballistics research with small, light-weight projectiles. While the university is in procession of a 38.1mm calibre, smooth bore, horizontal gas gun, it is limited to speeds of approximately 300m/s. This is due to the fact that it fires into atmosphere and any attempt to increase the firing pressure will not achieve the speeds that are required of the new piece of equipment. Therefore the proposed method to achieve this is with an evacuated impact vessel, single-staged gas gun; which essentially consists of a long barrel separating two pressure vessels. The high pressure gas is contained within the high pressure vessel until required by means of a firing mechanism and breech assembly. The barrel contains the expanding gas behind the accelerating projectile until the projectile exits the muzzle. The large vacuum vessel allows the projectile to accelerate with little restriction from gas compressibility effects.

II. Design Process

The approach the designer took was that of designing a prototype product and this is reflected in many of the design decisions. This meant the design was restricted in the manufacturing options through the fact that it is a ‘one off’ product and many of the manufacturing options, used when mass producing items, were immediately discounted due to excessive cost. However, after clarifying the task, the design was broken down into three problems: gas dynamic theory, the physical design of the gun and the manufacturability of the gun.

The purpose of understanding the gas dynamic theory was twofold: one to allow the creation of a mathematic model, and two to understand what conditions the gun would be operating under to enable proper application of the various codes and standards. The physical design of the gun needs to operate as close to the model as possible. This requires that the actual gun inherits all of the assumptions made in the model; such as, negligible leakage pass the projectile, negligible effects of friction and the repeatability of the firing mechanism. This effectively means that the gun must be manufactured with appropriate tolerances to effect these assumptions. Finally the manufacturability of key components of the gun was paramount. For example, if the barrel of the gun was not able to be produced, then further effort in modelling or design would be futile. It was then assessed that the first step in this project was to tender an appropriate agency to undertake the manufacture of the barrel and, to a lesser extent, the manufacture of the impact vessel. It was assumed that all other components could be locally manufactured or purchased.

III. Gas Dynamic Theory

In order to calculate the expected muzzle velocity of the gas gun, an understanding of the gas dynamics of the gun is required. At the instant the high pressure reservoir is opened to the chamber, the projectile is exposed to

large pressure differential between the back and front sides. The projectile is then exposed to an acceleration due to this pressure differential which is calculated using equation 1.

$$a_{proj} = \frac{\Delta P_{proj} . A_b}{m_{proj}} \qquad (3.1)$$

Once the projectile begins to move, further calculations are required to understand the effect of dynamic pressure on the system. This is best explained in figure 3.1 using the Bernoulli equation (John D. Anderson, Fundamentals of Aerodynamics, 2007).

