Development and evaluation of concepts for a high acceleration test rig

Development of a test rig, which aims to expose components to large and controllable accelerations

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Utveckling och evaluering av koncept för en hög-accelerations testrigg

Utveckling av en testrigg, som syftar till att utsätta komponenter för stora och kontrollerbara accelerationer

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Version 3

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Abstract

This thesis work is dedicated towards finding a feasible test rig design, which can expose small components, produced by SAAB, to a variety of accelerations under different conditions. A literature study is conducted with the objective of gathering information regarding high acceleration testing, where relevant components, designs and calculation methods are presented. A series of concepts are presented and evaluated against a requirement specification, the first concept iteration concerns the method of acceleration whereas the second and the third concept iterations concerns the design of the test rig on different levels of detail. The third concept evaluation is strengthened by several calculations, which indicates the feasibility of the concept in some manner. One concept achieved the highest score in the third concept evaluation and as such is presented as the best suited concept for further development.

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Sammanfattning

Denna avhandling är dedikerad till framtagningen av en möjlig design för en provningsrigg, som kan utsätta små komponenter, som produceras av SAAB, för flera olika accelerationer under olika förhållanden. En litteraturstudie genomförs med syftet att samla information om provning under höga accelerationer, där relevanta komponenter, designer och beräkningsmetoder presenteras. En serie koncept presenteras och utvärderas med hjälp av en kravspecifikation. Den första konceptiterationen berör metoden för acceleration, medan den andra och den tredje konceptiterationen berör designen av provningsriggen. Den tredje koncept utvärderingen stärks av flera beräkningar, som indikerar konceptets lämplighet ur något perspektiv. Ett koncept uppnådde högst poäng i den tredje koncept utvärderingen och presenteras därav som det bäst lämpade konceptet för vidare utveckling.

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Table of contents

Symbols & Abbreviations

Abbreviations

NATO - North Atlantic Treaty Organization
BLGG - Baby Light Gas Gun
NASA - National Aeronautics and Space Administration

Symbols

a_0 - Speed of sound for an ideal gas
γ - Ratio of specific heats
R - Universal gas constant
M - Molecular weight
T - Temperature
$v_{ideal\ max}$ - Ideal maximum velocity
A - Projectile area
m - Projectile mass
P_{gas} - Gas pressure
P_{atm} - Atmospheric pressure
f - Frictional force
x - Distance travelled by projectile
v - Projectile velocity
v_{muzzle} - Projectile velocity at the muzzle
a - Acceleration of projectile
KE - Kinetic energy
V - Volume
n - Number of moles
Γ - Factor relating specific heats
C_v - Flow coefficient
Q - Flow rate
G_g - Specific gravity
ΔP - Pressure drop
C_{drag} - Drag coefficient
N - Number of molecules
ξ - Pressure ratio
$\widehat{N}$ - Engineering constant
Z - Compressibility factor
ρ - Mass density

1 Introduction

In the following section the project will be introduced and described, covering a description of the project and the specific aims and delimitations set for the thesis. Furthermore, a literature study is presented, covering a broad range of relevant information regarding the project.

1.1 Project description

This master thesis is dedicated to find a plausible design for an acceleration test rig, which meets the requirements set by SAAB Dynamics. The project begins by developing a requirement specification and conducting a literature study, which aims to find existing solutions and methods used for test rigs with similar objectives. Three concept iterations are later conducted. The first iteration aims to conclude which method should be used to accelerate the components, the second iteration aims to decide, in a broad way, how the test rig should be designed and the third iteration seeks to evaluate different specific designs.

This thesis is to a large degree a collaborative endeavour, as this thesis and the thesis written by Axelsson. F. aims to solve the same goal, in finding a plausible design for an acceleration test rig. However, different aspects are covered in more depth in the two works. Therefore, this thesis should be read in conjunction with [1], for a complete understanding of the findings and conclusions.

1.1.1 Background

SAAB develops and produces a plethora of products, services and solutions for both military defence and civil security. Some products relevant for this thesis work are the handheld anti-armor, anti-personnel weapon systems AT4 and Carl-Gustaf, which belong to a group of products referred to as ground combat systems at SAAB Dynamics [2]. Due to the nature of the products and services that SAAB distributes, quality and assurance of function is critical, as such SAAB products are subjected to great amounts of quality control. Both AT4 and Carl-Gustaf contain several components which are of interest to test, such that the limit of their function under different conditions can be found.

1.1.2 Problem description

SAAB develops different components, which are supposed to carry out some function when subjected to a specific acceleration. Furthermore these components are designed to function in any temperature in the range from -54℃ to 71 ℃ in accordance with STANAG 4170 and AOP-20 [3, 4]. Currently SAAB conducts tests with a test rig owned by another company but that test rig has proven to be insufficient for some testing and expensive to use, thus SAAB is interested in a new test rig.

1.1.3 Purpose & aims

While the overarching purpose of this thesis is to find a plausible design for a test rig, the thesis aims to address the following:

- Develop a requirement specification, which covers and specifies the needs and wishes expressed by SAAB.
- Conduct a literature study with the broad aim of collecting valuable information regarding the design of a test rig. More specifically the literature study aims to find designs of test rigs which either expose components to high accelerations or high velocities. The literature study also aims to cover and explain the methods, components and calculations which are of importance when designing a test rig.
- Develop and evaluate different methods, by which the test rig will accelerate the components.
- Develop and evaluate different test rig concepts.
- Present a concept and future work, from which a complete test rig design can be obtained.

1.1.4 Delimitations

To limit the scope of the thesis the following points will not be considered.

- Braking and retardation of the components.
- Design of components external to the barrel and gas tank, such as the stand at which the barrel and tank will be placed and aligned on.
- Rotational stabilisation of the projectile during a launch.
- Calculations of structural rigidity for the considered components.
- Material selection for the different test rig components.
- Cost estimations for the different test rig components.

1.2 SAAB AB

Founded in 1937 under the name of Swedish Aeroplan AB with the aim of developing and manufacturing aircrafts to the Swedish military, SAAB has grown to a world leading corporation delivering defensive solutions and civil security to customers worldwide. While SAAB provides a plethora of products, five core areas stand out where SAAB is in a world leading position. SAAB is divided into five business areas, namely Aeronautics, Dynamics, Combitech, Surveillance and Kockums, where continuous improvements and innovations occur, through which SAAB has been able to achieve a world leading position with the vision of “keeping people and society safe” [5].

1.3 Ethical deliberation

SAAB produces products and services which are necessary for nations ability to protect their citizens. The way in which SAAB handles and sells their products is heavily regulated both by domestic laws and regulations, established by democratically elected representatives, and international laws and regulations set by the European Union and other international organisations. Therefore, in which hands the products and services produced by SAAB lands in, is mainly a consequence of decisions made by democratically elected representatives from Sweden and countries world wide. Whilst the products and services SAAB develops are distributed to nations in need of protection for their citizens, the damage that said products and services can inflict should not be underestimated or neglected in any way.

The author's belief is that any advancements brought by this thesis work is going towards a good cause, even though the nature of the products might be unsettling.

1.4 Confidential limitations & secrecy

Large amounts of information contained in SAAB is heavily controlled, as the information is classified in certain ways. As such details conserving SAAB products, methods and services might be excluded from this thesis work.

1.5 Current solutions

In the following section the acceleration test rig which is currently used by SAAB will be presented, as well as what the market has to offer in regards to test rigs for high acceleration and velocity.

1.5.1 Currently used acceleration test rig

Saab currently conducts acceleration tests with equipment from another company. The test rig provided by this company is a small gunpowder charged cannon, a rough illustration of it is presented in Figure 1 below.

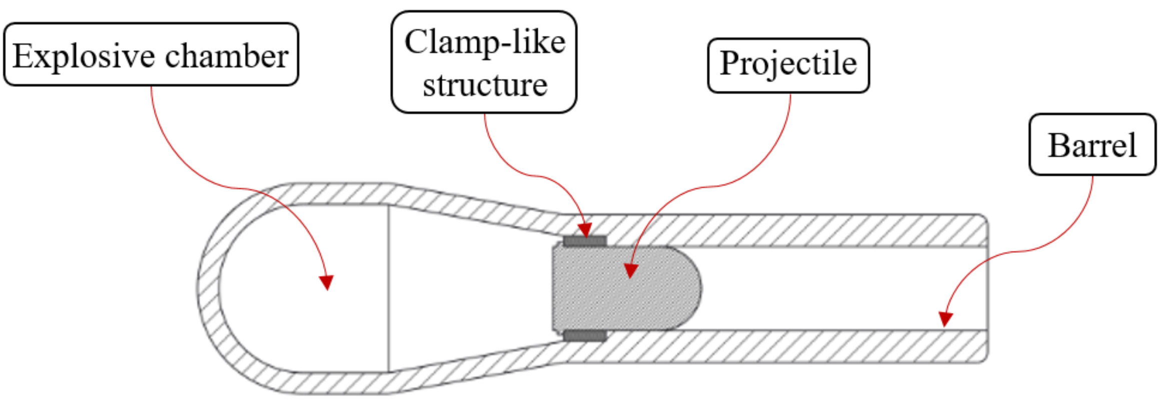


Figure 1: Illustration of gunpowder cannon currently used by SAAB, including a projectile with a deformation ring, an explosion chamber, a clamp-like structure and a barrel.

The components, which are of interest to be subject to high acceleration during a test, are placed in brass projectiles with an external diameter of 20 mm. In Figure 2 below, a schematic drawing of such a projectile can be viewed.

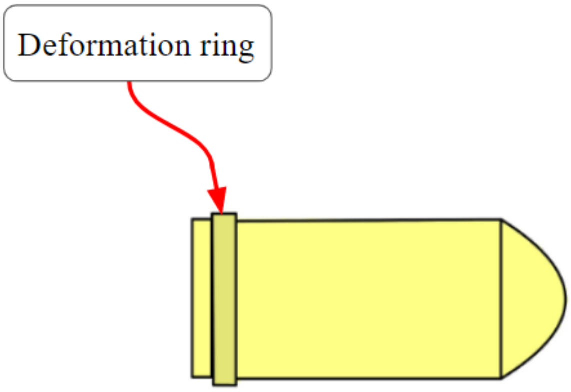


Figure 2: Brass projectiles used by Saab for acceleration tests with the aforementioned gunpowder cannon.

As Figure 2 above illustrates, the projectile is turned in such a way that an additional ring of material is present on the projectile, this ring is referred to as the deformation ring. This ring acts as a form of trigger mechanism for the cannon, since the projectile first starts to move through the barrel when this ring has been ripped apart by a clamp-like structure which is placed at the beginning of the barrel.

There are two main ways to manipulate the achieved acceleration in a launch with this canon. The first is to change the amount of gunpowder, thus changing the magnitude of kinetic energy held in the driver gas. The second is to change the amount of material in the ring, leading to a different threshold pressure for projectile movement. These manipulations have however proven to produce great variation of resulting accelerations, thus a new acceleration test rig is desired.

1.5.2 Acceleration rigs on the market

There is no abundance of acceleration test rigs on the market, largely this is a consequence of low demand and a wide variety of needs which require special designed features. However, there are a few companies which either sell acceleration rigs or equipment to acceleration rigs. Thiot is a French company, which for 30 years has designed and developed test equipment for fast dynamic studies. Thiot released Chronos in 2017, which, according to Thiot, is the first ever high-performance acceleration generator[1]. Chronos is built to expose embedded electronic systems and components in warheads to accelerations as high as 100 000Gs for testing. The detailed design and function of Chronos is not yet public knowledge, however the estimated cost of acquiring a Chronos is in the range of 700 000-1 000 000 €. Furthermore, Physics Applications Inc. is an american company which has developed different products concerning ballistic launching since 1982[2]. Physics Applications Inc. produces single stage gas guns, two stage gas guns and solid propellant guns, and they also produce rupture disks in different sizes with a variety of burst pressures.

[1] https://www.thiot-ingenierie.com/en/
[2] http://physicsapp.com/equipment.html

1.6 Literature study

The aim of this literature study is to examine different equipment and methods used to achieve high acceleration under different circumstances, this is done by gathering information from a variety of fields and applications. This literature study will start off by a broad description of acceleration testing, and further on delve deeper into relevant topics for construction of an acceleration test rig.

1.6.1 High acceleration testing

Tests and experiments which require high accelerations and high velocities are common in a couple of industries such as aerospace, civil engineering and military. In these industries high acceleration testing is required for dynamic stress-strain relationship experiments of materials [6], impact measurements of structures as well as reassuring function of mechanisms and components at high accelerations or velocities [7].

Split-Hopkinson pressure bars are commonly used to obtain dynamic stress-strain relationships for different materials. These material tests require high acceleration of some component(s), Sobczyk et al. used a pneumatic launcher to achieve sufficient acceleration for material testing in [6]. The test rig Sobczyk et al. uses can be seen in Figure 3 b) and a clarifying picture of the breach assembly can be viewed in Figure 3 a) below. In Figure 3 a) the letters (A)-(F) indicate components of the breach assembly, and in Figure 3 b) the roman numerals (I)-(V) indicate components or assemblies. In the section below these indicators will be described:

A. Projectile feeder
B. Two sealing O-rings
C. Projectile
D. Launcher barrel
E. Launcher tank
F. A hoes filling the tank with gas
G. A hoes applying pressure to the projectile

I. Breach assembly
II. Barrel
III. Measuring bars
IV. Tested sample
V. Damper

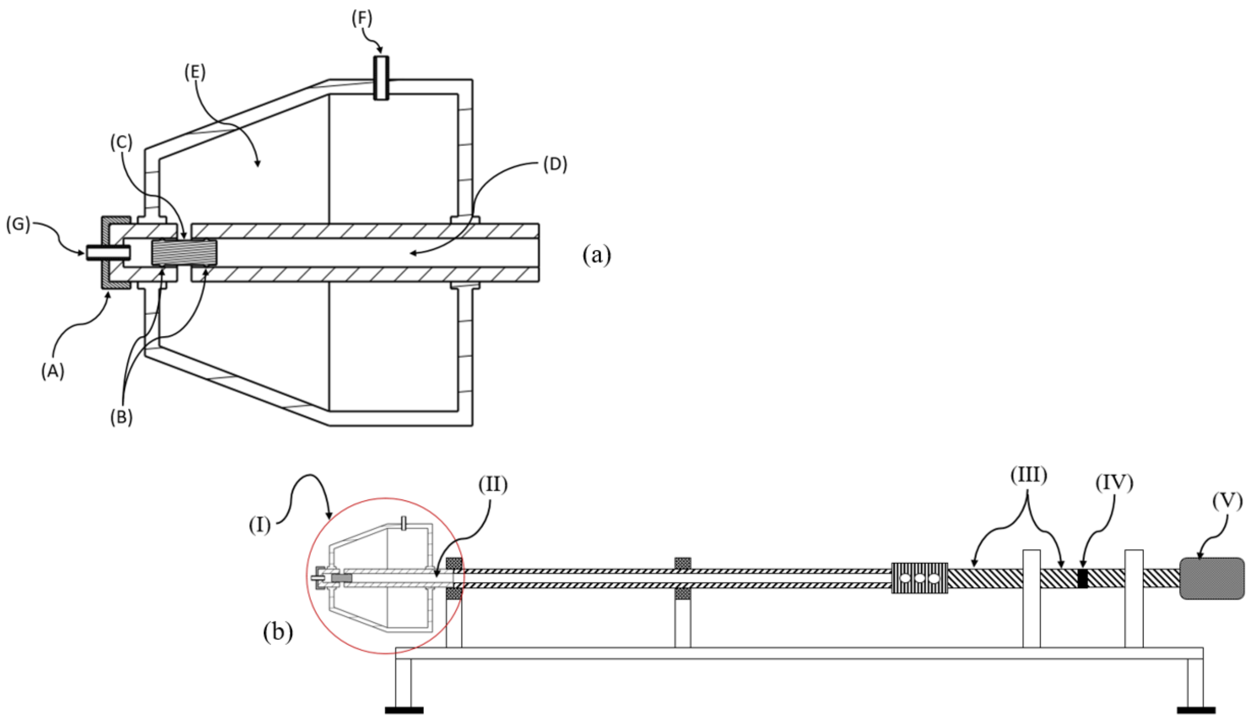


Figure 3: (a), Illustration of the breach assembly used in [6]. (b), Illustration containing the pneumatic launcher test rig with the split-hopkinson bar setup.

With this test equipment Sobczyk et al. achieved an average muzzle velocity of 21.6044 metres/second with a standard deviation of 0.6266, when launching bar-projectiles of 100 mm with a breech pressure of 1.5 bar [8].

Jonathan Fenelius developed a concept in their thesis work [9]. The objective of the thesis was to present a suitable high acceleration test method for SAAB Dynamics, due to a need for easy and cheap ways to test components such as embedded electronics and fuzes contained in other SAAB products. The most suitable concept, according to the requirements and methods used by Fenelius. J. is presented below in Figure 4.

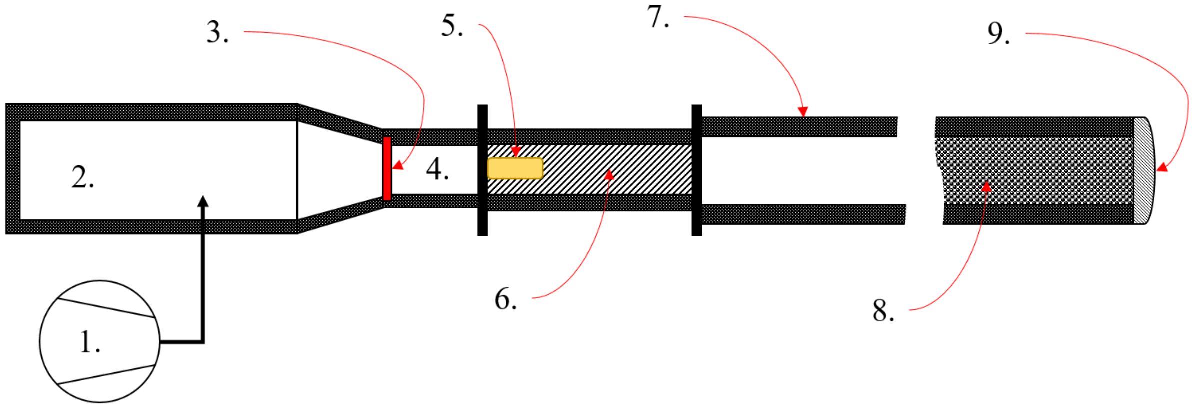


Figure 4: Final concept developed by Fenelius. J. in [9].

Where the numbers indicate the following.

1. A high-grade industrial compressor. Fenelius. J. recommends a compressor capable of producing pressures up to 300 bars to ensure that the force needed is achievable.
2. A pressure chamber. Here Fenelius. J. recommends a remodelling of an older SAAB Aeronautics pressure chamber, which is currently used to launch heavier projectiles into SAAB jets.
3. A pressure sensitive disk, often referred to as a rupture disk or a diaphragm.
4. A launch chamber that holds the test container. Fenelius. J. recommended that the design allowed the distance between the pressure sensitive disks and the test container to be changeable, to tune the acceleration curve obtained when testing.
5. A test container, in which the test object will be placed. Fenelius. J. did not develop any detailed design of the test container, and proposed further work on the subject. However, Fenelius. J. assumed that the container should be able to contain both the test component and a tachograph for data collection. Furthermore, Fenelius. J imagined that the container should be manufactured with a heel, which will generate rotation of the container when travelling through the rifled barrel.
6. A barrel, where the first section is rifled in order to generate rotation. Fenelius. J. recommended this first section of the barrel to be changeable, where either a smoothbore or a rifled barrel could be used to achieve different launches. Furthermore, Fenelius. J. preferred the barrel should be made of a steel with high hardness, to withstand the wear caused by many launches.
7. The second section of the barrel has a larger diameter such that the test container flies freely without contact with the barrel. The total length of both sections of the barrel is estimated to reach upwards to 15 metres.
8. In the second section of the barrel, foam or a material constructed with honeycomb structure breaks the test container until it reaches rest.
9. A removable end, which simplifies the removal and refilling of braking material after each launch. The end will be designed as a flange with high-grade screws.

1.6.2 Pneumatic launchers

Pneumatic launchers, sometimes referred to as gas cannons or gas guns, are commonly used for material testing. Pneumatic launchers can generally be described with the following components, a pressurised gas, a vessel or a tank which contains the gas, a trigger mechanism which releases the gas from the vessel, a barrel where the gas travels after the trigger mechanism has been activated, and lastly a projectile which is placed somewhere in the barrel and accelerates due to the pressure applied by the gas. According to Sobczyk et al. five properties are useful to categorise pneumatic launchers, which is presented by a scheme in Figure 5 below.