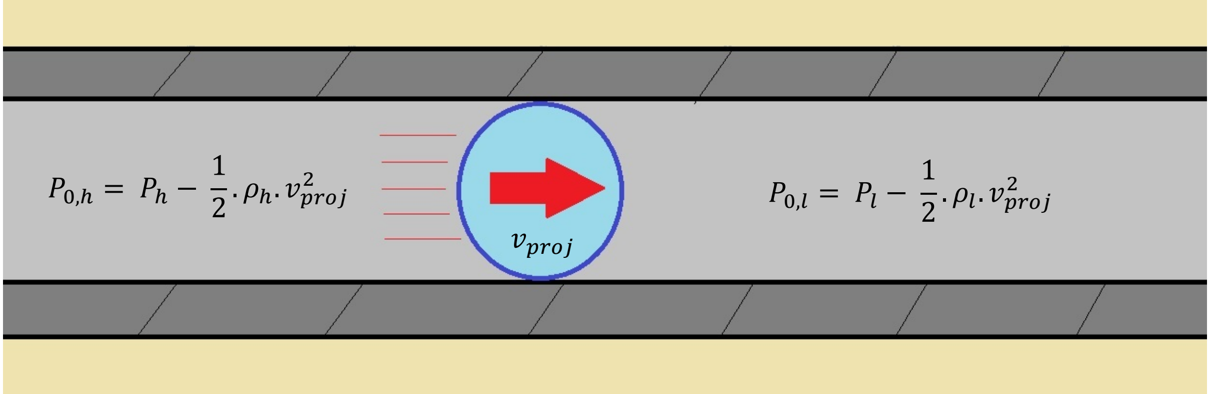

Figure 3.1 – Pressures acting on Projectile

The expansion of the high pressure air while the projectile is within the barrel, and subsequent 'firing' of the projectile, occurs quite rapidly. As a result of this rapid expansion it is assumed that the expansion is an adiabatic expansion (Bailyn, 1994) as there is not enough time for heat to be transferred to or from the surrounding. This can be expressed as:

$$\partial U + \partial W = \partial Q = 0 \qquad (3.2)$$

Since the initial stagnation pressure, initial volume and the volume with the projectile at any point along the barrel are known, it is possible to accurately estimate the stagnation pressure at any point along the barrel using a derivation of equation 2.x being:

$$P_0 V_0^{\gamma} = PV^{\gamma} \qquad (3.3), \text{ or}$$

$$P = P_0 \frac{V_0}{V}^{\gamma} \qquad (3.4)$$

where, P_0 and P are the static pressures initially and at any point along the barrel respectfully.

However, substituting this information into the Bernoulli equations (above) it can be seen that there are two unknowns and only one equation. Additionally, the Bernoulli equation only holds for incompressible flow (John D. Anderson, Fundamentals of Aerodynamics, 2007) and hence for compressible flows undergoing adiabatic expansion, the addition of compression and expansion waves are best accounted for using the Rayleigh formulas (John D. Anderson, Modern Compressible Flow, 1990). The Rayleigh formulas for such flows are as follows:

Subsonic: $$\frac{P_{0,1}}{P_1} = \left(1 + \frac{\gamma - 1}{2} M_1^2\right)^{\gamma/(\gamma-1)} \qquad (3.5)$$

Supersonic: $$\frac{P_{0,1}}{P_1} = \left(\frac{(\gamma+1)^2 M_1^2}{4\gamma M_1^2 - 2(\gamma - 1)}\right)^{\gamma/(\gamma-1)} . \frac{1 - \gamma + 2\gamma M_1^2}{\gamma + 1} \qquad (3.6)$$

As the projectile is accelerated to speeds beyond Mach 1 (Graebel, 2001), a shock wave forms in front of the projectile, much like that formed for a supersonic flow over a blunt body (John D. Anderson, Modern

Compressible Flow, 1990). In addition to this, an expansion wave is formed behind the projectile. These waves extract energy from the expanding gas and, as such, a reduction in the acceleration post Mach 1 occurs. This can be seen in figure 2 which depicts the speed of a 20g projectile along the 3m barrel.

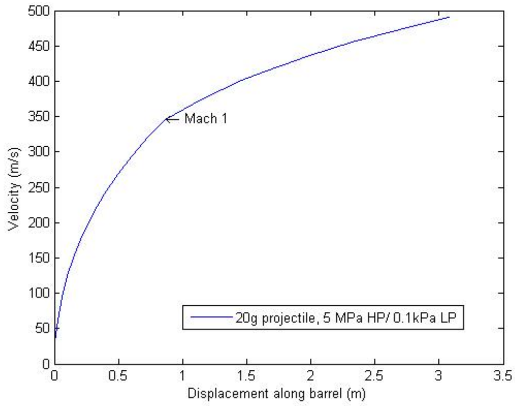

Figure 3.2 – Speed of 20g Projectile along Barrel

By converting the velocity of the projectile at any given point into a Mach number and using the adiabatic equation to determine the static pressure at that point, the stagnation pressures on either side of the projectile can be determined. The Mach number calculation was conducted using a speed of sound in air at room temperature (293K) of 343.1 m/s. By subbing the difference of these pressures into equation 3.1, and with a known projectile mass, the acceleration at any point can be determined. By iteratively integrating these equations a final muzzle velocity can be mathematically estimated. Solving for the muzzle velocity requires iteration using small steps sizes and therefore these equations need to be solved numerically using mathematical modelling. The mathematical modelling program chosen to solve these equations is Simulink[1] and will be discussed in the next section.