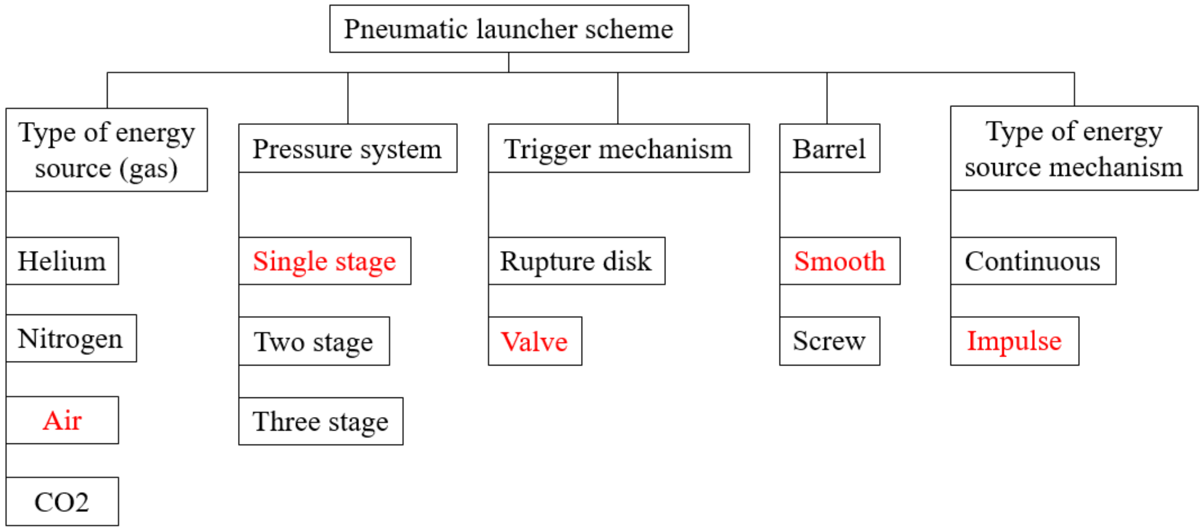


Figure 5: Example of a scheme of division into categories of a pneumatic launcher system according to Sobczyk et al.

The scheme division in Figure 5 corresponds to the pneumatic launcher in Figure 3 a). Even though this scheme covers far from all the details that should be taken into account when designing a new launcher, the scheme indicates some of the most critical design decisions to be made when designing a pneumatic launcher [8].

1.6.2.1 Gases used for pneumatic launchers

There are plenty of gases which could be used as the driving gas in pneumatic launchers. The following four are however the most common; air, nitrogen, helium and hydrogen [10]. One of the most important properties of the gas is its ability to quickly travel through a barrel carrying pressure, where the limiting factor is the sound speed of the gas, given by equation (1.1).

$$a_0 = \sqrt{\frac{\gamma R T}{M}} \quad (1.1)$$

Where a_0 is the sound speed of an ideal gas, $R = 8.314 \frac{J}{mole*K}$ is the universal gas constant, T is the temperature of the gas, M is the molecular weight and γ is the ratio of specific heats for the gas [11].

Henri Bernier provides a simplified equation in [12], presented in equation (1.2), which further illustrates the importance of sound speed for maximum launch capabilities. The equation is derived from a model which considers a one-dimensional barrel, where the reservoir or gas tank has the same diameter as the barrel, where the gas flow is assumed to be isentropic and the behaviour of the gas is given by a perfect gas equation of state with constant specific heats. It is also assumed that the length of the reservoir is long enough so that the rarefaction fan coming from the rear face does not catch up to the projectile during launch, furthermore losses by friction, heat transfer, etc. are not taken into account.

$$p = p_0 \left[1 - \frac{\gamma-1}{2a_0} v\right]^{\frac{2\gamma}{\gamma-1}} \tag{1.2}$$

Where p is the base pressure, and describes the pressure applied on the projectile by the gas after a certain time, p_0 is the initial gas pressure and v is the velocity of the projectile.

The equation manages to show how the pressure in the gas converts into velocity of the projectile in an ideal situation. From this equation the maximum projectile velocity achieved through a launch by pressurised gas can be obtained, by assuming that the base pressure p, the pressure applied by the gas on the projectile, will be zero when the projectile reaches the muzzle one obtains the following relationship:

$$\left[1 - \frac{\gamma-1}{2a_0} v\right] = 0 \quad \Leftrightarrow \quad v_{ideal\,max} = \frac{2a_0}{\gamma-1} \tag{1.3}$$

The ideal maximum velocity is an important property to take into account when choosing the right gas, however, there are further properties of these gases that have to be taken into account. Hydrogen is considered hazardous, being an extremely flammable gas when pressurised, which can complicate the design and manoeuvring of the test rig [13]. Moreover, the price and availability of these gases vary, whilst helium is expensive, nitrogen is readily available and cheap [10].

1.6.2.2 Pressure systems and trigger mechanism

Common to all types of pneumatic launchers is a pressure system, however there are some differences in design and function. The pressure system is composed of the components and mechanisms in the pneumatic launcher that contains and releases the gas. Two critical components of a pressure system are the gas tank, which holds the pressurised gas, and the trigger mechanism which releases the gas from the tank.

Pressure systems can be categorised in different ways, one common categorization is single, two and three stage pressure systems. Three common types of single stage pressure systems are presented in Figure 6 below:

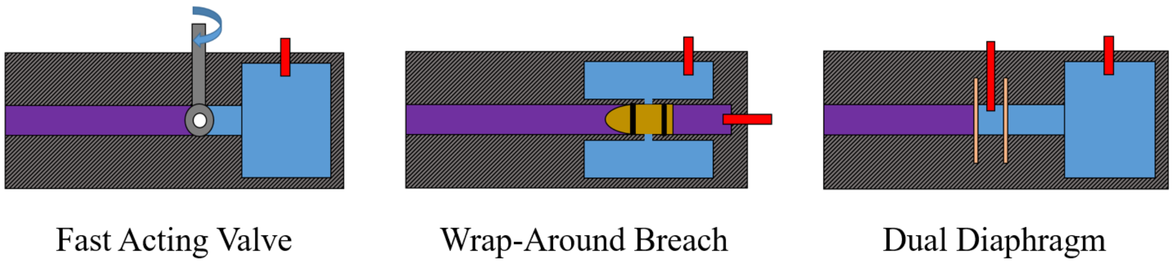


Figure 6: Figure containing single stage pressure systems, to the left a single stage valve activated pressure system, in the middle a wrap-around breach assembly and to the right a dual diaphragm activated breach assembly [10].

The leftmost pressure system in Figure 6 the pressurised gas, coloured blue, travels from the tank to the barrel, coloured purple, when a fast acting valve opens. In this system the fast acting valve acts as a trigger mechanism by regulating when and how the gas propagates from the tank to the projectile.

The pressure system in the middle of Figure 6 is a design which is often referred to as wrap-around breach assembly. In the wrap-around breach assembly the gas tank is wrapped around the barrel. Due to two O-rings placed on the projectile the gas does not travel through to the barrel until the projectile moves. To initiate the launch a pressure is added at the rear end of the projectile through an inlet, this results in the projectile moving and the gas can travel along to the barrel further accelerating the projectile.

The pressure system to the right in Figure 6 is a dual diaphragm breach assembly. The pressure system relies on diaphragms, often referred to as rupture disks, as a trigger mechanism. A rupture disk is a pressure sensitive thin sheet of metallic or plastic material, designed to rupture when a certain pressure difference between the up and downstream gas is reached. In Figure 6 a dual or double diaphragm solution is presented, however a single diaphragm pressure system could be used as well. For a single-diaphragm assembly the operator has to select a diaphragm that ruptures at the pressure which will lead to the desired acceleration of the projectile. Whereas with a double-diaphragm assembly the operator can control the gas pressure between the diaphragms. By carefully controlling the gas pressure outside and between the diaphragms, the operator can achieve different accelerations of the projectile.

To obtain higher pressures in the pneumatic launcher, which in turn can lead to higher acceleration and velocity of the projectile, a two or three stage system can be used. In a two stage pressure system, a piston is placed between the gas tank and the projectile. Resulting in two working gases, one that drives the piston, and a second that drives the projectile. Such a pressure system is used at Fraunhofer Ernst-Mach-Institut in their Baby Light Gas Gun, or BLGG. The working principles of BLGG can be viewed in Figure 7 below.

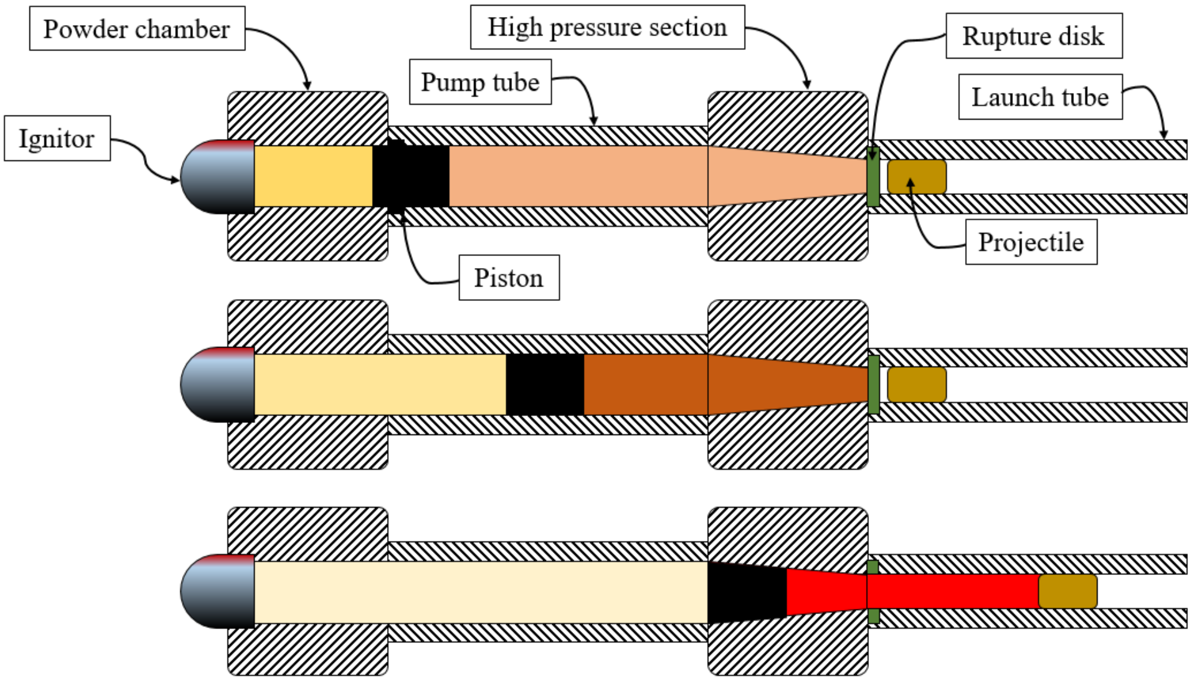


Figure 7: Illustration of the working principles of BLGG [14].

The piston in BLGG is driven by combustion of a nitrocellulose based propellant. The piston in a two stage pressure system could however be driven by pressurised gas, by replacing the powder chamber and propellent gas by any of the aforementioned single stage pressure systems. In the BLGG the combustion of the propellant leads to high levels of kinetic energy in the gas which drives the piston. The piston then pushes a column of light gas, either hydrogen or helium, in a pump tube. The compressed light gas then penetrates a diaphragm when sufficient pressure is accomplished, which in turn accelerates the projectile. By this method the BLGG is able to launch projectiles up to 9 km/s, and during such launches components of the gun can be subjected to pressures above 1 GPa [14].

Under NASA;s sponsorship a three stage light gas launcher was developed at McGill University, of which a schematic drawing is presented in Figure 8 below.

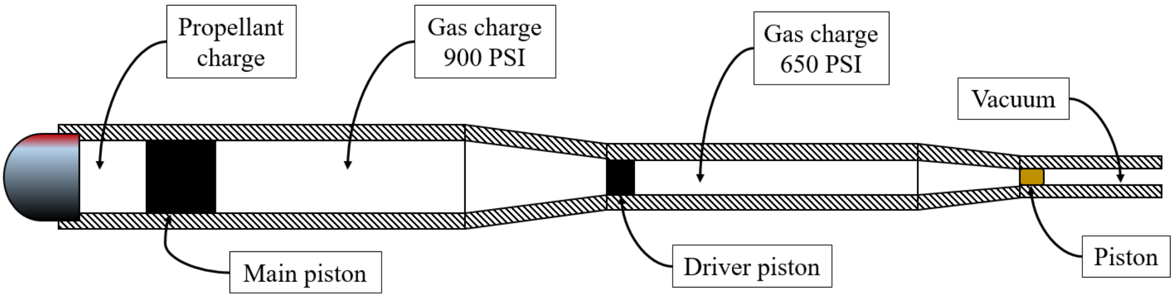


Figure 8: Schematic drawing of McGill University´s three stage light gas launcher.

The three stage light gas launcher at McGill University works much in the same way as the BLGG at Fraunhofer Ernst-Mach-Institut. However, to reach even higher projectile velocities another piston is introduced, leading to a pressure system with a main piston and a driver piston [7].

While the advantage of a two or three stage pressure system is clear, in being able to reach higher projectile accelerations and velocities, there are some disadvantages at least from a cost per launch perspective. Firstly, the pistons used in two or three stage systems are usually heavily deformed after a launch, leading to a need to frequently replace them. Secondly, multistage pressure systems usually rely on many burst disks to achieve the right launching conditions, which in turn leads to further expenses. Furthermore, the time between launches is also likely to increase, as there are more parts of the launcher which have to be disassembled and reassembled to replace burst disks and pistons.

1.6.3 Calculations for gas guns

In the following section some commonly occurring calculation methods and assumptions regarding projectile dynamics launched from gas guns will be presented.

1.6.3.1 Projectile dynamics

Depending on the objective of the test rig, different information regarding the dynamics of the projectile during a launch can be of interest. Commonly either the projectile muzzle velocity, the velocity of the projectile as it leaves the barrel of the gun, or the acceleration of the projectile throughout the launch is of interest to estimate. If sufficient information about the gas that pushes the projectile is known, both projectile muzzle velocity and projectile acceleration can be calculated with the help of Newton's second law.

$$F = PA = ma \tag{1.4}$$

Where the force F is equal to the pressure P asserted by the gas multiplied by the area A of the rear surface of the projectile. m is the mass of the projectile which accelerates with the magnitude of a . This is however a simplification, since the frictions between the projectile and the barrel as well as the pressure of the gas in front of the projectile is neglected. Rohrbach et al. uses the following equation to describe the dynamics of the projectile, where the friction f is assumed to be constant and pressure in front of the projectile is assumed to be the atmospheric pressure P_{atm} [15].

$$a = \frac{A}{m}(P_{gas} - P_{atm}) - \frac{f}{m} \tag{1.5}$$

Once the acceleration a is found, the velocity v and position x of the projectile is usually obtained through stepwise integration with respect to time t by the following equations.

$$v_{k+1} = v_k + a_{k+1}t \tag{1.6}$$

$$x_{k+1} = x_k + v_{k+1}t + \frac{1}{2}a_{k+1}t^2 \tag{1.7}$$

Where $k + 1$ indicates the next step.

1.6.3.2 Gas modelling

A proper gas model is crucial for the estimation of projectile dynamics, as the pressure of the gas is directly related to the acceleration of the projectile. There are however many different ways to model the gas as it evolves throughout a launch, in the following section some common gas models will be presented.

Isobaric model.

One of the simplest models is found by assuming that the gas is subjected to an isobaric process, meaning that the pressure of the gas is constant throughout the launch [16]. Implying that the gas pressure P_{gas} will be equal to the initial pressure of the gas $P_{initial}$.

$$P_{gas} = P_{initial} = constant$$

If one assumes, as Rohrbach et al. did in [15], that both the pressure of the gas in front of the projectile and the frictional force f is constant then the acceleration will be constant as well.

$$a = \frac{A}{m}(P_{initial} - P_{atm}) - \frac{f}{m} = constant \tag{1.8}$$

If the length of the barrel L is known, then the launch time t can be obtained through the use of equation (1.7).

$$x(t) = L = x_0 + v_0 t + \frac{1}{2} a_0 t^2 \tag{1.9}$$

Where,

$$x_0 = v_0 = 0$$

and,

$$a_0 = \frac{A}{m}(P_{initial} - P_{atm}) - \frac{f}{m}$$

Resulting in the following launch time t, which describes the time it takes for the projectile to reach the muzzle from the initiation of the launch.

$$t = \sqrt{\frac{2Lm}{A(P_{initial} - P_{atm}) - f}} \tag{1.10}$$

The projectile velocity is calculated by the usage of equation (1.6), and by the help of previously calculated launch time t the muzzle velocity v_{muzzle} is known.

$$v_{muzzle} = \left[\frac{A}{m}(P_{initial} - P_{atm}) - \frac{f}{m}\right]\sqrt{\frac{2Lm}{A(P_{initial} - P_{atm}) - f}} = \sqrt{\frac{2LA}{m}(P_{initial} - P_{atm}) - \frac{2Lf}{m}} \tag{1.11}$$

The isobaric model is simple, however it is also inaccurate since the pressure of the gas will decrease greatly throughout the launch [10].

Isothermal model.
Another way of modelling the gas is to assume that the gas undergoes an isothermal process, as it pushes the projectile throughout the launch. An isothermal process, which implies that the temperature of the gas is constant throughout the launch [16], allows for a kinetic energy approach to the calculations. If the gas in front of the projectile is neglected, the kinetic energy of the projectile can be described in the following way.

$$KE = \int_{V_i}^{V_f} P_{gas} dV - \int_0^x f dx = \frac{1}{2}mv^2 \tag{1.12}$$

Where KE is the kinetic energy, x is the length at which the projectile has exerted frictional force to the barrel, V_i is the initial volume of the gas and V_f is the final volume. By introducing an equation of state, here the ideal gas law which is expressed in equation (1.13) is used for simplicity, the kinetic energy can be expressed in the following way.

$$PV = nRT \Leftrightarrow P = \frac{nRT}{V} \tag{1.13}$$

$$KE = \int_{V_i}^{V_f} \frac{nRT}{V} dV - \int_0^x f dx$$

With the new expression for the kinetic energy, expressed above, the integration can be conducted which results in the following.

$$KE = nRT \cdot ln(\frac{V_f}{V_i}) - fx \tag{1.14}$$

Where, the final volume V_f is equal to the initial volume V_i and the added volume caused by the projectile travelling down the barrel a length x.

$$V_f = V_i + Ax$$

Furthermore, since the process is isothermal the whole term nRT is constant throughout the launch and can therefore be replaced by the known initial volume V_i and initial pressure P_i by equation (1.13)

$$P_i V_i = nRT = constant$$

Simplifying equation (1.14) to the following.

$$KE = V_i P_i \cdot ln(\frac{V_i + Ax}{V_i}) - fx = \frac{1}{2}mv^2 \tag{1.15}$$

From which the velocity of the projectile can be obtained as a function of x, which in turn can describe the dynamics of the projectile [10].

$$v(x) = \sqrt{\frac{2}{m}\left(V_i P_i \cdot ln\left(\frac{V_i+Ax}{V_i}\right) - fx\right)} \tag{1.16}$$

Adiabatic model.
Yet another way to model the gas, is to assume that the gas during the launch undergoes an adiabatic process. An adiabatic process is defined as a thermodynamic process where no heat or mass is transferred from the system to the surrounding environment [16]. With an adiabatic model the projectile dynamics can be found much in the same way as with the isothermal model, which starts off by expressing the kinetic energy of the projectile and once again neglecting the pressure of the gas in front of the projectile.

$$KE = \int_{V_i}^{V_f} P_{gas} dV - \int_0^x f dx = \frac{1}{2}mv^2 \tag{1.17}$$

For adiabatic processes the following expression, relating pressure P, volume V and specific heat γ of the gas is assumed to be constant.

$$PV^\gamma = constant = C \Leftrightarrow P = \frac{C}{V^\gamma} \tag{1.18}$$

By substituting P_{gas} in equation (1.17) with the expression given by equation (1.18) the kinetic energy can be integrated resulting in the following expression.

$$KE = c\frac{V_f^{1-\gamma} - V_i^{1-\gamma}}{1-\gamma} - fx = \frac{1}{2}mv^2 \tag{1.19}$$

Once again the final volume V_f can be expressed as the initial volume V_i with added volume caused by the travelled distance by the projectile x.

$$V_f = V_i + Ax$$

And the constant C can be expressed by the known initial pressure P_i and volume V_i resulting in the following expression for the projectile velocity as a function of x [10].

$$v = \sqrt{\frac{2}{m}\left(\frac{P_i V_i^\gamma}{1-\gamma}\left(\left(V_i + Ax\right)^{1-\gamma} - V_i^{1-\gamma}\right) - fx\right)} \tag{1.20}$$

Other models.
As stated previously there are many ways to model the gas, the isobaric, isothermal and adiabatic assumptions are simple methods which quickly describe the dynamics of the projectile. According to [10], the adiabatic assumption is preferable, since it describes the gas propagation in better accordance with reality compared to the isobaric and isothermal assumptions. There are however more sophisticated models, which aim to include more physical properties and phenomena which the aforementioned simpler models neglect.