IV. Gas Gun Model

In order to save time in experimentation and to better understand the gun's operating conditions, a Simulink model has been produced to predict the muzzle velocity. The simulation makes use of equations discussed in section 3 of this report to iteratively solve the ordinary differential equation. A number of solvers were tried with the resulting configuration parameters being found to be the most suitable:

- simulation run time of 0.05 seconds;
- using a variable-step ODE 45 (Dormand-Prince) with relative tolerance of $1x10^{-3}$ (Dormand & Prince, 1980); and
- an automatic, un-constrained periodic sample time.

[1] Software provided under license to UNSW from MathsWorks Australia.

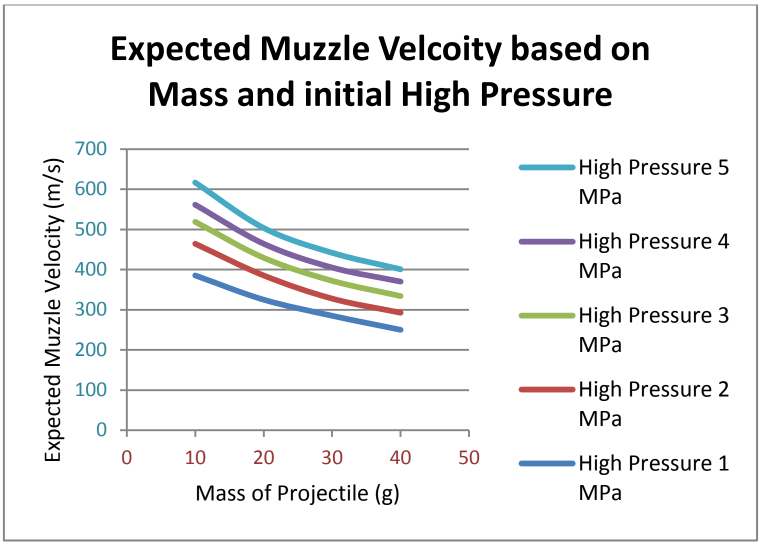

Figure 4.1 – Simulated Muzzle Velocities

Figure 4.1 depicts the expected muzzle velocities, using the gas gun model, which the gun should achieve based on an initial vacuum of 0.1 kPa and the specified initial high pressures and mass of the projectile.

While it is difficult to interpolate a set of accurate initial settings, this figure serves to give the experimenter a 'ball park' start point for simulation to accurately determine the initial gun settings. An electronic copy of the model can be obtained from Prof Paul Hazel or Mr Alan Fein; however, a pictorial representation of the model is contained within appendix A

V. Component Design

The component design was conducted with an understanding of and in reference to the following Australian standards:

- AS 1200 – 2000, Pressure Equipment.
- AS 1210 – 2010, Pressure Vessels.
- AS 3920 – 1993, Pressure Equipment Manufacture.
- AS 4343 – 2005, Pressure Equipment Hazard Levels.