To find a better gas model, the gas cannot be treated as a uniform gas where the state properties are uniform throughout the whole body of gas. Instead, the gas model has to take into account the fact that the body of gas will contain different state properties in different sections of the body of gas, as the gas propagates through the barrel. In [17] a model called Lagrange Gradient is developed, which builds on the continuity equation for a compressible fluid, which is expressed for one dimension in equation (1.21) below.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_g}\left(\rho V_{x_g}\right) = 0 \tag{1.21}$$

Where ρ is the density, t is time, x_g denotes the x-location measured from the mass centre of the gas behind the projectile to some reference and V_{x_g} is the velocity of gas.

The Lagrange Gradient model, which is derived to completion in [17], results in better estimations of the projectile dynamics than the previously described models according to [10].

Furthermore, different codes and softwares have been developed over time to model the performance of different types of launchers. With the added computational ability that computer simulations now allow for, more physical phenomena can be accounted for. One example of such a software can be viewed in [18], which was developed at NASA Ames Research Center to simulate two stage light gas guns. Some of the things that the NASA software can account for are the creation and propagation of shockwaves, the burn time of the gunpowder, different geometries of tanks, barrels and pistons, the friction between projectile and barrel as well as the friction between piston and its surrounding pipe and the viscous effects which occur in the barrel.

1.7 Alternative trigger mechanisms

There are alternatives to the previously mentioned trigger mechanisms, which accomplishes the same goal in the sense that these alternative trigger mechanisms also lead to higher acceleration. Whereas trigger mechanisms aim to contain and release the gas when the right launch conditions are met, alternative trigger mechanisms aim to release the projectile when the right launch conditions are met. Alternative trigger mechanisms can be used either as a substitute to a trigger mechanism or in conjunction with one or several trigger mechanisms. In the following section some types of alternative trigger mechanisms will be presented.

Deformation rings: Deformation rings are a commonly used alternative trigger mechanism. Deformation rings can be placed on any critical moving part in the test rig, in the case of the test rig which SAAB currently uses the deformation ring appears as a consequence of the manufacturing on the projectile, and in the case of the BLGG the deformation ring is positioned on the piston instead. Two properties of deformation rings which make them useful are that they do not require a lot of space, which make them fit in many designs and reduce the material costs, and that deformation rings do not obstruct the area at which the gas pressure is supposed to act on. However, depending on how well the deformation ring is removed for the component, the remnants of the deformation ring can lead to high amounts of wear on the surrounding pipe or barrel.

Shear pins: Shear pins are not as common as deformation rings even though they share a lot of properties. This is due to the fact that shear pins often occupy more space which can limit the design options, furthermore the shear pin occupies space in front of the projectile which obstructs the gas. However, shear pins can be designed in such a way that they do not wear on any surrounding surfaces, which is of importance if the test rig is supposed to accomplish many launches.

Explosive bolts: Explosive bolts are in contrast to the aforementioned alternative trigger mechanism not actuated by mechanical failure, i.e. releasing the projectile and actuating the launch by some component like a deformation ring or a shear pin breaking. Instead explosive bolts are actuated by combustion by some explosive material placed inside a bolt which is connected to the projectile. In certain circumstances a combustion actuated alternative trigger mechanism is advantageous, since the operator has better control over the point at which the launch will initiate, however combustions can be dangerous and lead to more requirements which the test rig has to meet.

2 Theory

In the following section the theoretical framework is presented, which aims to lay the theoretical foundation for the following method section. The theoretical framework covers properties of gases and mechanical components, and describes the product development procedure, furthermore calculation models are presented for a valve based and a rupture disk based design which aims to describe the dynamics of a launched projectile.

2.1 Van der Waals equation of state

If a system of gas were to undergo no change, and all the properties of the gas could be measured and calculated throughout the entire system, a complete description of the condition or the state of the system would be obtained. To calculate properties of a system an equation of state can be used. Any equation that relates the temperature, pressure and specific volume of a substance is called an equation of state. A commonly used equation of state for gases is the ideal-gas law, presented in equation (2.1) below.

$$Pv = RT \tag{2.1}$$

Where P is the pressure of the gas, v is the specific volume, R is the gas constant and T is the temperature.

The Van der Waals equation of state was proposed in 1873, and sought to improve the ideal-gas equation of state by including two effects that are neglected in the ideal-gas model. Firstly the intermolecular attraction forces between the molecules in the gas, and secondly the volume occupied by the molecules themselves. The Van der Waals equation of state is presented below in equation (2.2).

$$(P + \frac{a}{v^2})(v - b) = RT \tag{2.2}$$

Where a and b are the Van der Waals constants, and the term $\frac{a}{v^2}$ accounts for the intermolecular forces while b represents the volume occupied by the molecules in the gas [16].

2.2 Properties of gases used in pneumatic launchers

As stated in the literature study, the most commonly occurring gases for pneumatic launchers are air, hydrogen, nitrogen and helium. In Table 1 below, the ideal maximum velocity for these different gases are presented by usage of equation (1.3).

Table 1: Specific heat γ, speed of sound a_0 and ideal maximum velocity $v_{ideal\ max}$ for different gases.

gas	γ	$a_0 [m/s]$	$v_{ideal\ max} [m/s]$
Helium	1.663	973 at 0℃	2926
Hydrogen	1.406	1320 at 27℃	6197
Nitrogen	1.400	354 at 29℃	1715

In Table 2 below, all the gas properties that were used in the calculations are presented. These properties are the Van der Waals constants a and b as well as the molar mass M.

Table 2: Calculation properties for helium, hydrogen and nitrogen.

gas	$a\ [bar * L^2/mol^2]$	$b\ [L/mol]$	$M\ [kg/kmol]$
Helium	0.0346	0.0238	4.003
Hydrogen	0.2453	0.0265	2.016
Nitrogen	1.370	0.0387	28.013

2.3 Adiabatic process

A process during which no heat transfer is occurring is called an adiabatic process. Kumar et al. provides solutions in [19] to describe a Van der Waals gas undergoing an adiabatic process. Kumar et al. showed that the Van der Waals equation of state for an adiabatic process can be described in the following way.

$$(P + \frac{an^2}{V^2})(V - nb)^{\Gamma} = Constant \tag{2.3}$$

With the following alternative forms.

$$T(V - nb)^{(\Gamma-1)} = Constant \tag{2.4}$$

$$(P + a\frac{n^2}{V^2})T^{\frac{\Gamma}{1-\Gamma}} = Constant \tag{2.5}$$

In contrast to equation (2.2), where the Van der Waals equation of state was described with the specific volume v, the specific volume is here described with the volume V and the number of moles n of the gas instead. Here Γ is a factor which relates the specific heat at constant volume and pressure. Where the relation between Γ and the ratio of specific heat γ is the following.

$$\gamma = 1 + \frac{\Gamma-1}{f_v} \tag{2.6}$$

Were

$$f_v = 1 - \frac{2na}{RTV^3}(V - nb)^2 \tag{2.7}$$

2.4 Valves

Valves are mechanical devices that control the flow of fluids such as gases, liquids, or slurries by opening, closing, or partially obstructing different flow paths. They are widely used in various applications, ranging from industrial processes and chemical plants to consumer goods and household appliances. Different types of valves exist, such as ball valves, gate valves, globe valves, butterfly valves and needle valves, each with their own advantages and limitations. Some important properties of valves are the following [20].

Operating pressure: Which refers to the maximum pressure at which the valve can operate effectively, without any structural damage. The operating pressure varies between valves depending on the type, size and design [20].

Switch time: Which refers to the time it takes the valve to transition from a fully closed state to a fully open state, or vice versa. The switch time of any particular valve is influenced by multiple parameters, such as the pressure of the fluid, the size of the valve and the type of actuator used in the valve. Furthermore, the fluid flow during the time that the valve transitions from a fully closed state to a fully open state is dependent on the type of actuator used in the valve. Generally, the flow, during the time the valve switches, can be categorised into one of three flow characteristics, either quick-open, linear or equal percentage. In Figure 9 below the flow, as a percentage of the maximum flow, is plotted for a quick-open, linear and equal percentage valve against the valve lift which indicates how open the valve is [20].

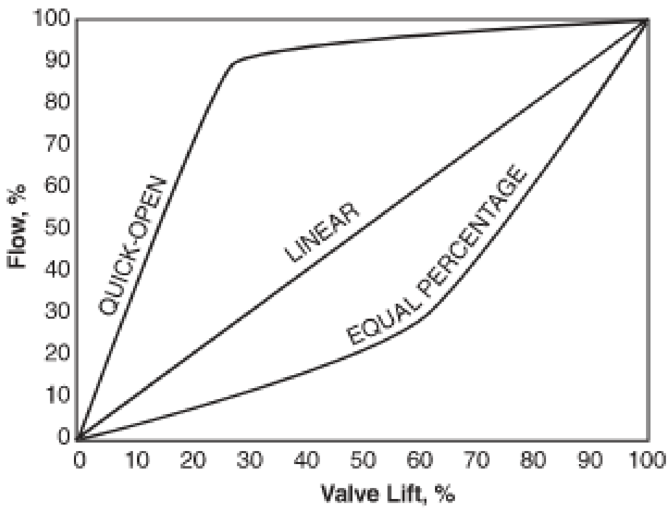


Figure 9: Typical flow characteristics, during the transition time from fully closed to fully open.

Flow coefficient, C_v: The flow coefficient C_v of a valve is a measurement of a particular valve's capacity to allow fluid to flow through it. The flow coefficient is a unitless parameter, which is defined by the volume of water at 15.6℃ that can pass through the valve in 60 seconds under a pressure drop of 1 psi. The flow coefficient C_v is largely depending on the size, shape and the design of valve, and is an important parameter for valve calculations and valve selection. To calculate the value of C_v the following equation is used.

$$C_v = Q\sqrt{\frac{G_g}{\Delta P}} \tag{2.8}$$

Where Q is the flow rate, G_g is the specific gravity of the fluid and ΔP is the pressure drop over the valve [20].

2.5 Rupture disks

Rupture disks used in different gas guns are usually made of mylar, steel, aluminium, copper or bronze. In the gas guns the rupture disks are commonly placed in the junction of two pressure chambers, such as in between the gas tank and the barrel, and works as a sort of valve which allows the fluid to travel along once the right conditions are met. Rupture disks can have different geometries, commonly rupture disks are flat and circular, however there are also hemispherically shaped rupture disks. Hemispherically shaped rupture disks are at an advantage since their geometry allows for higher burst pressures and faster opening time. However, the added manufacturing steps can increase the cost as much as five times compared to a flat design, where high pressure flat rupture disks already cost about $50 each. Furthermore, rupture disks are usually designed with grooves, which provide two functions. Firstly, the grooves provide an area for the stress to concentrate, which makes the disks burst in a reliable way. Secondly the grooves are often formed in such a way that the disks burst open like a petal, referred to as petalopening, which is advantageous for the flow of the fluid through the opened disk.

To select a rupture disk for a certain gas gun application the following approximative burst pressure relationships can be used for hemispherical and flat disks, respectively.

$$\frac{P_{burst}}{E} = 2\left(\frac{\sigma_{ult}}{E}\right)\left(\frac{d}{t}\right)\left(\frac{t}{a}\right) \tag{2.9}$$

$$\frac{P_{burst}}{E} = 2\left(\frac{\tau_{ult}}{E}\right)\left(\frac{t}{a}\right) \tag{2.10}$$

Where E is the modulus of elasticity, d is the thickness of the material left at the bottom of the groove, t is the thickness of the disk sheet material, a is the radius of the unsupported disk area, P_{burst} is the pressure at which the disk bursts and σ_{ult} and τ_{ult} indicates the ultimate strength in tension and shear.

In the following plot, which can be viewed in Figure 10, burst pressure is plotted against the thickness ratio $\left(\frac{t}{a}\right)$ for hemispherical and flat disks manufactured from stainless steel 304 and 305. These curves facilitate rupture disk design and selection, by providing the relationship between a disks burst pressure and a possible geometry [10, 21].

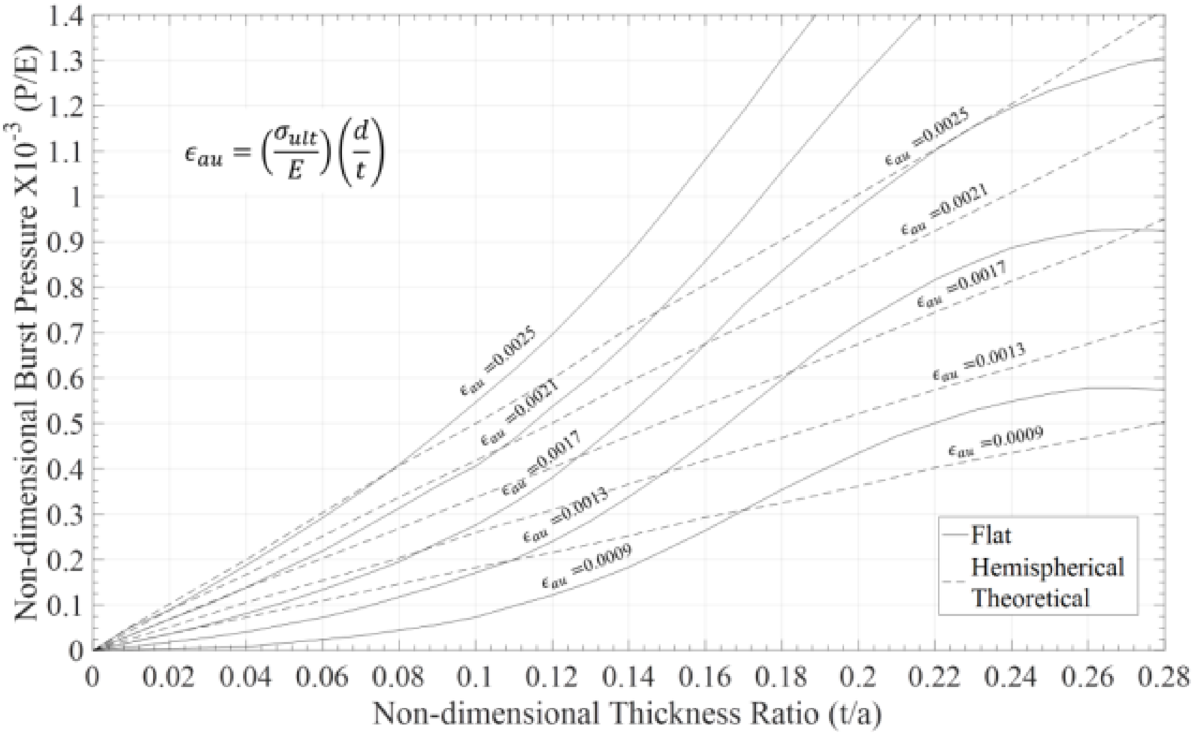


Figure 10: Burst pressure vs thickness ratio for different apparent ultimate strain ϵ_{au} *values for flat and hemispherical rupture disks, where the flat disk values are experimentally found and the hemispherical disk values are theoretical.*

Furthermore Andrews, D.R. found an expression in [22] which gives an estimation of the opening time of a rupture disk without groves. Given that rupture disks are held firmly in place by gas-tight seals, which leaves a circular cross section of the rupture disk open for the gas to apply pressure to the disk, the disk will deform into part of a sphere until it eventually bursts. Examination of bursted rupture disks indicates that they fail as a consequence of a ductile fracture initiated at some point along the circle of contact with the gas-tight seals. A tear then propagates along the circle of contact, which allows the central section of the disk to rotate about any part of the circumference which still remains intact. The following equation of motion describes a disk rotating about an axis tangential to its circumference, due to a force acting in through the centre of the disk.

$$I\frac{d^2\theta}{dt^2} = \pi a^3 cos(\theta)\Delta P \qquad (2.11)$$

Where ΔP describes the pressure difference over the rupture disk, θ is the angle of rotation, a is the radius from the centre of the disk to the circumference and I is the moment of inertia of the disc which is calculated by the following formula.

$$I = \frac{1}{4}\pi a^2 \rho L(\frac{1}{3}L^2 + 5a^2) \qquad (2.12)$$

Where L is the thickness of the disk and ρ is the mass density of the disk material. By solving for opening time t in equation (2.11) the following expression is obtained.

$$t = \sqrt{\frac{I}{2\pi a^3 P}} \int_0^{\pi/2} \frac{d\theta}{\sqrt{\sin\theta}} \tag{2.13}$$

It is important to note that the upper limit of the integration represents a fully open rupture disk. Therefore, the opening time t given by equation (2.13) should be regarded as the maximum opening time, where the rupture disk in practice might be effectively open before the position represented by the upper limit of the integral have been reached.

2.6 Valve based model

One potential design solution to accelerate the projectile, is to use a valve as the trigger mechanism. Such a design of a pneumatic launcher simply consists of a gas tank, a barrel and a valve which allows the gas to travel from the tank to the barrel where the projectile is placed. Rohrbach et al. present a couple of methods in [15] that can be used to calculate the dynamics of the projectile in such a model. In Figure 11 below an illustration of the model can be viewed.

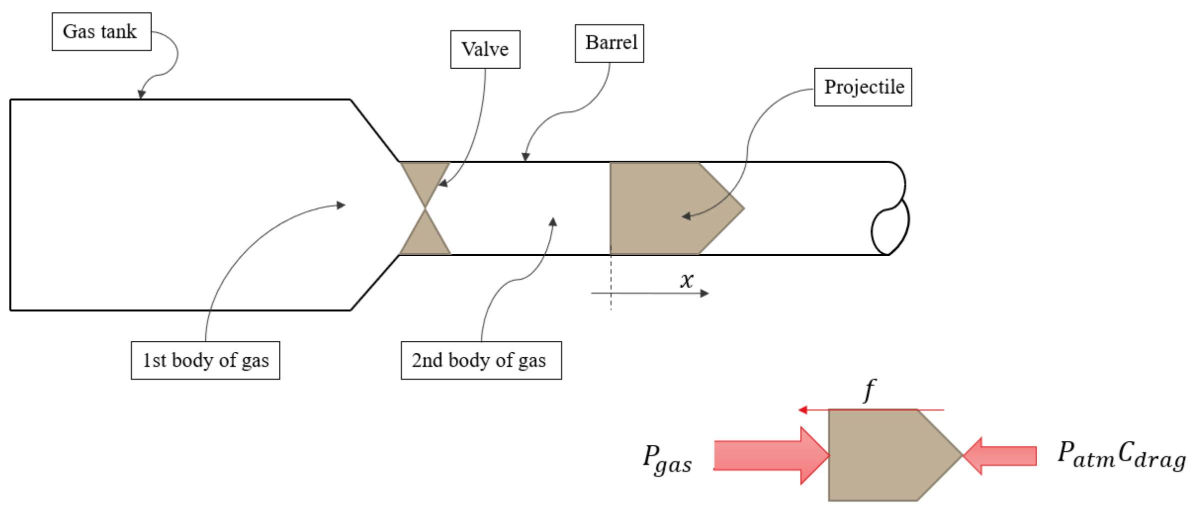


Figure 11: Illustration of the valve based model, consisting of a gas tank, valve, barrel, projectile and two bodies of gas. Where the first body of gas is present in the gas tank and the second body of gas occupies the volume between the valve and the projectile.

Newton's second law describes the acceleration of the projectile:

$$a = \ddot{x} = \frac{A}{m}(P_{gas} - P_{atm}C_{drag}) - \frac{f}{m} \tag{2.14}$$

Where P_{gas} is the pressure asserted by the gas upon the projectile, the pressure of the gas in front of the projectile in the barrel is assumed to be the atmospheric pressure P_{atm}, the frictional force is assumed to be constant and described by f, C_{drag} is the drag coefficient of the projectile, furthermore m is the mass of the projectile and A is the area of the projectile which the gas is acting upon.

To describe P_{gas} an equation of state is needed, here Rohrbach et al. used the ideal gas law. However in this model equation (2.2) is used instead, since the Van der Waals equation of state neglects less physical phenomena.

$$(P + \frac{an^2}{V^2})(V - nb) = nRT \tag{2.2}$$

In this model the Van der Waals equation is used for two bodies of gas. The first body of gas is present in the gas tank, this gas will throughout a launch travel through the valve into the barrel. The second body of gas occupies the space between the valve and the projectile in the barrel, the initial pressure of this gas is assumed to be at atmospheric pressure, then the pressure will increase due to the flow of gas through the valve. Whereas the volume of the first body of gas is constant, given by the measurements of the tank, the volume of the second body of gas will increase as the projectile moves through the barrel. Furthermore, both gases are assumed to be homogeneous in the sense that the pressure, temperature and density is assumed to be uniform throughout the whole body of gas.

$$(P_T + a\frac{n_T^2}{V_T^2})(V_T - n_T b) = n_T RT \tag{2.15}$$

$$(P_{gas} + a\frac{n^2}{(V_0+Ax)^2})((V_0 + Ax) - nb) = nRT \tag{2.16}$$

In equation (2.15) which describes the first body of gas, P_T is the pressure of the gas in the tank, n_T is the number of moles in the gas and V_T is the volume of the tank. In equation (2.16) which describes the second body of gas, P_{gas} is the pressure of the gas, which also pushes the projectile, V_0 is the initial volume in the barrel between the valve and projectile, Ax describes the added volume of the gas due to the projectile moving down the barrel and n is the number of moles in the gas. In both equation (2.15) and (2.16), a and b are Van der Waals constants for the gas.

The number of molecules in the tank N_T and in the barrel N are governed by the flow of molecules through the valve Q. Where the following relationships connected equation (2.15) and (2.16).

$$\frac{\partial N}{\partial t} = -\frac{\partial N_T}{\partial t} = Q \tag{2.17}$$

To describe the flow of molecules Q Rohrbach et al. introduces a new variable ξ, which describes the ratio between the pressures of the gases upstream and downstream of the valve. ξ is defined in the following way by Rohrbach et al.

$$\xi \equiv \frac{P_T - P_{gas}}{P_T} \tag{2.18}$$

At some point throughout a launch the ratio ξ will reach a maximum value, this maximum value is indicated by ξ_{max}.

And the molecular flow Q is approximated with the following equation.

$$Q = \widehat{N}P_{gas}C_v(1 - \frac{\xi}{3\xi_{max}})\sqrt{\frac{\xi}{G_g TZ}} \quad (2.19)$$

Where $\widehat{N}$ is an engineering parameter which converts pressure into flow units, $\widehat{N} = 3.11 * 10^{19}\ molecules\sqrt{K}/(Pa * s)$, and C_v is a unitless coefficient which describes the flow capacity of the valve, G_g is the specific gravity of the gas, T is the temperature in Kelvin and lastly Z is the compressibility factor.

2.7 Rupture disk based model

The rupture disk based model consists of a gas tank, a barrel and two rupture disks. A schematic figure of such a model can be viewed in Figure 12 below.

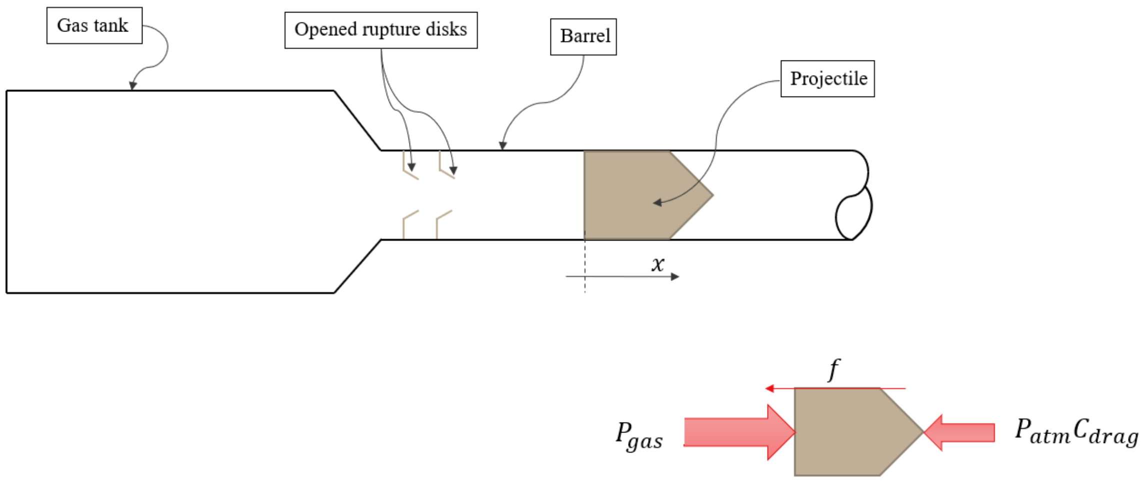


Figure 12: Illustration of the rupture disk based model, consisting of a gas tank, barrel, projectile and two opened rupture disks.

Newton's second law is again applied to the projectile, which results in the following relation between the gas pressure P_{gas} and the acceleration of the projectile $\ddot{x}$.

$$a = \ddot{x} = \frac{A}{m}(P_{gas} - P_{atm}C_{drag}) - \frac{f}{m} \quad (2.14)$$

In contrast to the valve based model, the rupture disk based model does not differentiate the gas into two gas bodies, instead just one homogeneous body of gas is modelled here. It is important to note that this assumption does not describe the gas and projectile dynamics in total accordance with reality. Most importantly the assumption neglects the impact of flow disturbance due to the rupture valves, and furthermore that the density and pressure in the gas will not be uniform in the gas during such fast gas propagations through obstructing rupture disks.

Once again the chosen equation of state is Van der Waals equation.

$$(P + \frac{an^2}{V^2})(V - nb) = nRT \tag{2.2}$$

To account for the temperature loss of gas during a launch, adiabatic expansion is assumed. Since the gas will travel quickly through the barrel, the heat transfer from the surroundings is presumed to be neglectable. Here the equations presented in the theory section 2.3 provided by Kumar et al. are used, where the Van der Waals gas undergoing an adiabatic process is assumed to follow the following constant relationships [19].

$$(P + \frac{an^2}{V^2})(V - nb)^{\Gamma} = Constant \tag{2.3}$$

$$T(V - nb)^{(\Gamma-1)} = Constant \tag{2.4}$$

Where the volume V will expand as the projectile travels down the barrel in the following way.

$$V = V_0 + Ax \tag{2.20}$$

As stated previously Γ is a factor which relates the specific heat at constant volume and pressure. Where the relation between Γ and the ratio of specific heat γ is the following.

$$\gamma = 1 + \frac{\Gamma-1}{f_v} \tag{2.6}$$

Were

$$f_v = 1 - \frac{2na}{RTV^3}(V - nb)^2 \tag{2.7}$$

2.8 Product development

The development of a new product can be a complex and lengthy procedure, however it can be broken down to smaller more manageable product development phases. Toll-gates occur between the product development phases, and work as a tool for decision making and documentation where the progress is evaluated before moving on to the next development phase. Specific phases included in a product development phase can vary depending on the nature of the product and industry, however the following product development phases are often present in the early stages of a product development process [23].

Feasibility study: A feasibility study is an unbiased problem analysis which takes place at the start of a new development process. Such a study starts by gathering information from a wide variety of sources and an uncritical search for possible solutions. Often such a gathering of information includes, the existing solutions on the market, the detailed solutions for design problems and the technology and methods used for different functions. Furthermore, a feasibility study aims not only to see potential problems and solutions, but also to analyse said problems from different perspectives, such as economical, manufacturing, usage and functional perspectives which leads to a more holistic solution [23].

Product specification: The main objective of a product specification is to establish what shall be achieved as a result of the product development process. In a product specification relevant criteria concerning the developing product should be captured and clearly described. The criteria could either be present from the inception of the product development or occur as a result or consequence of analyses or extensive design decisions. Such criteria can be differentiated in two main categories, firstly criteria which is related to the perceived function of the product and secondly criteria that in a broad sense sets the boundaries for the possible solutions [23].

Concept development and generation: The term concept is defined differently depending on the context it is used in. In this thesis concept refers to an initial description of a solution to a particular construction problem. Development of concepts has their basis in the product specification, where the functional criterion should guide the developments. Concept development begins by widening the formulation of the specifications outlined in the product specification, and the purpose of this is to find broader general solutions. In the next step of concept development a functional analysis is carried out, where the objective is to find a functional structure where the product's complex total function can be differentiated into subfunctions. The final step in the concept development phase is to find solutions to all the individual subfunctions [23].

Concept evaluation and choice of concept: Concept evaluation is the phase in which a certain concept is chosen to be further developed in the product development. There are a plethora of tools and methods that can be used to conduct a concept evaluation, like Pugh matrix, SWOT analysis and weighted decision matrix [23].

3 Method

In the following section the methods used in this thesis will be presented, which aims to portray how the results were obtained. This section will cover how the feasibility study was conducted, as well as how a product specification was developed. Furthermore, several concept iterations will be presented, which describes and evaluates different concepts.

3.1 Feasibility study

In the beginning of the project, SAAB employees presented a broad description of the design problem which this thesis work is dedicated to solve. Furthermore Fenelius. J. who in 2019 tried to find a suitable concept for an acceleration test rig, provides much valuable information in [9]. However, the work of Fenelius. J. did not provide sufficient technical depth for further design, moreover some of the criterions which lead Fenelius. J. concept development has since changed. Therefore, a literature study was conducted to gather more information and explore a variety of solutions.

3.2 Product specification

A requirement specification, which can be viewed in Appendix A, was developed early in the project, which differed in some aspects from the requirement specification developed by Fenelius. J. Most criterions covered in the requirement specification was provided by SAAB from the start of the project, whereas other criterions were added as new solutions were addressed. The requirement specifications contained 8 requirements and 9 wishes from SAAB and one wish from the students. These requirements and wishes were weighted by their level of priority by SAAB employees, on a scale from 1 to 5, resulting in 8 criteria which were deemed of highest priority.

3.3 Concept generation & evaluation

A total of 10 different concepts were produced throughout 3 concept generation iterations in this thesis work. The first two iterations were conducted early on in the project, with the aim of guiding the focus of further research and work to a limited and manageable pool of solutions. As such the first two concept evaluation processes were mainly based on the experience of SAAB employees and assumptions made from other designs found in the literature.

Evaluation of the concepts were conducted by the usage of an evaluation matrix. The matrix evaluates the different concepts in relation to the requirement specification which can be viewed in Appendix A, where the level of priority set on any individual criterion acts like a weight for the concept evaluation. Every concept was rated on its perceived ability to meet each requirement by the thesis workers. A number in the range from 0 to 5 was assigned to the different concepts in relation to each criterion, where a 0 indicates that the concept would not be capable of meeting the requirement and higher numbers indicates that the concept would be more likely to meet the requirements. These numbers are summed in the evaluation matrix, and the concept(s) with the highest magnitude are best suited for further development.

3.3.1 First concept iteration

These concepts are in a broad way trying to solve the problem of how the acceleration of the projectiles will occur. As such these concepts do not aim to find any detailed designs of individual components, instead they decide which underlying acceleration method should be used to achieve the desired acceleration during a test. In the following section the concept A, B and C will be presented.

Concept A, acceleration achieved through impact between metallic bodies.
In the early stages of the project an idea was that some sort of hammer that hits the projectiles could be a way of accelerating the projectiles. Where the collision between the hammer and the projectile would lead to a high acceleration of the projectile. The arguments for such a method are firstly that it would likely be a cheap solution, both to build and continuously use, and secondly that it would likely lead to a test rig which is simple to operate. The arguments against such a method are firstly that the acceleration against time curve would not resemble the acceleration curve obtained for the components when used in the applications they were designed for. And secondly, that a solution like this, acceleration testing by impact, was not found in the literature, indicating that there might be some problems with such a solution.

Concept B, acceleration achieved through usage of explosive materials.
In concept B the acceleration of the projectile is achieved through the combustion of some propellant. This method of acceleration is perhaps the most common solution found in the literature, where different cannons are used to conduct the tests. Furthermore the currently used acceleration rigg utilises propellant as a means to accelerate the projectiles. The main argument against concept B is that combustions are dangerous and lead to further operational obstacles due to further safety requirements, which in turn can lead to a higher cost per test.

Concept C, acceleration achieved through usage of pressurised gas.
Both concept B and C accelerates the projectiles by letting a pressurised gas apply a load to the projectile. However in the case of concept C, the pressurisation of the gas does not occur as a consequence of combustion, instead either a compressor or a gas booster system would pressurise the gas in a tank from which the gas would be released. This method is quite common in literature, furthermore it is the method recommended by Fenelius. J.

The relevant criterions which concept A, B and C got evaluated against are, criterion 1, 4, 5, 7, 9, 13, 14 and 15 from the requirement specification. Two criterions largely decided the outcome of the evaluation which concept C won. Firstly criterion 5, which is related to the characteristics of the acceleration against time curve of the projectile, were concept A scored a 0. Secondly criterion 14, which is related to how safe the acceleration rigg would be to use, concept B scored a 0. The evaluation of concept A, B and C can be viewed in Appendix B.

3.3.2 Second concept iteration

As stated earlier both the first and second concept development iterations were conducted early on in the project to limit the scope of the project. Once the underlying method of acceleration was settled, by evaluation of concept A, B and C, it became clear that some type of pneumatic launcher would be used as the future acceleration rigg. However, there are many different designs of pneumatic launchers which differ from each other in fundamental ways, so to further limit the scope of possibilities a second concept iteration was conducted with the following concepts:

Concept I, single stage gas gun.
There are several examples of single stage gas guns or single stage pneumatic launchers found in the literature, building on different design solutions like the double-diaphragm or the wrap-around breech assembly. A single stage gas gun would likely be both faster and cheaper to conduct tests with than the other concepts which will be presented below. An illustration of a single stage gas gun system can be viewed in Figure 13 (a) below.

Concept II, two stage gas gun.
Concept II covers the two stage gas gun solutions, an illustration of which is presented in Figure 13 (b) below. By introducing a piston and differentiating the gases into one driving gas, which drives the piston, and one working gas, which applies pressure to the projectile, higher pressures can be asserted to the projectile compared to the single stage gas guns. However, the addition of a stage, which in most designs found in the literature implies at least a piston and a rupture disk, will increase the cost per launch as well as the operational time.

Concept III, three stage gas gun
Concept III covers all the three stage gas guns, an illustration of a three stage gas gun can be viewed in Figure 13 (c) below. Three stage gas guns are rarely purly pneumatic, instead the first piston is driven by the combustion of some propellant. However, a three stage gas gun, with two pistons and three bodies of gas, is assumed to produce even higher pressures than the aforementioned concepts.

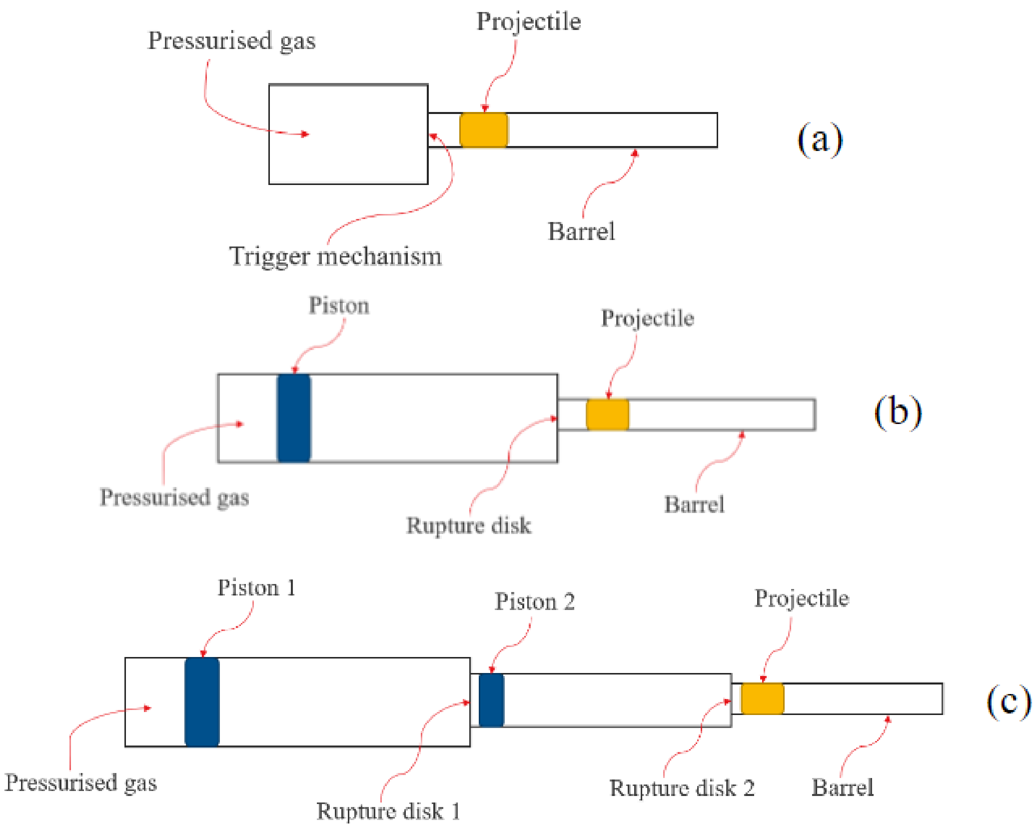


Figure 13: Containing illustrations of different gas guns, (a), single stage (b), two stage and (c), three stage.

Relevant for the evaluation of concept I, II and III are criterion 1 and 9. In Appendix C the complete evaluation can be viewed, where concept I scored the highest total points. The simplicity and lower cost of a single stage pneumatic launcher in conjunction with the fact that the desired acceleration was assumed to be plausible to reach, was the reason that concept I was chosen for further development.

3.3.3 Third concept iteration

The third concept iteration covers the design solutions that could be used for a single stage pneumatic launcher. More specifically the third concept iteration aims to evaluate which components, mechanisms and strategies should be used to contain the pressurised gas and release it to accelerate the projectile.

Concept 1, Alternative trigger mechanism design.
Concept 1 relies on an axial shear pin as an alternative trigger mechanism, in Figure 14 below an illustrative drawing of concept 1 can be viewed. The axial shear pin is a rod of some metal which is threaded in both ends, where one rod end is threaded to the projectile and the other is threaded to some structure in the gas tank. The rod also has a section with reduced diameter, when the tank pressure is high enough the rod will break at the reduced diameter which releases and launches the projectile. Alternative trigger mechanisms are not covered at any depth in the literature, however there are still many options in their design and function. These alternative trigger mechanisms have an advantage compared to usual trigger mechanisms in that designs with alternative trigger mechanisms can avoid shockwave disruptions a bit easier. They avoid shockwave disruptions better since the projectile is fixated until the right launching conditions are met, whereas with a trigger mechanism design the shockwaves that occur as rupture disks burst for example can disrupt the projectile during the launch.

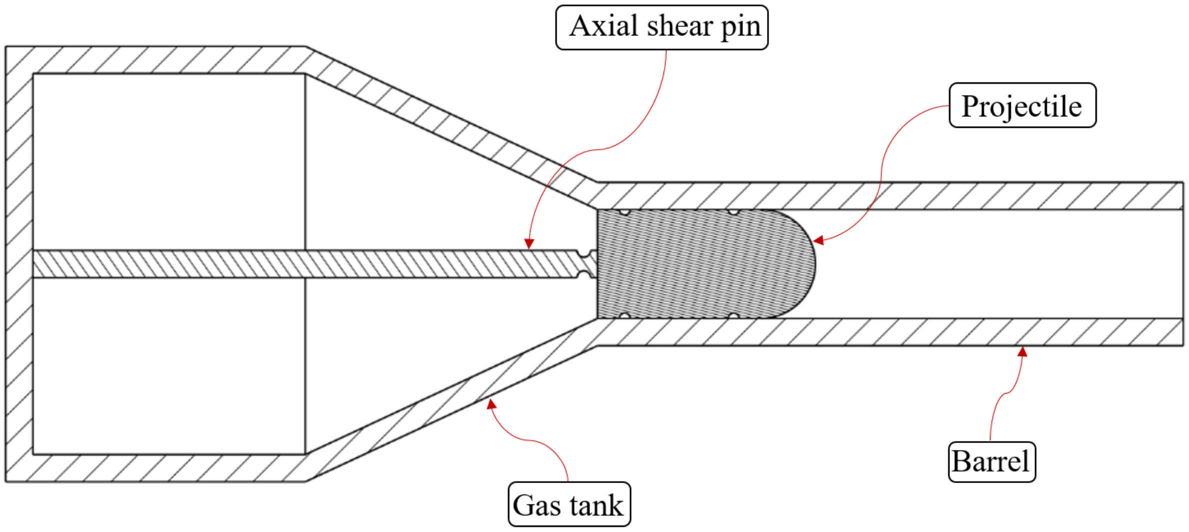


Figure 14: Drawing of concept 1, axial shear pin design. Containing a gas tank, an axial shear pin, a projectile and a barrel.

Concept 2, Valve based design.
Concept 2 relies on a valve as the trigger mechanism, which releases the pressurised gas from the gas tank to the barrel and launches the projectile. It is hard to find a valve on the market with the right properties for the unusual requirements this acceleration rigg demands. A valve based design would however be a cheap and simple solution since no components fail during a launch.

Concept 3, Rupture disk based design.
Concept 3 relies on two rupture disks to release the pressurised gas down the barrel. Since the acceleration rig should be able to achieve a broad range of projectile accelerations, two rupture disks are used instead of a single rupture disk. As two rupture disks introduces more operational freedom, and allows the projectile to be launched at a wider range of gas pressures. In Figure 15 below, an illustrative figure of a rupture disk based design can be viewed.

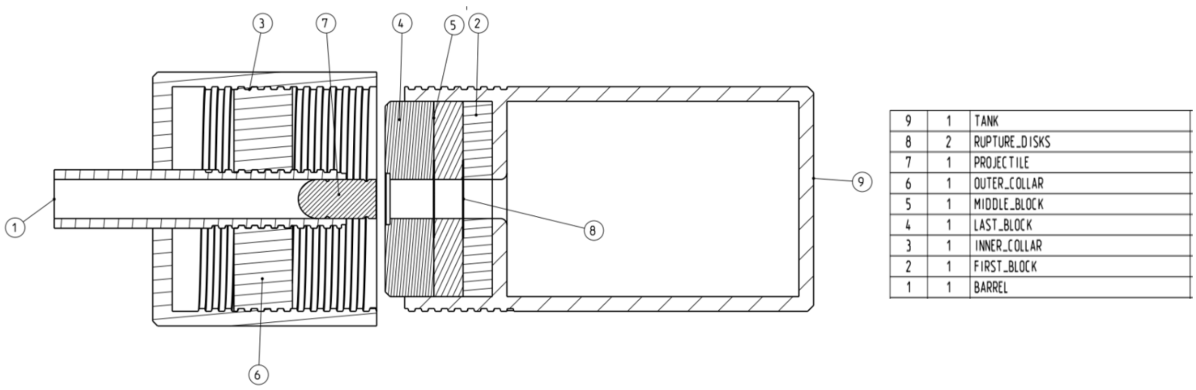


Figure 15: Illustration of a rupture disk based design, similar to the design in [10], containing a gas tank, two rupture disks, a small camber with an inlet between the disks, a barrel and a projectile.