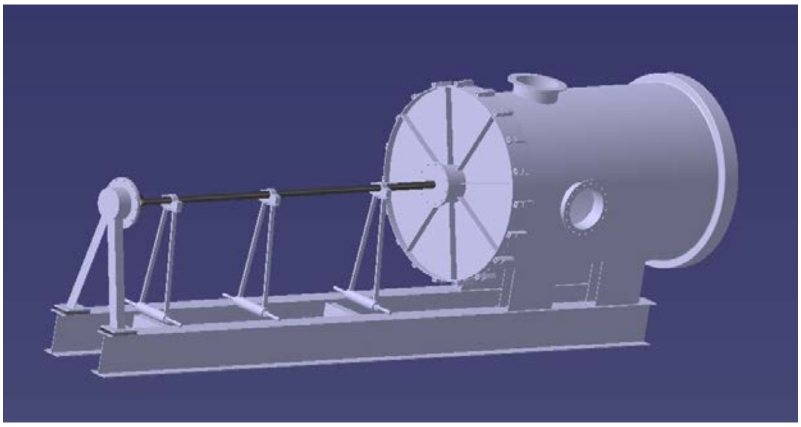

Figure 5.1 – Artist's Representation of the Gas Gun

Base. The purpose of the base is to allow correct and repeatable mounting of all Gas Gun components. It shall be made using sufficiently rigid structural members to ensure that all gas gun components are firmly secured preventing misalignment or relative movement during the evacuation, firing and normalising phases. The base must also accommodate any recoiling forces. Given the estimated weight of the barrel is 38.71kg, the high

pressure cylinder and stand is 30.87kg and the breech is 19.05kg, it can be approximated that the recoiling mass of the gun is >85kg. For the purpose of calculating the recoiling force, a recoiling mass of 85kg and a projectile mass of 40g with a muzzle velocity of 625m/s was used2. To calculate the recoiling energy, the following formulas were used:

$$v_{rec} = \frac{m_{proj}}{m_{rec}} . v_{proj} \quad (5.1)$$

$$E_{rec} = \frac{m_{rec} v_{rec}^2}{2} \quad (5.2)$$

Using these formulas and data it was determined that the recoiling energy would not exceed 3.676 J this was further rounded to 4 J to ensure a safe working factor.

High Pressure Vessel. As this is a prototype design, it is advantageous to minimise the requirement for any design and manufacturing certification. The requirement and interval for inspection and certification of a pressure vessel is determined by the pressure vessels hazard level (Ltd., AS4343 Pressure Equipment Hazard Levels, 2005). The hazard level is governed by the product of the maximum operating pressure and the volume of the vessel (pV). To negate the need for any certification or licensed inspection, the pV must be less than or equal to 30 MPa.L (Ltd., AS4343 Pressure Equipment Hazard Levels, 2005, pp. 17, table 1) As previously discussed, the preferred maximum operating pressure is 5 MPa inferring the maximum volume to be 3litres or 0.003m3.

The requirements for the high pressure vessel are as follows:

- It shall be built to API 620 or equivalent.
- It shall not have a combined pV value greater than 30 MPa.L[3] at 5MPa.
- It shall be able to retain a pressure of 5 MPa for a continuous period of 1 hour.
- It shall be able to retain a pressure of 5.5 MPa without plastic deformation.
- It shall have all external ports located on the centreline on the lowest portion of the main body of the vessel.
- It shall be fitted with a Pressure Relief Valve (PRV) tested to open at a pressure no greater than 5.25MPa.
- It shall be fitted with a maintenance/drain port.
- The mounting fixture between the base and the vessel shall be able to absorb a recoiling energy of 4J.
- It may be of cylindrical shape with a diameter as near to the diameter of the breech.

Breech and Firing Assembly. The design of the breech and firing assembly was not considered as part of the project. However, the breech and firing assembly is to satisfy the following requirements:

- It shall enable fast opening and separation to allow loading.
- It shall be able to with stand a pressure of 6 MPa without leakage.
- It shall be able to fully opened in less than 0.1 seconds.
- It shall allow the vacuum to be present on both sides of the projectile until firing.

Barrel. Due to the highly complex nature of the machining of the barrel, only one manufacture was identified - this was Baker & Provan4 from St Marys, NSW. The barrel is to be constructed from a 50mm diameter 4140 H&T PLD round bar 3000mm and then drilled with a diameter of 20mm from one end along the centreline. It must then be cylindrically ground to a roughness value (Rα) of 0.4µm, 300mm from one end only. A quote for the supply of the drilled barrel is contained in enclosure 1. The barrel is required to be internally honed after boring and heat treated to reduce residual stress. This can be conducted at Heat Treatment Australia , Brisbane Queensland. The external diameter is not due to the need to withstand design loads, as the

[2] These values used a combination of the heaviest projectile and highest expected muzzle velocity which is in no way the highest expected muzzle velocity for that weight projectile.
[3] In accordance with AS 4343 – 2005, Table 1.
[4] Baker & Provan, 9-11 Power St, St Marys NSW 2760, ph: 02 8801 9000.

maximum hoop stress associated with the barrel was calculated to be 1.67MPa using the Young-Laplace equation (5.3) (Young, Budynas, & Sadegh, 2012).

$$\sigma_\theta = \frac{P_{max} d_b}{2 t_b} \qquad (5.3)$$

And the ultimate tensile stress for 4140 H&T PLD is 1030 MPa (Rohler Uddeholm Australia, 2013). This gives a factor of safety for the barrel of 0.0016; however, it is essential that the barrel be this thick as it is necessary to enable the boring operation to occur.

The barrel is to be supported by three rolling supports. The supports provide the means to traverse the barrel to enable breech loading. The reason why the barrel has been selected to be the moving portion of the gun to enable loading, is to prevent any recoiling energy being transmitted into the impact vessel as the barrel will be free to move within the impact vessel and sealed using dynamic seals. This does mean, however, that the entire barrel and high pressure vessel forms the recoiling mass and this mass must have a means of dissipating this energy effectively. In addition to this requirement and as the manufacturing mechanism cannot guarantee the bore will be perfectly parallel to the external diameter, the supports provide the mean to perform fine adjustment to ensure the barrel is as straight as practicable.

Barrel Bush. The barrel bush is the interface between the impact vessel front plate and the barrel. The purpose of the barrel is to allow the barrel to be moved axially to enable loading of the breech. It shall be made of a relatively soft material when compared to the barrel to ensure any non-intended contact between the barrel and the bush results in damage to the bush only. It must also provide a positive seal to ensure the vacuum in the impact vessel can be created and maintained prior to firing. A secondary function of the barrel bush is to allow the extension of the projectile travel length for future experimentation. For example it will allow the muzzle of the barrel to move away from the impact vessel with the addition of a large piece of pipe.

Impact Vessel. In keeping with the prototype theme and minimising the amount of design effort and certification, the designer discovered an existing product that could be manufactured locally known as Vacvator hydro-vacuum excavation tank[5]. These tanks ideally suited the impact vessel application as they were designed to be used as a very large liquid vacuum cleaner for the purpose of excavating earth to produce trenches and holes. This meant they were specifically designed to contain a very low vacuum and were of sufficient size to allow easy access to install targets and sensory equipment. It also meant that all of the detailed design had be completed and could be adopted with very little modification. A copy of the letters sent and received from Vacvator is contained in Enclosure 2. The only drawback to using these tanks was that they are manufactured form rolled 6mm mild steel which has limited resistance to impact should an experiment 'go wrong'.

When an experimenter is preparing to use the gas gun, one of the steps will be to calculate whether or not the vessel can withstand an experiment that has missed the target and impacted the impact vessel either directly or at an oblique. They must then determine what the likely impact velocity is and ensure that it falls within the safe range as determined using the modified DeMarre equation (5.4) (Pugh, 1970).

$$V_{50} = 0.64 \, x \, 10^4 \, x \left(\frac{T}{m_{proj}}\right)^{0.75} \qquad (5.4)$$

[5] Vacvator Pty Ltd 2012, 107 Cathcart St Goulburn Nsw 2580, ph: 02 4822 4542.