Concept 4, Wrap-around design.
Concept 4 is the wrap-around design, where the gas tank wraps around the barrel in which the projectile is placed. The projectile launch is initiated by a small gas inlet, where added gas moves the projectile such that the pressurised gas in the wrap around gas tank gets released and accelerates the projectile, an illustration of which can be viewed in Figure 16 below.

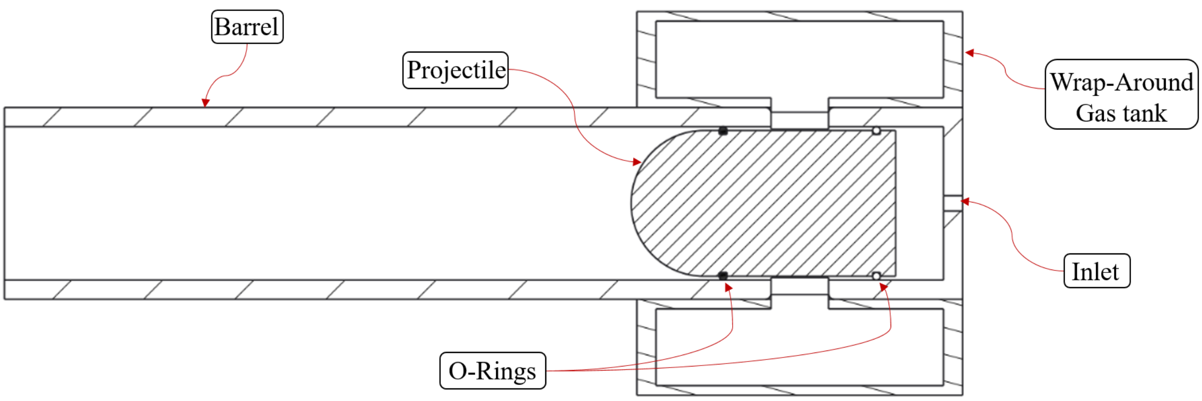


Figure 16: Illustration of the wrap-around design, containing a wrap-around gas tank, a projectile, a barrel, two O-rings mounted on the projectile and a gas inlet.

Before evaluating concept 1, 2, 3 and 4 further investigations of the feasibility of concept 2, 3 and 4 will be present in the following sections.

3.4 Calculations of concept 2 & 3

To investigate the feasibility of concept 2, a valve based design, and 3, a rupture disk based design, calculations were conducted, which will be presented in the following sections. The calculations aim to achieve a few things, firstly to describe the projectile dynamics throughout a launch, secondly the calculations should give a rough indication of the sufficient magnitudes for different design parameters, for example how large the gas tank has to be to achieve a projectile acceleration of 20000Gs. These calculations were carried out in MATLAB, and the code used for concept 2 can be viewed in Appendix F whereas the code used for concept 3 can be viewed in Appendix G. Throughout these calculations plenty of parameters will be used, these are differentiated into three groups, which is presented below.

Fixed parameters, which includes gas properties and gas constants.

Design parameters, which includes parameters that can be changed before construction of the acceleration test rig, containing parameters such as tank volumes, cross-sectional area of the barrel and valve properties.

Operational parameters, which includes parameters that are in the control of the operator, covering parameters such as gas pressure/pressures and gas temperature.

3.4.1 Calculations of the valve based model

By usage of the valve based model presented in section 2.6 calculations of concept 2 will be conducted, the results of said calculations will guide the evaluation of concept 2.

3.4.1.1 Calculation scheme, valve based model

In this section a generic calculation scheme of the MATLAB code used for the valve based model, which can be viewed in full in Appendix F, will be presented. In Figure 17 below, a scheme of calculations conducted by the MATLAB code is presented.

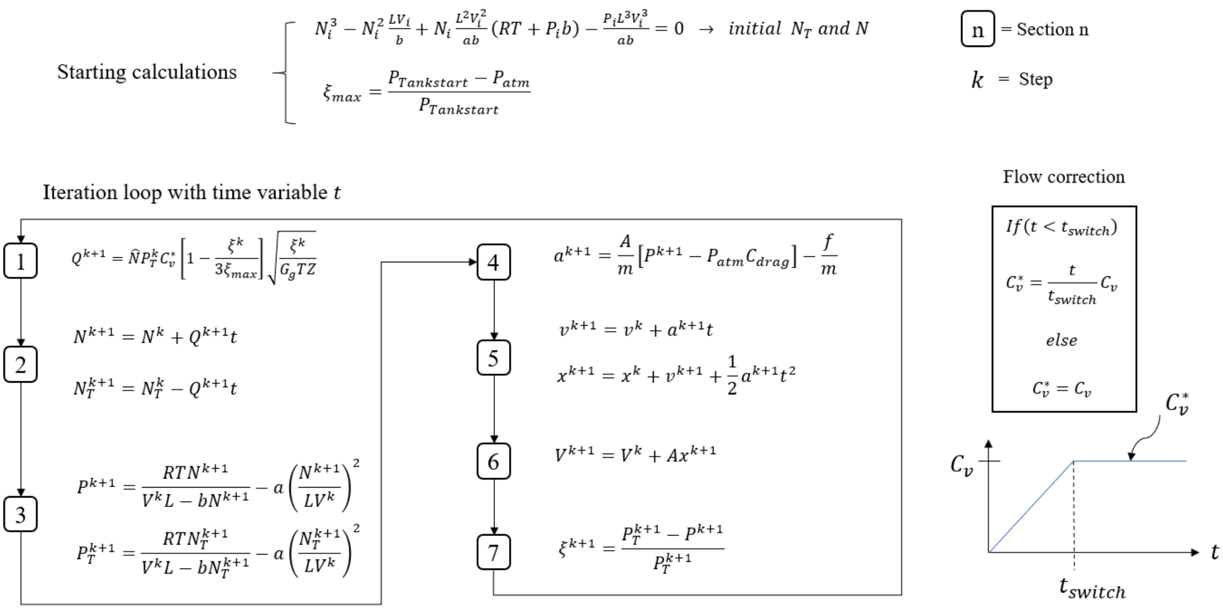


Figure 17: Calculation scheme of the valve based model MATLAB code, where k indicates the step and t is the iteration parameter.

The calculations start of by solving for the number of molecules in the tank N_T and the barrel N. This is done by first converting moles to molecules in Van der Waals equation of state, equation (2.2), with the help of Avogadro's constant L, then rearranging to a polynomial of order 3. By finding the non-imaginary root in the polynomial the number of molecules in the gas is obtained. Furthermore, the maximum pressure ratio ξ_{max}, will occur at the inception of the launch and can therefore be calculated in the beginning of the code.

The iterative calculations begin by determining the molecular flow Q for the next iteration step $k + 1$ by the usage of equation (2.19). The molecular flow Q will lead to a change in the number of molecules in the two bodies of gas, which is calculated in section 2. The change of molecules in the two bodies of gas will change the pressure of the gases, this is calculated in section 3 by the usage of Van der Waals equation rearranged to solve for pressure. Once the pressure in the second body of gas P is obtained, the acceleration of the projectile can be calculated by equation (2.14), this is done in section 4. In section 5 the velocity and in turn the distance travelled by the projectile is calculated by stepwise integration. The travelled distance of the projectile will lead to an added volume which the second body of gas can occupy, hence the new volume is calculated in section 6. Lastly, before looping back to section 1, the new pressure ratio between the two bodies of gas ξ is calculated.

To correct for the limited flow, which occurs under the time it takes for the valve to switch from fully closed to fully opened, an if else statement is implemented in the code. The limited flow characteristic is assumed to be linear. A parameter C_v^* is introduced in the code, which is equal to C_v as long as the valve is fully opened. However, as long as the time variable t is less than the switch time t_{switch} the molecular flow Q gets scaled down by the parameter C_v^*, which is equal to the ratio between t and t_{switch} multiplied by C_v.

3.4.1.2 Capacity of valve based model

In the following section the results given by the MATLAB code provided in Appendix F will be presented, described in the previous section, calculation scheme valve based model. This section will begin by presenting the chosen values for the fixed, design and operational parameters, and then the results given by said parameters will be presented.

Table 3: Design parameters, used for calculations of the valve based model.

Design Parameters, Valve based model		
Parameter	Value	Unit
Tank volume, V_T	$0.35\pi(\frac{0.15}{2})^2 \approx 6.185 * 10^{-3}$	m^3
Cross-sectional area of barrel, A	$\pi(\frac{0.04}{2})^2 \approx 1.2566 * 10^{-3}$	m^2
Volume, between projectile and valve, V_0	$0.1\pi(\frac{0.04}{2})^2 \approx 1.2566 * 10^{-4}$	m^3
Projectile mass, m	0.15	kg
Drag coefficient, C_{drag}	1.3	dimensionless
Friction force, f	100	N
Flow coefficient, C_v	1.95	dimensionless
Switch time of valve, t_{switch}	$1.6 * 10^{-3}$	s

It is important to note that all of the values given in Table 3 can be subject to change in the future due to further research or developments. The values were in large part selected on intuition and similarity to values found in previous designs. Furthermore, the flow characteristic of the gas through the valve under the switch time duration was assumed to be linear for the sake of simplicity.

Tabel 4: Fixed parameters, used for calculations of the valve based model.

Fixed Parameters, Valve based model		
Parameter	Value	Unit
Compressibility factor Z	1.1	dimensionless
Specific gravity G_g	1	dimensionless

The chosen gas for the calculations is air, where several fixed parameters such as Van der Waals constants can be found in Table 2. In Table 4 above, the values used for Z and G_g can be found. These parameters were assumed constant throughout the launch, even though both these parameters are subject to change as the gas state evolves. This however, will not drastically change the results given by the calculations, thus letting Z and G_g be constant for the first rough calculations of concept 3 was deemed sufficient.

Table 5: Operational parameters, used for calculations of the valve based model.

Operational Parameters, Valve based model		
Parameter	Value	Unit
Initial tank pressure P_T	$40 * 10^6$	Pa
Temperature T	300	$Kelvin$

The temperature was assumed to be held constant throughout the launch, which will overestimate the achieved acceleration of the projectile. Furthermore, it would be unlikely to find a valve which can manage a pressure drop of roughly 40 MPa while having a flow coefficient of 1.95 and a switch time of 1.6 milliseconds. However this calculation is supposed to give a rough indication of the capacity of concept 2.

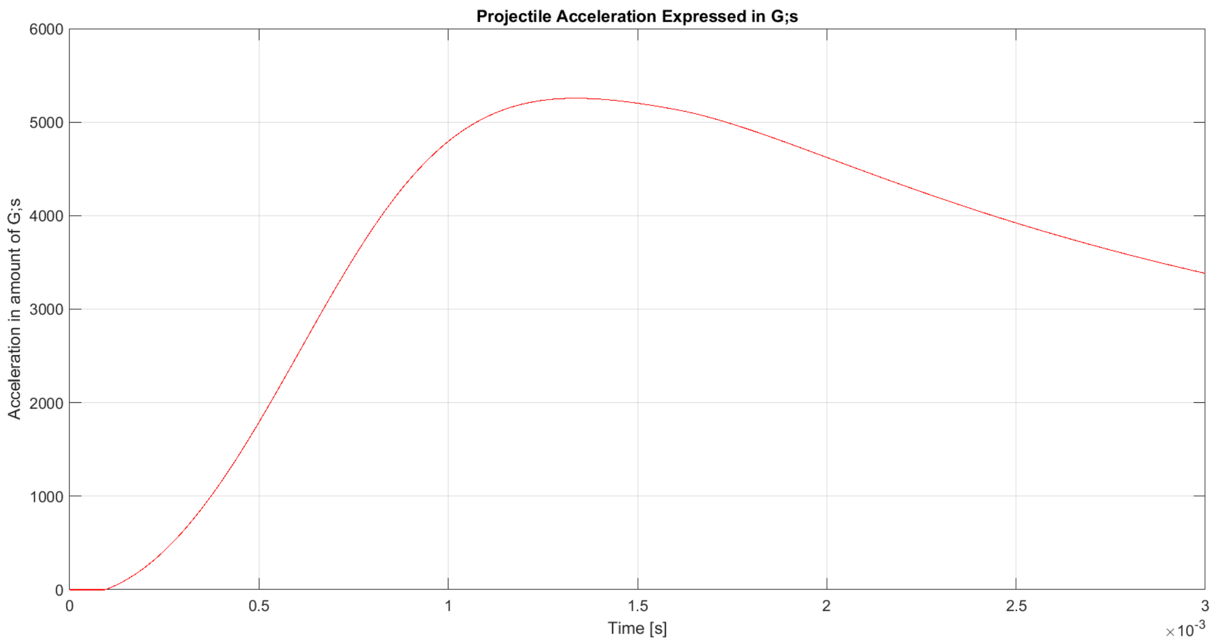


Figure 18: Plot of projectile acceleration against time, when using the values presented in Table (3, 4 & 5).

In Figure 18 above, the acceleration curve for a projectile launched under the conditions expressed by Table (3, 4 & 5) is presented. As the curve indicates the maximum acceleration, just above 5250Gs, is reached in about 1.3 milliseconds, and the projectile acceleration stays above 5000Gs for about 0.7 milliseconds.

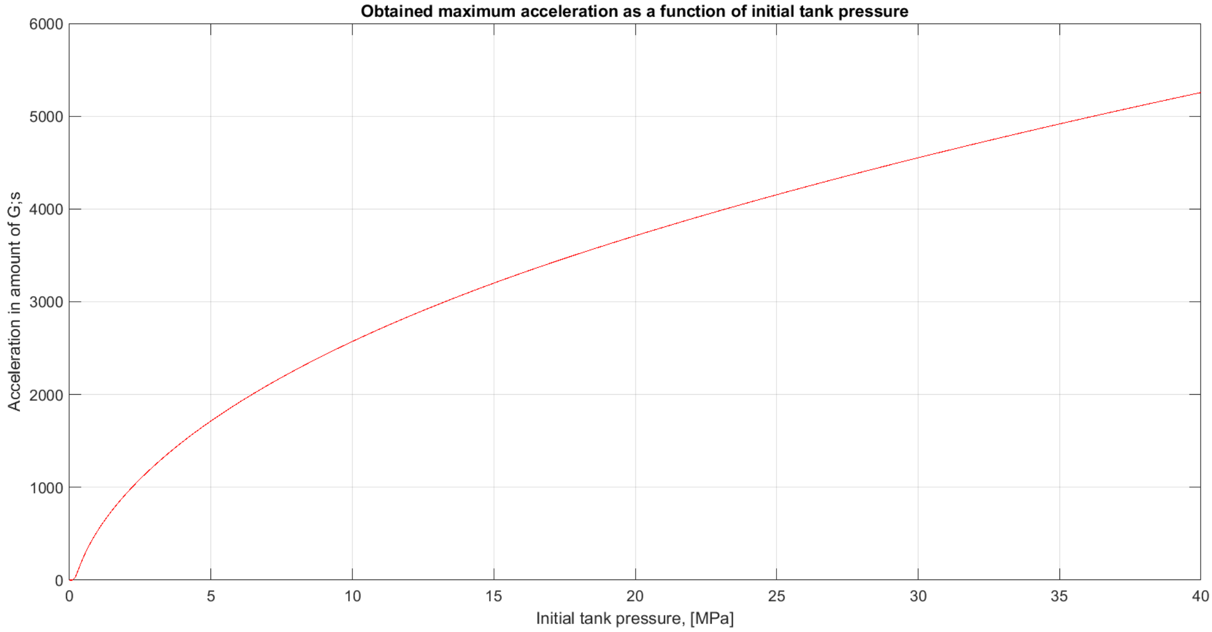


Figure 19: Plott of the maximum projectile acceleration as a function of the initial tank pressure.

In Figure 19 above, maximum projectile acceleration is plotted as a function against initial tank pressures. It is possible to further increase the initial tank pressure, above 40 MPa by introducing gas boosters which is explained by Axelsson. F. in [1]. However, it would be highly unlikely to find a valve which had the capability to function properly under such high pressure differentials. Therefore, no further development of the valve based concept, concept 2, was conducted since the calculations indicate that such a design would not meet criterion 1 in the requirement specification.

3.4.2 Calculations of the rupture disk based model

By usage of the rupture disk based model presented in section 2.7 calculations of concept 3 will be conducted, the results of said calculations will guide the evaluation of concept 3.

3.4.2.1 Calculation scheme, rupture disk based model

In the following section the calculation scheme of the MATLAB code used for the rupture disk based model is presented. The full MATLAB code can be viewed in Appendix G.

Starting calculations

$$N_i^3 - N_i^2 \frac{LV_i}{b} + N_i \frac{L^2V_i^2}{ab}(RT + P_i b) - \frac{P_i L^3 V_i^3}{ab} = 0 \;\rightarrow\; initial\ N\ for\ gas \begin{cases} in\ the\ tank,\ N_1 \\ in\ between\ the\ rupture\ disks, N_2 \\ at\ the\ start\ of\ the\ barrel, N_3 \end{cases}$$

$$N_{tot} = N_1 + N_2 + N_3 \;\rightarrow\; n_{tot} = \frac{N_{tot}}{L}$$

$$P_{gas} = \frac{RTn_{tot}}{V - nb} - a\frac{n_{tot}^2}{V^2}$$

$$f_v = 1 - \frac{2an_{tot}}{RTV^3}(V - bn_{tot})^2$$

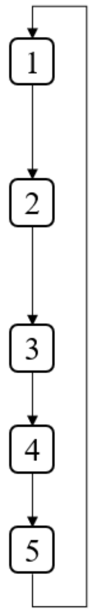
$$\begin{cases} C_1 = \left(P_{gas} + a\frac{n_{tot}^2}{V^2}\right)(V - bn_{tot})^{\Gamma} \\ C_2 = T(V - bn_{tot})^{\Gamma - 1} \end{cases}$$

$$\Gamma = f_v(\gamma - 1) + 1$$

Figure 20: First part of the calculation scheme, which is describing the MATLAB code used to calculate the projectile dynamics for the rupture disk based model.

In the first part of the calculation scheme, which can be viewed in Figure 20 above, the starting calculations are presented. Much in the same way as the previous calculation scheme regarding the valve based model, the calculation begins by obtaining the number of molecules for the different gases. Here N_1 is the number of molecules in the gas tank, N_2 is the number of molecules present in the gas which occupies the volume in between the two rupture disks and N_3 is the number of molecules in the gas which occupies the volume in between the downstream rupture disk and the projectile. Once the rupture disks burst, the different bodies of gas are assumed to mix into one homogeneous body of gas. It is assumed that no molecules are added or lost during this process, hence the total number of molecules of the homogeneous body of gas N_{tot} is equal to the sum of N_1, N_2 and N_3. Furthermore, it is assumed that the three different gas bodies have the same temperature, and that no thermal change occurs when the three bodies of gas perfectly mix into one. By converting the total number of molecules N_{tot} to moles n_{tot} by the usage of Avogadro's constant L, the gas pressure P_{gas} can be obtained through the usage of Van der Waals equation of state. Once the equation of state for the gas is known, f_v and Γ can be calculated by using equations (2.7) and (2.6) respectively. Finally, the constants given in equation (2.3) and (2.4) can be obtained, with the usage of the previously calculated values.

Iteration loop with time variable t



$$a^{k+1} = \frac{A}{m}\left[P_{gas}^{k} - P_{atm}C_{drag}\right] - \frac{f}{m}$$

$$v^{k+1} = v^{k} + a^{k+1}t$$

$$x^{k+1} = x^{k} + v^{k+1} + \frac{1}{2}a^{k+1}t^{2}$$

$$V^{k+1} = V^{k} + Ax^{k+1}$$

$$P_{gas}^{k+1} = \frac{C_1}{(V^{k+1} - bn_{tot})^{\Gamma}} - a\frac{n_{tot}^{2}}{(V^{k+1})^{2}}$$

$$T^{k+1} = \frac{C_2}{(V^{k+1} - bn_{tot})^{\Gamma-1}}$$

n = Section n

k = Step

Figure 21: Second part of the calculation scheme, which is describing the MATLAB code used to calculate the projectile dynamics for the rupture disk based model.