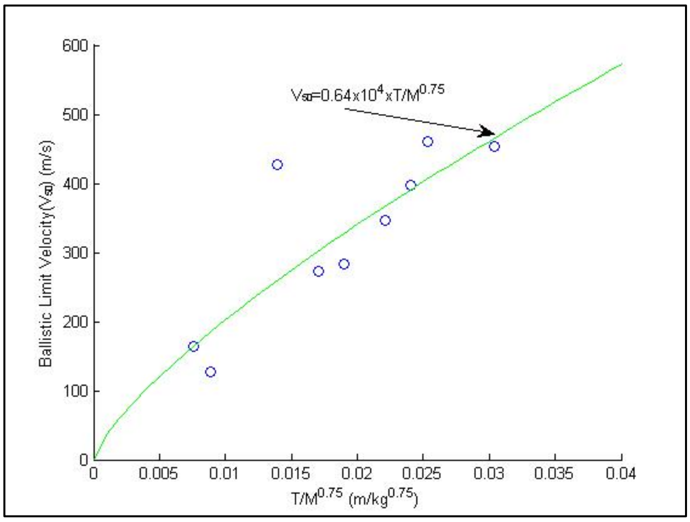

Figure 5.2 – Ballistic Limit Velocity Correlation: mild steel plate

The safe range is when V_{50} ≥ the likely impact velocity. This modified DeMarre equation was determined using empirical data supplied by Professor Paul Hazel. This can be seen in figure 5.2 where the line represents the line of best fit to the data points, small circles, obtained. It can also be seen that the data has been normalised for any thickness of mild steel.

Many of the experiments being conducted require the impact to be observed. Therefore the impact vessel requires three 250mm viewing ports to be mounted 300mm from the front at the top and horizontally opposed on either side. In addition to these requirements, the impact vessel is to be fitted with the following items fitted on the centreline on the bottom of the vessel:

- a pressure relief valve set at 200kPa,
- a port to connect the vacuum pump, and
- a vacuum relief valve.

VI. Digitisation

As has been shown in this summary report, this gun using relatively simple physics to produce a relatively simple and safe outcome; however, the operation and manufacturing of this gun is far from simple and if operated incorrectly could be highly dangerous. To prevent any dangerous occurrence, an electronic system of safety devices is to be installed. The digitised system is to make use of digital sensors that will monitor the pressures in both vessels, the condition of the impact vessel access door and the condition of the breech. This data will then be used to control actuators that will prevent the breech and or impact vessel access door from being opened when the pressures with the vessels is at a dangerous level. Additionally, these sensors can be used to log the use of the gun and by monitoring this data predictions can be made on the overall condition of the gun and should be used in conjunction with a detailed maintenance program.

VII. Further Work

Validation. As there was no official empirical data available to the designer, no analytical validation of the model could be conducted. Once assembled, further work to validate the model will be required.

Certification. While there is no requirement under the Australian standard for the gun to be inspected and certified by any authorised inspection agency, there is a requirement to ensure the gun is safe to operate within the university. A thorough inspection of all sub-assemblies is required to ensure that all mandatory requirements have been meet as detailed in this summary report.

Training. Prior to any use, all operators and experimenters are to be authorised as competent in accordance with school policy. A training directive including assessment criteria is to be produced and authorised by Mr Heath Pratt prior to final assembly of the gun.

Maintenance. A scheduled maintenance plan is to be produced prior to introduction into service (IIS). The maintenance plan should include a time based preventative maintenance schedule and an 'on use' maintenance schedule. This will be produced by the designer prior to IIS.

VIII. Acknowledgements

I would like to take this opportunity to thank the support I received during this project from the two companies Baker & Provan and Vacvator, Mr Heath Pratt, Mr Lorin Coutts-Smith and Dr Harald Kleine for their time and expert guidance. I would also like to acknowledge my two supervisors who's extraordinarily, extensive knowledge and support was truly appreciated throughout the entire project.

IX. Conclusion

This is an 80 to different uses percent solution to this gas gun problem. By adapting existing technology it is possible to reduce the design time and detail. This is essential when time money and resources are restricted due to the fact that it is a one off design. What has also been identified is the necessity to include any assumptions used in the simulation in the physical design of the gun. By not doing this, the physical gun will not perform as predicted which will result in the model becoming invalid.

As stated, this is only an 80 percent solution. There is still outstanding work that will need to be completed prior to IIS and this has been summarised in section VII of this report. However, as this report has shown, the concept is feasible and the barrel and vacuum vessel should be ordered as funds become available. This report has summarised the design process used which included the simulation of the gun and the physical design of the gun. It has also included a comprehensive list of mandatory and desirable requirements for the manufacture of the gun.

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