Once the starting calculations are conducted the iteration process can start, which is described in Figure 21 above. The iteration begins in step 1 by calculating the acceleration a in the next step $k + 1$ with Newton's second law, equation (2.14). In section 2, the velocity and travelled distance of the projectile is calculated. In section 3 the added volume, due to the projectile movement, is calculated. The expansion of the gas, will lead to a reduced gas pressure P_{gas}, which is corrected by the usage of equation (2.3) in section 4. Lastly the temperature T is calculated with equation (2.4) in section 5 before looping back to section 1 in the iteration loop. Throughout this iteration loop the parameters f_v and Γ are assumed to be constant, however parameters can be continuously iterated upon by utilising equation (2.7) and (2.6). A calculation scheme which includes the iteration of the parameters f_v and Γ can be viewed in Appendix E.

3.4.2.2 Capacity of rupture disk based model

In the following section the results given by the MATLAB code provided in Appendix G, described in the previous section, calculation scheme rupture disk based model, is presented. This section will begin by presenting the chosen values for the fixed, design and operational parameters, and further on the results given by said parameters will be presented.

Table 6: Design parameters, used for calculations for the rupture disk based model.

Design Parameters, Rupture disk based model		
Parameter	Value	Unit
Tank volume	$0.3\pi(\frac{0.1}{2})^2 \approx 2.3562 * 10^{-3}$	m^3
Cross-sectional area of barrel	$\pi(\frac{0.04}{2})^2 \approx 1.2566 * 10^{-3}$	m^2
Volume, between rupture disks	$0.02\pi(\frac{0.04}{2})^2 \approx 2.5133 * 10^{-5}$	m^3
Volume, between downstream rupture disk and projectile	$0.02\pi(\frac{0.04}{2})^2 \approx 2.5133 * 10^{-5}$	m^3
Projectile mass	0.15	kg
Drag coefficient C_{drag}	1.3	dimensionless
Friction force f	100	N

Much in the same way as the previous calculations for the valve based model, these design parameters can be subject to change, if future research or developments suggest a different value to any individual parameter. Furthermore, the value of these design parameters have emerged from intuition and suggestions given by the design choices done in other gas guns found in the literature and suggestions given by SAAB employees.

The chosen gas for the following calculations is air, as such the fixed parameters can be viewed in Table 2. The operational parameters can be viewed in Table 7 below, where the temperature in contrast to the previous valve based model is not held constant throughout the launch.

Table 7: Operational parameters, used for calculations of the rupture disk based model.

Operational Parameters, Rupture disk based model		
Parameter	Value	Unit
Initial tank pressure P_T	$40 * 10^6$	Pa
Temperature T	300	$Kelvin$

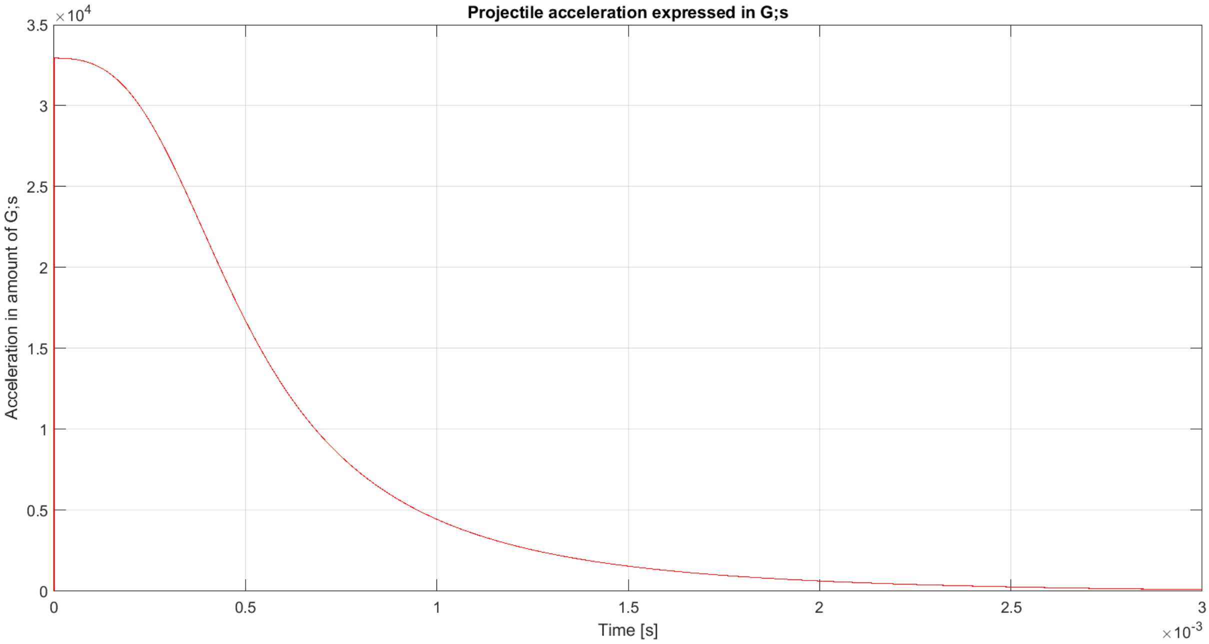


Figure 22: Plot of projectile acceleration vs time, when using the values presented in Table (6 & 7).

In Figure 22 above, the acceleration curve for a projectile launched under the conditions expressed by Table (6 & 7) is presented. Whereas the peak acceleration is reached after some time duration for the valve based model, the highest acceleration for the rupture disk based model is found in the beginning of the launch, i.e. just as the rupture disks break. For the aforementioned operational parameters, initial tank pressure of 40 MPa and a temperature of 300 Kelvin, the value of the peak acceleration is just below 33000 Gs and the projectile manages to have an acceleration higher than 30000 Gs for about 0.15 milliseconds. It is important to note that, while the peak acceleration of the projectile probably will be reached quicker with a rupture disk based design compared to a valve based design, the peak acceleration of the projectile occurring just as the rupture disks burst is a consequence of the assumptions made in the calculation model and is therefore not in accordance with reality.

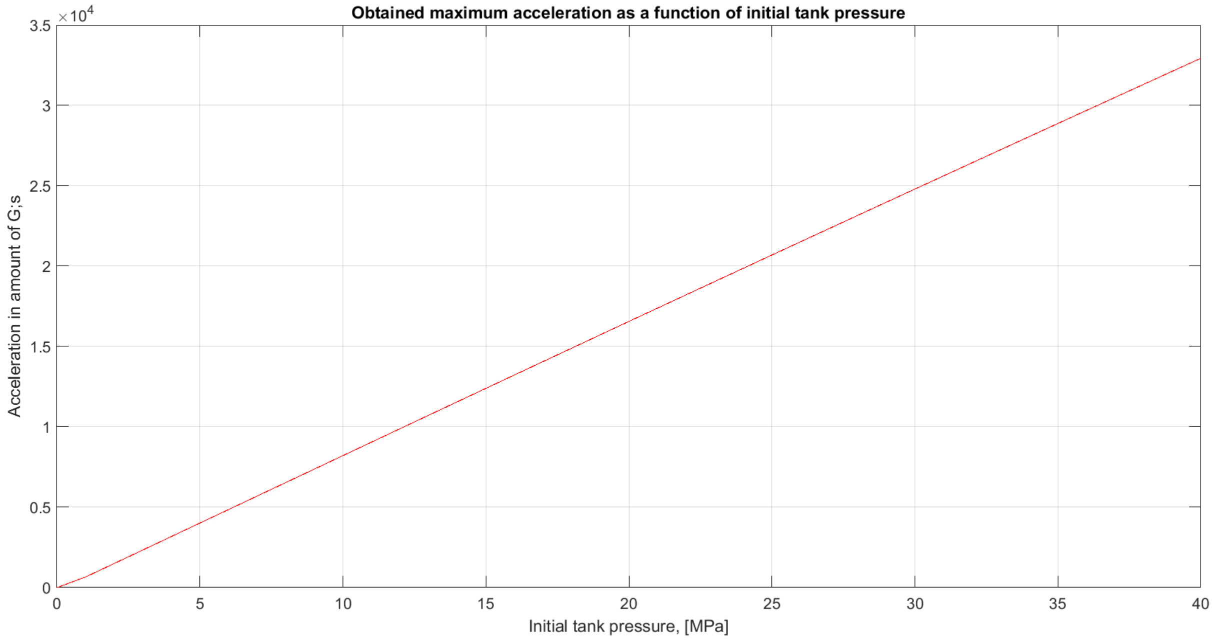


Figure 23: Plot of the maximum projectile acceleration as a function of the initial tank pressure.

In Figure 23 above, maximum projectile acceleration is plotted as a function against initial tank pressures. In contrast to the valve based model, the relationship between obtained maximum acceleration and initial tank pressure for the rupture disk model is linear. However, it is questionable to assume that the whole range of initial tank pressures, from zero to 40 MPa, could be utilised. Since any given initial tank pressure requires a combination of rupture disks that functions correctly under those conditions.

3.5 Calculations of concept 4

In contrast to the other concepts the wrap-around design, concept 4, is to a large degree limited by the projectile's ability to withstand the radial pressure applied from the gas tank. While a lighter projectile will need a lower gas pressure to reach a given acceleration, compared to a heavier projectile, the lighter projectile will also have a reduced ability to withstand the radial pressure applied from the tank. This introduces an optimisation problem with regards to the design of the projectile, where the projectile's weight and drag coefficient needs to be minimised while the projectile's ability to withstand radial pressure needs to be maximised. To investigate the feasibility of concept 4, the wrap-around design, a simple calculation regarding a projectile's ability to withstand the gas pressure necessary to reach 20000Gs was conducted.

The choice of material and the design of the projectile will have a large impact on the aforementioned optimisation properties. Due to the geometry of the components which are of interest for SAAB to test, the possible projectile designs are limited. The choice of material, from which the projectiles are manufactured, is however not as constrained.

In the following section a rough calculation will be presented, which aims to estimate the feasibility of the wrap-around design.

To start the calculations, a simplistic projectile geometry was selected, which can be viewed in Figure 24 below.

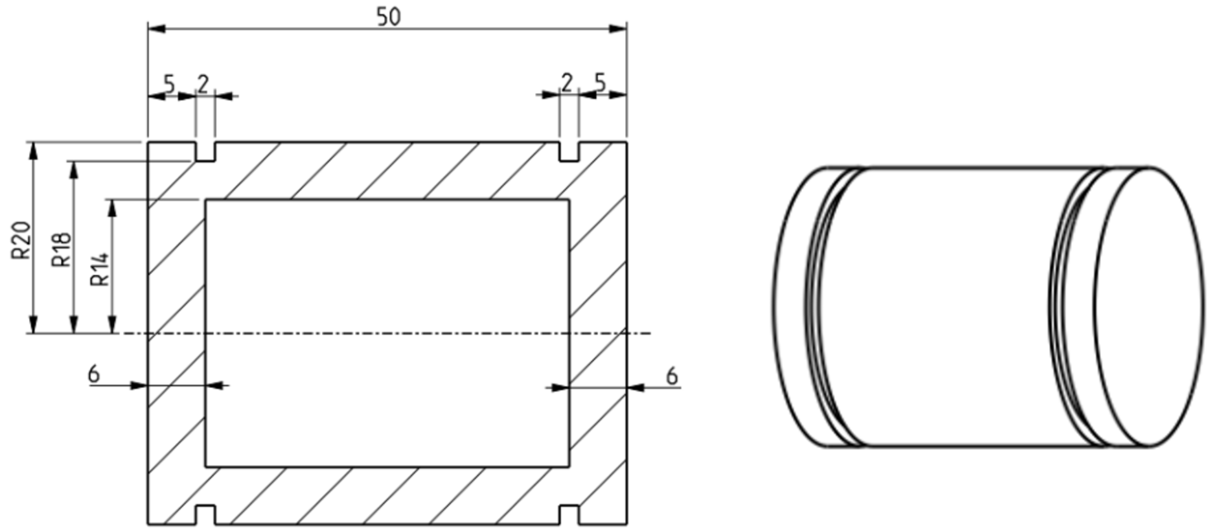


Figure 24: Selected geometry for the projectile.

The important parameters for the selection of projectile material are the modulus of elasticity E and the density ρ, where E should be high in relation to ρ, furthermore the cost of the material is preferably low. No exhaustive material research was conducted for these calculations, however both materials used for the following calculations are often used in the aerospace industry [24, 25], due to their great properties relating to stiffness and weight. The selected materials are aluminium 6061 and titanium 6AL-4V, which material properties can be viewed in Table 8. By calculating the volume of the projectile, the weight of both a titanium projectile and a aluminium projectile is simply found by multiplying with ρ.

Table 8: Containing the modulus of elasticity E, poisson's ratio ν and density ρ of materials used for calculations as well as the mass of the projectile m [26, 27].

Material	E	ν	ρ	m
Aluminium 6061	70 GPa	0.33	2700 kg/m^3	56 g
Titanium 6Al-4V	113.8 GPa	0.342	4430 kg/m^3	92 g

To calculate what pressures the projectiles will be exposed to, equation (2.14) can be used.

$$a = \ddot{x} = \frac{A}{m}(P_{gas} - P_{atm}C_{drag}) - \frac{f}{m}$$

Which can be rearranged for P_{gas} resulting in the following equation.

$$P_{gas} = \frac{m}{A}a + P_{atm}C_{drag} + \frac{f}{A}$$

For a first rough calculation the influence of the friction f and the term $P_{atm}C_{drag}$ is neglected. The gas pressure P_{gas} which the titanium and aluminium projectile needs to withstand if the projectile should reach an acceleration of 20000Gs, can now be calculated. To address the weight of the components which the projectiles are to carry through the launch 100 grams are added to the projectile weights.

Aluminium: $P_{gas} = \frac{0.056+0.1}{\pi \cdot 0.02^2} \cdot 20000 \cdot 9.81 = 24,356\, MPa$

Titanium: $P_{gas} = \frac{0.092+0.1}{\pi \cdot 0.02^2} \cdot 20000 \cdot 9.81 = 29,977\, MPa$

It is important to note that the required tank pressures to achieve a projectile acceleration of 20000Gs is higher, not only since due to the neglectance of friction and the term $P_{atm}C_{drag}$, but also due to the fact that the gas will be obstructed and have to occupy more space before it can sufficiently apply pressure to the projectile.

By using Abaqus, a finite element method software, the stresses and displacements in the projectile which the gas pressures would result in can be calculated. How the gas pressure is applied to the projectile can be viewed in Figure 25 below.

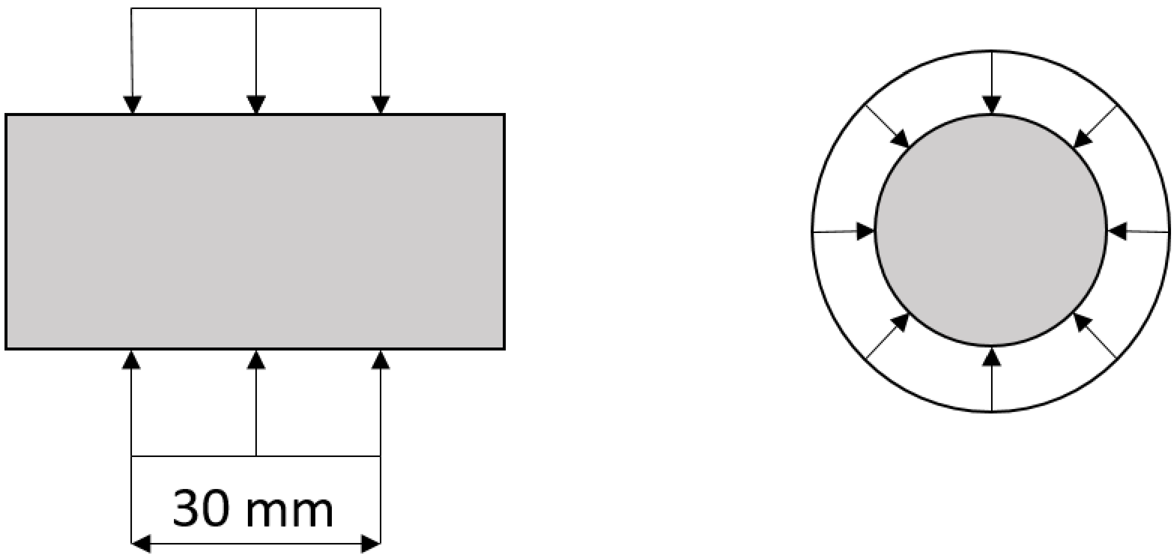


Figure 25: Illustration of the applied radial pressure on the projectile.

In Abaqus a quarter model of the projectile was implemented, meshed with 130211 tetragonal elements. The resulting displacement and von Mises stresses of the aluminium projectile can be viewed in Figure 26 and 27 below.

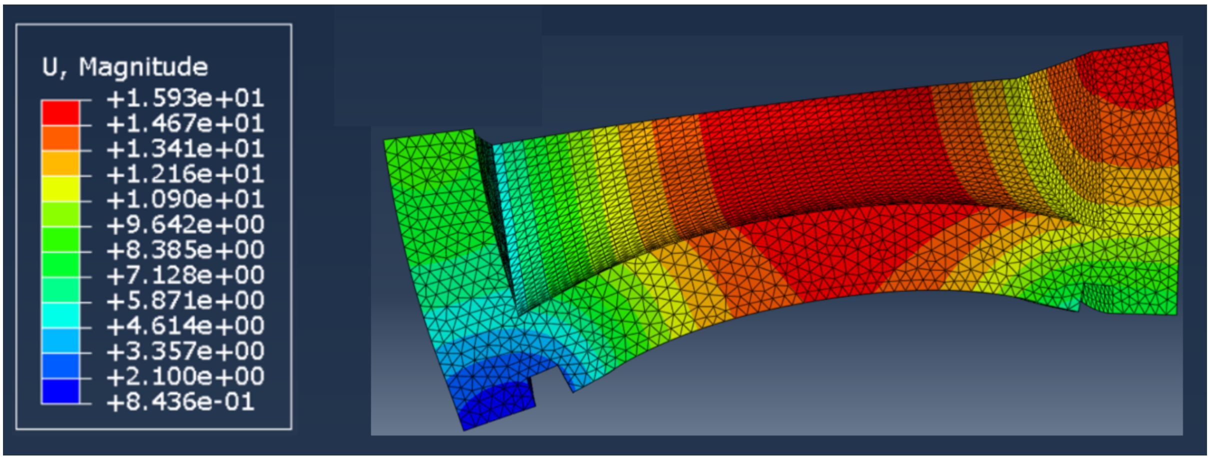


Figure 26: Resulting displacement of the aluminium projectile [μm].

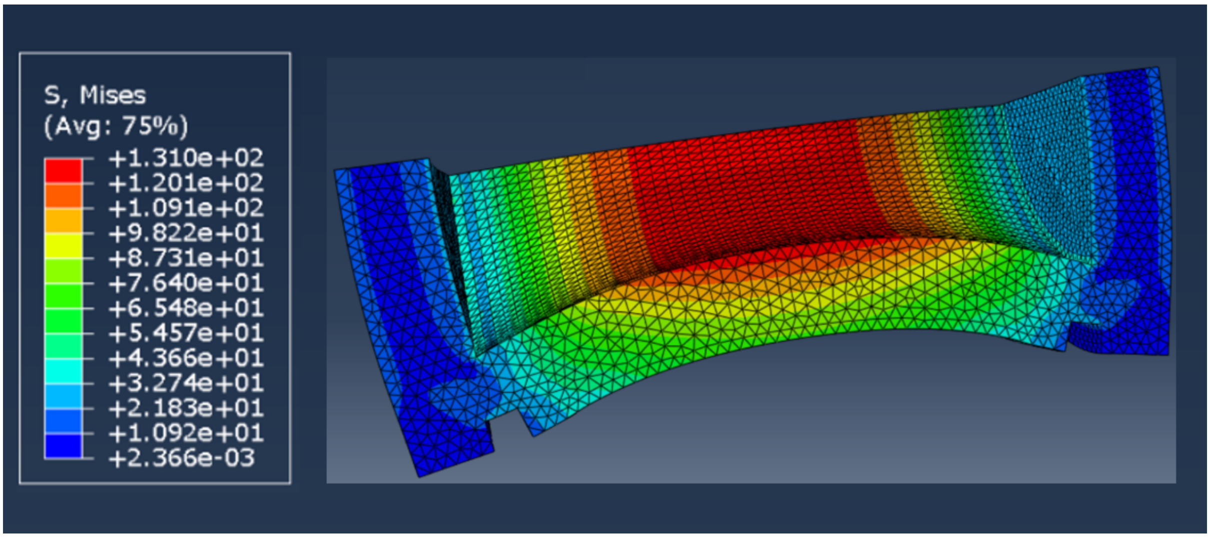


Figure 27: Resulting von Mises stresses for the aluminium projectile $[MPa]$.

And the resulting displacements and von Mises stresses for the titanium projectile can be viewed in Figure 28 and 29 below.

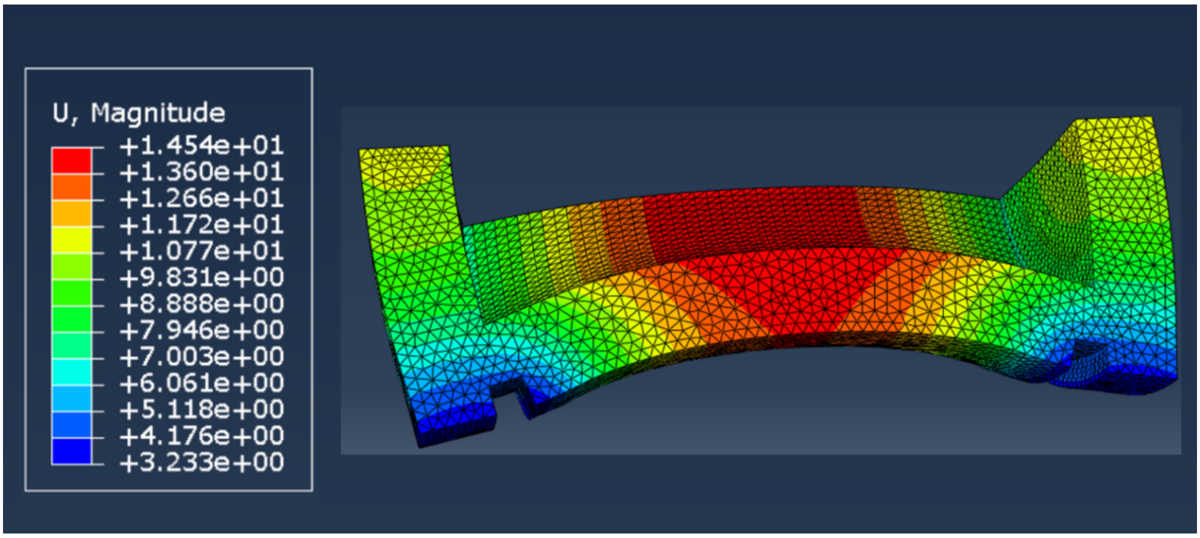


Figure 28: Resulting displacement of the titanium projectile [μm].

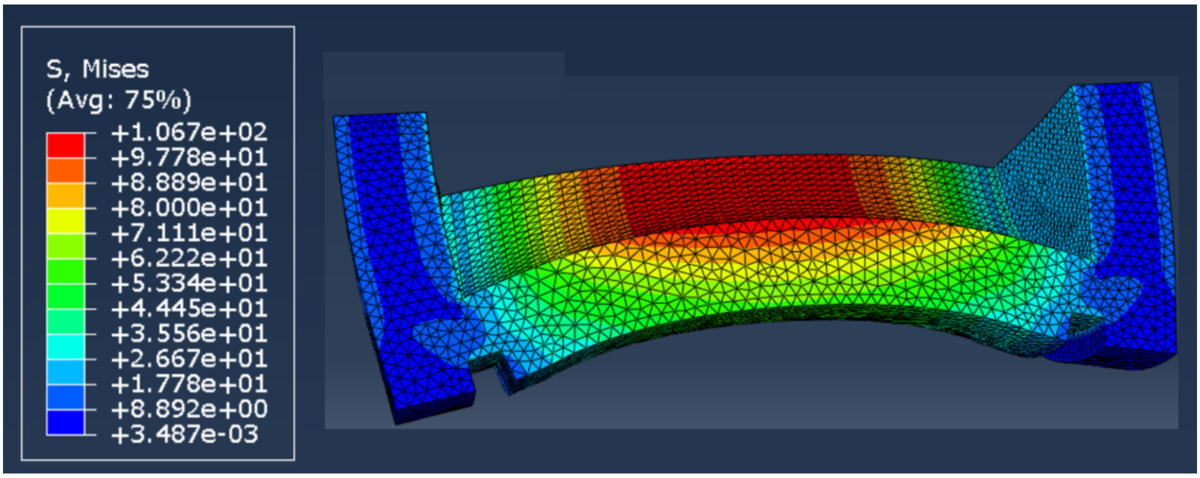


Figure 29: Resulting von Mises stresses for the titanium projectile [MPa].

In Figure 26 and 28 the unit of displacement is μm, and in Figure 27 and 29 the unit of stress is MPa. In Table 9 below the maximum values of displacement and von Mises stress is presented for the aluminium and titanium projectile.

Table 9: Maximum displacements and von Mises stresses found by the Abaqus model.

Material	Maximum displacement [mm]	Maximum von Mises stress [MPa]
Aluminium	0.0159	131
Titanium	0.0145	106.7

The results given by the finite element method simulations in Abaqus does not give any clear indication of whether or not the wrap-around design is a feasible solution. The magnitude of the maximum effective stress does bring some cause for concern, yet it seems possible to produce a projectile which would not become plastically deformed under the load asserted by the gas in the wrap-around tank. However the displacements might cause the O-rings to unseal the projectile, which would inhibit the operator to control when and how the launch is initiated.

3.6 Evaluation of concept 1, 2, 3 & 4

The third concept evaluation can be viewed in Appendix D. Whilst the evaluation portrays that all concepts are plausible, since the summation of each concept is roughly equal, both concept 2 and 4 score 0 in relation to criterion 1. As such concept 2 and 4 are dismissed as design solutions, instead either concept 1 or 3 should be further developed as the evaluation indicates that they could meet all requirements. However, concept 3, is presumed to have a greater ability to expose the components to the desired accelerations, therefore concept 3 is the best suited concept for further development.

4 Results

The third concept iteration resulted in concept 2 and 4 being dismissed, due to concept 2 not having the ability to reach sufficiently high accelerations to meet criterion 1, and concept 4 is dismissed due to it being unclear whether or not the concept would function as intended for higher accelerations. Furthermore concept 3 was elected before concept 1 due to greater capacity to expose the components to the sought after acceleration. As such concept 3 according to the evaluation process is the best suited concept for further development. In Figure 30 below an illustrative drawing of concept 3 can be viewed.

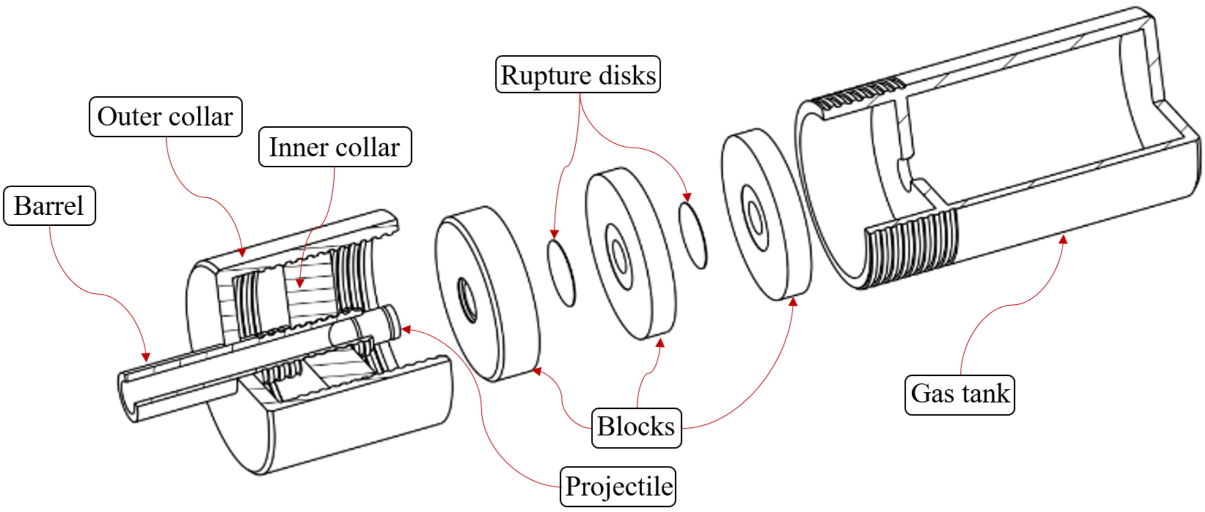


Figure 30: Illustration of concept 3, containing the gas tank, three separate blocks, 2 rupture disks, a projectile, a barrel, an inner collar and an outer collar.

Figure 30 illustrates the necessary components, which will be further elaborated on in the following section.

Gas tank: A gas tank with an internal volume given by the measurements in Table 6. The gas tank has an open volume where the blocks and rupture disks are mounted and lastly a trapezoid thread is present on the outside of the gas tank. Not shown in Figure 30 is a gas inlet and a mounting stand for the gas tank, which would be needed in the final design. In Appendix H a drawing of the gas tank is presented, the drawing should not be regarded as the final design, rather it is meant as an example of how the gas tank could be designed.

Rupture disks: Rupture disks are placed in between the barrel and the gas tank, and are replaced after each launch.

Blocks: Blocks are placed in between the gas tank and the barrel, these blocks have multiple purposes. Firstly, the rupture disks are mounted in between the blocks keeping the disks sealed and fixed during the launch, secondly the disks have the same internal diameter as the barrel minimising the flow obstructions between the barrel and the projectile. Furthermore, the disk closest to the barrel has a sloth, in which the barrel can be sealed. Not presented in Figure 30 is some inlet which passes through the middle block, an inlet which controls the gas pressure in between the rupture disks.

Barrel: A barrel which gets sealed in one of the aforementioned blocks, furthermore the inner collar is assembled by a trapezoid thread present on the barrel. The length of the barrel is mainly a consequence of future design choices, therefore the length of the barrel in Figure 30 should not be taken as a realistic depiction of the barrel.

Projectile: The projectile is placed in the barrel and the block next to the barrel when assembled, two O-rings are mounted on the projectile to minimise gas leakage in between the projectile and the barrel and to reduce the frictional force asserted on the projectile throughout a launch.

Inner & outer collar: An inner collar is mounted on the barrel, threaded on both sides. The outer collar assembles the barrel to the gas tank by acting as a cap nut.

5 Discussions & future work

In the following section both discussion and future work will be presented in conjunction, with the objective of discussing the assumptions, limitations and work procedure of the methods used and the future work required to alleviate the found problems.

5.1 Feasibility study

The feasibility study was a fruitful endeavour, which led to wide exploration of different test rigs and their respective solutions and methods. However, valuable information regarding design and calculation was hard or impossible to obtain. While many studies and companies provide a schematic and general description of how their test rig functions, the details of specific components and results of calculations are commonly not presented. This lack of specific information made it hard to quickly estimate the feasibility of different designs and methods. To give a concrete example, the wrap-around breech assembly seemed like a promising design solution in the early stages of the project. However, it was implied in the literature that the wrap-around design was not suitable for tests which required higher pressures, but at which specific pressures and why the design would fail to function was not described [10]. Furthermore, several designs of test rigs are not accessible for the public to view due to secrecy reasons, which further limited the gathering of valuable information.

5.2 Product specification

The requirement specification conducted early on in the project proved to be a powerful tool, as many ideas and concepts quickly could be dismissed once they were evaluated against the requirement specification. Some requirements arose as a consequence of new ideas or concepts, indicating that the requirement specification is not complete and is in need of further work. Specifically, criteria number 4 and 5 was introduced later on in the project, as SAAB employees expressed that some new ideas might not work since the obtained acceleration against time curve that the components are exposed to would be too dissimilar to that of a real launch. Future work might be needed for some criterions, especially criterion 13 and 14 which relates to how dangerous and how easy the test rig is to operate. Both criterion 13 and 14 are important and have been relevant for the project, however as the test rig develops further what exactly “non dangerous” and “easy to use” means should be concretely described.

5.3 First concept iteration

The first concept iteration was conducted to decide which method of acceleration the test rig should utilise. Three different concepts with three different methods were considered, including concept A, acceleration achieved through impact between metallic bodies, concept B, acceleration achieved through the usage of explosive materials and concept C, acceleration achieved through the usage of pressurised gas.

Yet another method which seems worthy of careful consideration was found later in the project, due to limited time this method was however neglected. The method resembles concept C, in the way that the components are placed in a projectile and accelerates due to pressurised gas being exerted on the projectile. With this method a closed barrel is used, which means that shockwaves will travel from the projectile to the end of the barrel and back to the projectile, leading to a retardation of the projectile. If the components in the projectile are placed in reverse, compared to the direction of the projectile's movement, the retardation of the projectile will be felt as an acceleration for the components, thus the components can be exposed to a large acceleration at the same time as the projectile slows down. An illustrative drawing of the aforementioned acceleration method can be viewed in Figure 31 below.

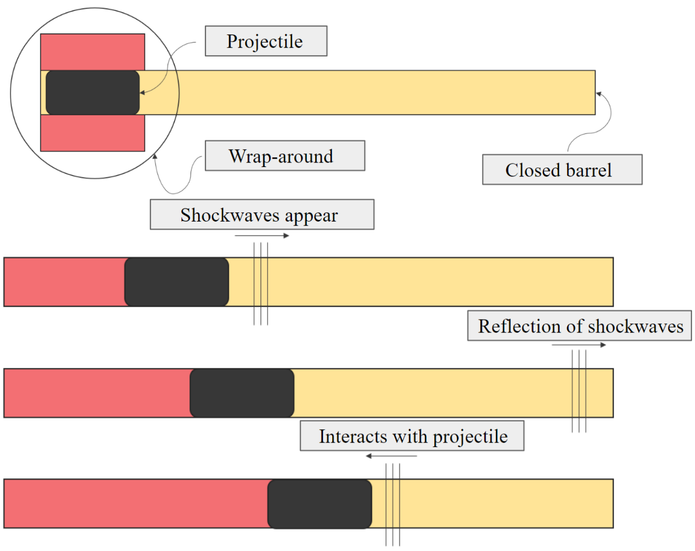


Figure 31: Illustration of alternative acceleration method.

While concept A was dismissed due to an inability to fulfil criterion number 5, which is a requirement, concept B was dismissed due to criterion number 13 which is a wish. Therefore, concept B should not be completely neglected, since a modularly designed test rig which combines concept B and C might be a good solution. The main reason to combine concept B and C is that concept B, according to the literature, is better suited to reach higher projectile accelerations, while concept C might be a better solution for lower accelerations.

5.4 Second concept iteration

The second concept iteration concerned the design of the test rig and aimed to limit the scope of possible designs. Both concept II and III were presumed to be unnecessarily powerful, therefore concept I was chosen for further development. Furthermore, concept II and III would likely have a higher cost per launch and a longer reload time due to a need for disassembling and reassembling of more components.

5.5 Third concept iteration

The third concept iteration aims to find a more specific design solution which could launch the projectiles in accordance to the requirement specifications.

Future work regarding the trigger mechanisms used for the concepts in the third iteration will be covered later on in the discussion. The following is a list of subjects for future work that has to be conducted if any concept were to be designed to completion.

- External components necessary to the test rig have not been considered, such as a stable stand at which the barrel and the gas tank can be placed.
- Rigorous structural calculations for the gas tank and barrel, such that the tank and the barrel are manufactured to withstand hundreds of launches without failing due to the pressure and temperature cycles said componentes are subjected to.
- The barrel length needs to be decided. While it varies for the different concepts, the peak acceleration of the projectile should be reached before the projectile has travelled approximately 1 metre in the barrel, so a longer barrel is not necessary for the acceleration of the components. However, there might be other reasons to extend the length of the barrel, a longer barrel could for example, through applying friction to the projectile, reduce the velocity of the projectile before reaching the muzzle.
- Components through which the gas will travel during a launch should be optimised, such that the gas flow is not obstructed by unnecessary sharp angles for example.

For concept 1, the axial shear pin based design, future work could be conducted to design a mounting bracket. The mounting bracket should be placed inside the tank and fixate the axial shear pin such that the pin is coaxial to the barrel during every launch. Furthermore, the mounting bracket should also be removable from the tank such that the operator can replace the broken shear pin and conduct a new test.

Future work is needed for concept 3, the rupture disk based design, to optimise the reloading processes between launches. Once the tank and the barrel are disassembled by unthreading the outer collar, there should be sufficient space for the operator to remove blocks and replace rupture disks and a projectile with ease. Furthermore, future design work is needed to introduce an inlet, which controls the gas pressures between the rupture disks, either by passing it through the middle block or by some other method.

5.6 Calculations

Calculations were carried out to estimate what the projectile dynamics would be for a test rig which is designed in accordance with concept 2. No detailed design of concept 2 was developed when the calculations occurred, therefore all design parameters are estimated. The valve based model contains two notable assumptions, firstly that the temperature of both gases are constant throughout the launch and secondly that both bodies of gas are assumed to be homogeneous in relation to state properties, following the assumptions made in [15]. Even though both assumptions will overestimate the acceleration of the projectile, the calculations indicate that a valve based design would not reach the desired projectile accelerations.

Calculations were also carried out to estimate the projectile dynamics of a test rig designed in accordance with concept 3. Like the calculations regarding the valve based model, the design parameters were to a large degree estimated. The gas was assumed to undergo an adiabatic process, which is a good approximation according to [10]. In contrast to the valve based calculations the change in gas temperature is taken into account, however the gas is assumed to be homogeneous. The calculations indicated that a design based on rupture disks would be able to reach projectile accelerations just above 32000Gs, if it was possible to pressurise the gas in the tank to 40 MPa and find rupture disks with a burst pressure above 20 MPa.

Both calculations are however conducted by models which lack accurate information. To estimate the projectile dynamics in closer accordance to reality the following steps can be taken.

- Use a more sophisticated gas model, either the Lagrange Gradient model, found in [17] could be used or some software which allows for computationally heavy and sophisticated gas models.
- Calculate and account for the recoil force, the degree to which this impacts the projectile dynamics is unknown.
- Analyse the frictional force between the barrel and the O-ring(s) mounted on the projectile, and how the magnitude of frictional force changes throughout the launch.
- Analyse the drag coefficient of the projectile, and quantify the magnitude of drag losses which reduces the acceleration of the projectile.
- Analyse the shockwaves, where they occur, how they propagate and how they impact the projectile during a launch.

Although the aforementioned steps were proposed as ways in which a better estimation of the projectile dynamics could be obtained, the steps are also useful in more ways. For example, the magnitude and propagation of the shockwaves and a more accurate description of the gas pressure and temperature throughout a launch, are all important factors to account for when selecting the material for the gas tank and the barrel. Furthermore, the recoil force will not only impact the projectile, it will also impact the whole launcher, which requires that sufficient damping has to be integrated into the design of the test rig.

5.7 Trigger mechanisms

As concepts and ideas were proposed, developed and evaluated throughout the project, it became clear how big the impact the choice of trigger mechanism was for the test rig. Further work is recommended on this subject, as the author(s) believe that there is some better suited trigger mechanism yet to be discovered. Therefore, a section of the discussion and future work chapter is dedicated to trigger mechanisms, to elaborate on the advantages and disadvantages of different trigger mechanisms and suggest topics for further research and work.

A quick calculation with the help of equation (2.14), suggests that a gas pressure of 23.5 MPa would be sufficient to reach a projectile acceleration of 20000Gs, if the weight of the projectile is 150 g and have a cross-sectional area of $\pi 0.02^2$ square metres and if friction and P_{atm} is neglected. Although this calculation is oversimplified, its outcome is promising since it wouldn't be challenging to pressurise a gas in a tank to 23.5 MPa and design a projectile with said weight and cross-section. The role of the trigger mechanism is twofold. Firstly to allow the gas to become sufficiently pressurised without letting the gas act on the projectile, secondly to release the gas and launch the projectile so that the components are exposed to the pressure which leads to the desired acceleration.

One phenomena that has to be taken into account with trigger mechanisms is that any trigger mechanism will take some time to open, during which the flow of the gas will be limited. In other words some time will pass from the moment the trigger mechanism is closed until the trigger mechanism is completely open. In the case of valves this opening time is referred to as switch time, which is a measurement of the time it takes a valve to switch from completely closed to completely open or vice versa. In Figure 32 below, the influence of the switch time is illustrated.

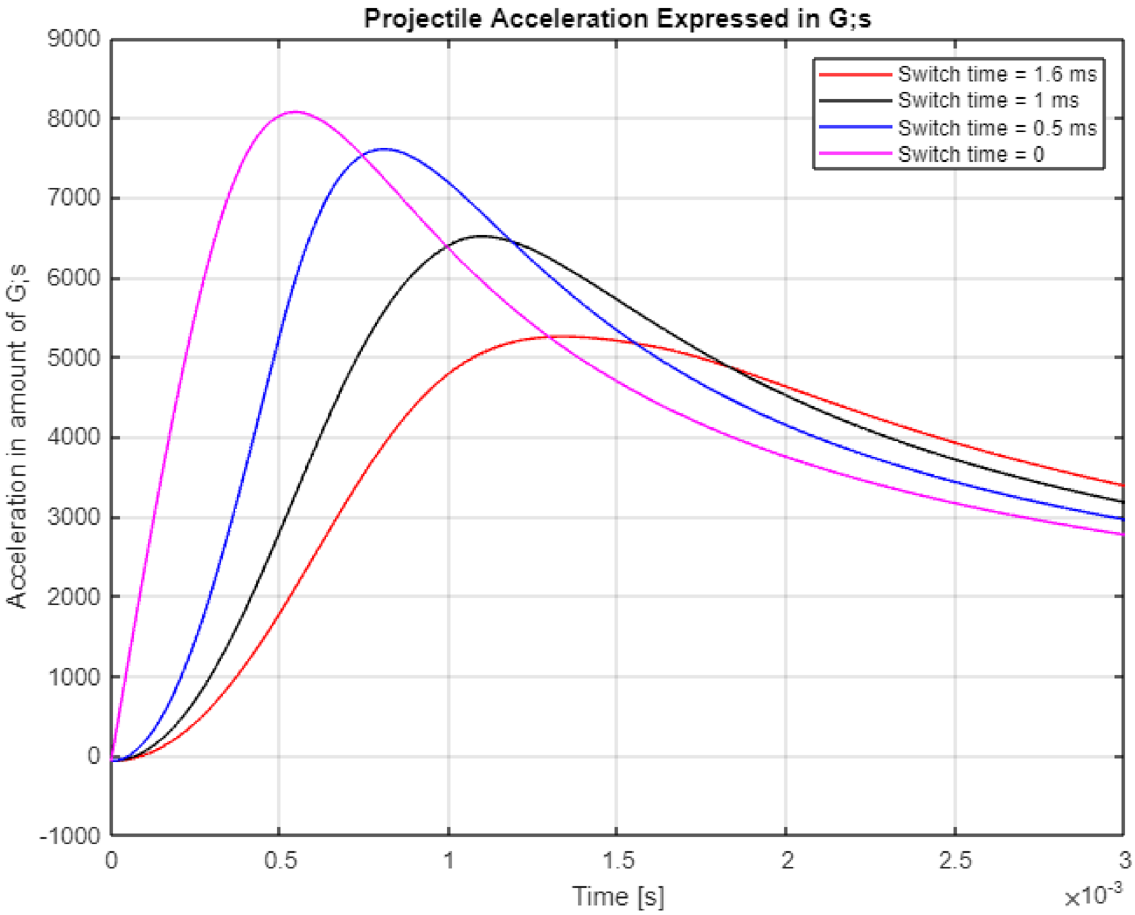


Figure 32: Acceleration against time curves for projectiles in the valve based design, where the only differing parameter is the switch time.

The curves presented in Figure 32 are obtained through the usage of the valve based model and the code in Appendix F, with the design, fixed and operational parameters presented in Table (3, 4 & 5) but with different switch times, t_{switch}. While the curves presented in Figure 32 are completely dependent on the calculation model and the chosen parameters a clear trend is presented, where quicker switch times leads to higher accelerations achieved in shorter timespans.

Another phenomena which is of importance is the flow capacity of the trigger mechanism, that is how much fluid can travel through the trigger mechanism under a given time span. The flow capacity of a valve is often calculated through the flow coefficient C_v, which is a unitless coefficient determined by the valve's capacity to let a fluid of a given temperature pass through it under a given pressure drop under a certain timespan. In Figure 32 below the influence of the flow coefficient C_v is illustrated.

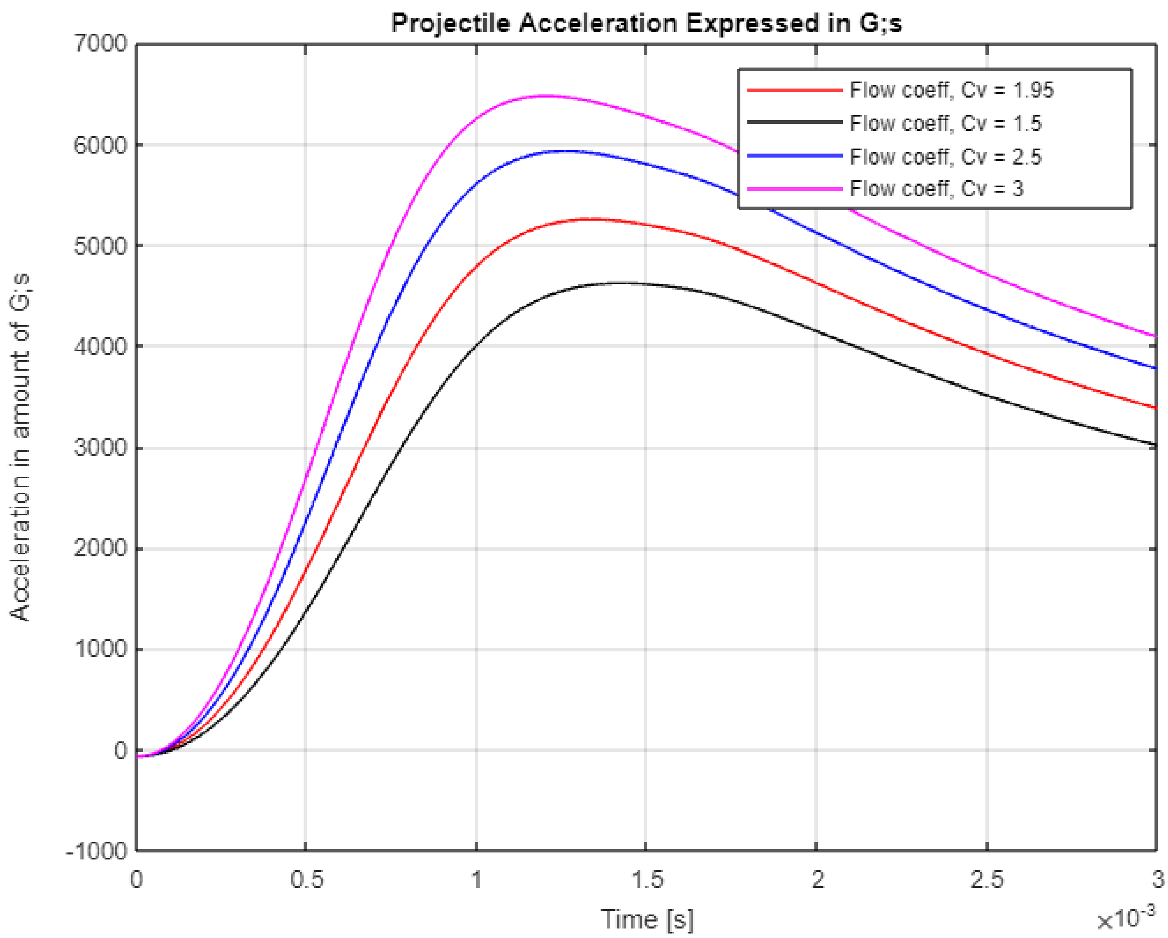


Figure 33: Acceleration against time curves for projectiles in the valve based design, where the only differing parameter is the flow coefficient C_v.

Again the curves presented in Figure 32 are obtained through the usage of the valve based model and the code in Appendix F, with the design, fixed and operational parameters presented in Table (3, 4 & 5), however the flow coefficient C_v is altered instead of t_{switch}. According to the curves presented in Figure 32 the flow coefficient also influences the achieved acceleration and to a lesser extent the timespan in which the maximum acceleration is reached. Furthermore, the flow coefficient is not as limited as the switch time, when it comes to possibilities to optimise the design. As indicated by Figure 32 and 33 the switch time and the flow coefficient plays a large role in the achieving higher accelerations, however both parameters can be very challenging to find reliable values for. The influence of both parameters were neglected in the rupture disk based calculation model, due to the difficulty in finding values for switch time and flow coefficient for rupture disks. The switch time can be estimated with equation (2.13), however the equation fails to describe what the flow characteristic of the gas will be during the disk opening. The flow coefficient of a rupture disk is commonly not presented by the manufacturers. However the coefficient can be calculated, but such a calculation would require the values of many parameters as presented in [28].

A valve was considered as a trigger mechanism, the calculations conducted in section 3.4.1 concluded it would be hard or even impossible to find a valve with sufficient properties, where the critical properties are the operating pressure, the flow coefficient and switch time. However, a valve as a trigger mechanism has some obvious advantages compared to other options. From an economical perspective a valve is an outstanding option as a trigger mechanism, as the valve does not introduce any cost per launch. Furthermore, depending on the choice of valve, it can be simple to regulate the gas flow such that a broad range of projectile accelerations can be achieved. Future work can be conducted on the subject of finding or manufacturing a valve with a combination of quick enough switch time, large enough flow capacity and the rigidity to withstand operating pressures around 40 MPa. It is however unclear how fruitful such an endeavour would be.

The chosen type of trigger mechanism was rupture disks, on the basis that a design with rupture disks could, according to the calculations conducted in section 3.4.2, meet the requirements set by SAAB. A rupture disk based design seems like a good solution, since it accomplishes sufficiently high projectile accelerations and allows for a wide range of projectile accelerations by selecting rupture disks with a certain burst pressure. However, a rupture disk design has some problematic features. Firstly, two rupture disks are bursted in every launch, leading to a high cost per launch. Secondly in between every launch the used rupture disks needs to be disassembled such that two new rupture disks can be mounted, which leads to longer times between tests. To mitigate said problematic features, further work has to be conducted on a design which simplifies and quickens the rupture disk assembly and disassembly process, secondly, more work has to be conducted on the subject of minimising the cost of obtaining rupture disks.

Mainly mechanical failure actuated alternative trigger mechanisms were considered, which releases the projectile as a consequence of some component(s) breaking. Using projectiles with a deformation ring was quickly dismissed, mainly due to the fact that such a solution would lead to great amounts of wear in the barrel. An axial shear pin seemed like a better alternative, however both alternatives need to be further investigated to answer the following questions.

- How reliable is the load at which the pin or the ring fails, i.e. how much does the magnitude of pressure which actuate the trigger mechanism vary?
- What is the cost of these solutions, and how do they compete against the cost of two rupture disks?
- How much will the shear pin and the deformation ring elongate before failure, and is there a design solution which accounts for these deformations and still accomplishes good projectile launches?
- Will any splinters from the failure damage parts in the test rig, such as the barrel?

There are however other ways to actuate alternative trigger mechanisms. A slightly different version of the axial shear pin is to fixate the projectile to a burst bolt, which is a bolt with some integrated explosive material. In contrast to the axial shear pin, the burst bolt can be actuated externally by the operator, which avoids the problem of having to rely on the shear pin to fail under the right gas pressure. However, combustions at gas pressures from 35 MPa and above can be dangerous, especially if the gas is hazardous at said pressures. A trigger mechanism which is mechanically actuated by some arm which holds and releases the projectile was also considered. Such an arm would however be very difficult to design, due to the fact that the arm must be small enough to not disrupt the flow, be strong enough to withstand the gas pressure and be placed in the gas tank without implementing any gas leakage.

Some other methods exist, which completely avoids the use of any trigger mechanism. One example is the wrap-around breach assembly, where the projectile by the means of two O-rings seals the gas from the gas tank until a pressure is applied to the projectile by an inlet, initiating the launch. The wrap-around design seems like a good solution, since the design is comparatively cheap due to no parts in need of replacement in between launches. Furthermore, the design allows the operator to easily expose the projectile to a wide range of gas pressures. However, future work is required to analyse which magnitudes of displacements that are allowable. Too big displacements can lead to damage to the components inside the projectile and more importantly misfiring due to O-rings not sealing in the correct way. Further work can be conducted on the wrap-around concept by optimising the choice of material and geometry of the projectile, and then finding out what the acceleration limit would be with a rigorously optimised projectile. There are however other questions which have to be answered before a wrap-around design could be finalised, some of which are presented below.

- Analysis of the O-rings. That is, how well do they fixate/seal the projectile until launch? How big is the risk of misfiring, due to bad mounting of O-rings or wear in the barrel etc? And how can these risks be minimised?
- How will the gas propagate from the wrap-around gas tank down and through the barrel? What pressure will the projectile be exposed to, given an initial gas pressure in the wrap-around tank?
- What are the magnitudes of the frictional forces the projectile will be exposed to during a launch?
- What is the optimal design of the wrap-around tank?

6 Conclusion

Below follows the main conclusions which can be drawn from this thesis work based on the used methods.

- A test rig designed with a valve as a trigger mechanism will not have the capability to accelerate the components to a sufficient magnitude. If a valve with greater properties in regards to operating pressure, switch time and flow capacity is obtained, then a valve based design could meet the requirements set in criterion 1. However, if no such valve is obtained, the maximum acceleration such a test rig could expose the components for seems to be around 5000Gs.

- A test rig designed with the wrap-around breach assembly is a promising solution. However further analysis is required to conclude which projectile displacements lead to malfunction of the O-rings.

- A test rig with two rupture disks as a trigger mechanism has the capability to meet all the requirements set in the requirement specification, indicated by the calculations conducted in this study. A concept containing two rupture disks as a trigger mechanism has been developed, which is presented in the results section.

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Appendix A - Requirement specification

Nr	Criteria	Requirement / which	From	Level of priority
1	The test rig should be able to accelerate the projectiles in the span of 4000Gs-20000Gs.	Requirement	SAAB	5
2	The projectiles, accelerated by the test rig, should have the ability to carry components with a diameter up to 30mm and a weight of at least 90g.	Requirement	SAAB	5
3	The test rig should have some reliable system in place, which measures the acceleration of the projectiles for every launch.	Requirement	SAAB	5
4	The projectiles shall reach the desired acceleration, measured from rest, in 2 milliseconds.	Requirement	SAAB	5
5	The projectile shall have an acceleration equal to, or greater than, the desired acceleration for 0.5 milliseconds during every launch.	Requirement	SAAB	5
6	The components should be able to be tested with any temperature in the range from -54℃ to 71 ℃ in accordance with STANAG 4170 and AOP-20.	Requirement	SAAB	5
7	The maximum allowable difference between the desired acceleration and the obtained acceleration is + / - 500Gs for every launch.	Requirement	SAAB	5
8	The test rig should contain some system, which retards the projectile in an unharming way such that further analysis can be conducted.	Requirement	SAAB	5
9	Any individual test done with the acceleration rigg should cost less than 1000 kr.	Wish	SAAB	4

10	The test rig should also be able to accelerate the projectiles in the span of 1700Gs-4000Gs.	Wish	SAAB	4
11	The test rig should be able to launch the following component	Wish	SAAB	2
12	The test rig should also be able to accelerate the projectiles in the span of 20000Gs-40000Gs.	Wish	SAAB	2
13	The test rig should be non dangerous, which excludes usage of explosive and toxic matter.	Wish	SAAB	3
14	The test rig should be easy to use, which implies that no special education or critical manual labour should be needed to use the equipment.	Wish	SAAB	2
15	The projectiles should be reusable.	Wish	SAAB	3
16	The test rig should also be able to launch components with ...mm in diameter.	Wish	SAAB	2
17	The retardation of the projectile should be measured every launch.	Wish	SAAB	1
18	The test rig should be modularly designed, which allows for different components, like barrels, to be changed to optimise the launch conditions.	Wish	Students	3

Appendix B - First concept evaluation

Nr	Criteria	Requirement/ which	Level of priority/weight	Concept A	Concept B	Concept C
1	The test rig should be able to accelerate the projectiles in the span of 4000Gs-20000Gs.	Requirement	5	3	5	4
4	The projectiles shall reach the desired acceleration, measured from rest, in 2 milliseconds.	Requirement	5	5	5	4
5	The projectile shall have an acceleration equal to or greater than the desired acceleration for 0.5 milliseconds during every launch.	Requirement	5	0	5	5
7	The maximum allowable difference between the desired acceleration and the obtained acceleration is + / - 500Gs for every launch.	Requirement	5	2	3	3
9	The test rig should be cheaper per launch than the current test rig, currently (roughly estimated) one launch costs 1000kr.	Wish	4	5	3	3
13	The test rig should be non dangerous, which excludes usage of explosive and toxic matter.	Wish	3	5	0	4
14	The test rig should be easy to use, which implies that no special education or critical manual labour should be needed to use the equipment.	Wish	2	5	3	5
15	The projectiles should be reusable.	Wish	3	1	4	4
Summation without weights				26	28	32
Summation with weights				98	120	126

Appendix C - Second concept evaluation

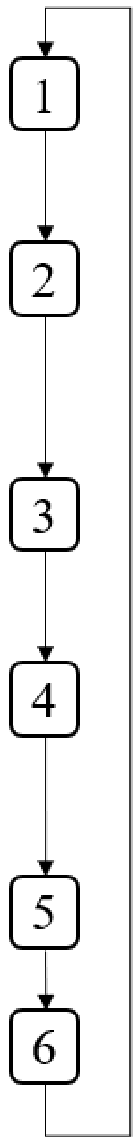
Nr	Criteria	Requirement/which	Level of priority/weight	Concept I	Concept II	Concept III
1	The test rig should be able to accelerate the projectiles in the span of 4000Gs-20000Gs.	Requirement	5	4	5	5
9	The test rig should be cheaper per launch than the current test rig, currently (roughly estimated) one launch costs 1000kr.	Wish	4	5	3	1
Summation without weights				9	8	6
Summation with weights				40	37	29

Appendix D - Third concept evaluation

Nr	Criteria	Requirement/ which	Level of priority/weight	Concept 1	Concept 2	Concept 3	Concept 4
1	The test rig should be able to accelerate the projectiles in the span of 4000Gs-20000 Gs.	Requirement	5	4	0	4	0
7	The maximum allowable difference between the desired acceleration and the obtained acceleration is + / - 500Gs for every launch.	Requirement	5	2	4	4	4
9	The test rig should be cheaper per launch than the current test rig, currently (roughly estimated) one launch costs 1000kr.	Wish	4	3	5	2	5
14	The test rig should be easy to use, which implies that no special education or critical manual labour should be needed to use the equipment.	Wish	2	3	5	3	5
Summation without weights				11	14	11	13
Summation with weights				48	50	53	50

Appendix E - Alternative calculation scheme

Iteration loop with time variable t



$$a^{k+1} = \frac{A}{m}\left[P_{gas}^{k} - P_{atm}C_{drag}\right] - \frac{f}{m}$$

$$v^{k+1} = v^{k} + a^{k+1}t$$

$$x^{k+1} = x^{k} + v^{k+1} + \frac{1}{2}a^{k+1}t^{2}$$

$$V^{k+1} = V^{k} + Ax^{k+1}$$

$$f_v^{k+1} = 1 - \frac{2an_{tot}}{RT^{k}(V^{k+1})^{3}}\left(V^{k+1} - bn_{tot}\right)^{2}$$

$$\Gamma^{k+1} = f_v^{k+1}(\gamma - 1) + 1$$

$$T^{k+1} = \frac{C_2}{(V^{k+1} - bn_{tot})^{\Gamma^{k+1}-1}}$$

$$P_{gas}^{k+1} = \frac{C_1}{(V^{k+1} - bn_{tot})^{\Gamma^{k+1}}} - a\frac{n_{tot}^{2}}{(V^{k+1})^{2}}$$

Appendix F - MATLAB code, valve based model

```
clc
% Fixed parameters
  kB=1.380649*10^(-23);      % Bolzmanns Constant
  R=8.314462618;             % Gas Constant
  EN=3.11*10^19;             % Engineering constant, [Molecules*sqrt(K)/(Pa*s)]

  Ave=6.02214076*10^23;      % Avogadro's Constant [1/mol]
  Molm=28.97*10^3;           % Molarmass for air [kg/mol]
  A=1.374*10^-1;             % Van der Waals constant [Pa*m^6/mol^2]
  B=3.6*10^-5;               % Van der Waals constant [m^3/mol]
  Z=1.1;                     % Compressibility factor
  Gg=1;                      % Specific gravity of air
% Design parameters

  % Geometry
  VTank=0.35*pi*(0.15/2)^2;  % Tank volume
  ABarrel=pi*(0.04/2)^2;     % Cross sectional area of barrel
  VBarrelgap=0.01*ABarrel;   % Initial volume between barrel and valve

% Projectile
  m=0.15;                    % Projectile mass
  Cdrag=1.3;                 % Drag coefficient of projectile
  f=100;                     % Friction between projectile and barrel

% Operational parameters
  PTank=40*10^6;             % Tank pressure [Pa]
  T=300;                     % Gas temperature [Kelvin]
  Patm=101.325*10^3;         % Atmosphere pressure
  PBarrel=Patm;              % Initial barrel pressure

% Starting calculations

% Solving for the number of molecules in the tank and the barrel
  NTankpoly=[1 -(Ave*VTank/B) ((Ave*VTank)^2)*(B*PTank+R*T)/(A*B)
-PTank*((Ave*VTank)^3)/(A*B)];
  NTankroots=roots(NTankpoly);
  NTank=NTankroots(imag(NTankroots)==0);

  NBarrelpoly=[1 -(Ave*VBarrelgap/B) ((Ave*VBarrelgap)^2)*(B*PBarrel+R*T)/(A*B)
-PBarrel*((Ave*VBarrelgap)^3)/(A*B)];
  NBarrelroots=roots(NBarrelpoly);
  NBarrel=NBarrelroots(imag(NBarrelroots)==0);

  % Calculating the maximum ratio
  MaxRatio=(PTank-Patm)/(PTank);

% Miscellaneous
  t=1*10^(-8);               % Stepsize
  x=0;                       % Distance traveled by projectile [m]
  v=0;                       % Projectile velocity [m/s]
```

```
 a=0;                    % Projectile acceleration [m/s^2]
 n=1;
 Ratio=MaxRatio;
 VBarrel=VBarrelgap;
 PenaltyT=1.6*10^-3;        % Switch time, (time it takes for the valve      to fully open)

% Iteration
for Tid=0: t: 3*10^-3
    if (Tid<PenaltyT)
       Cvent=1.95*(Tid/PenaltyT);
    elseif (Tid>=PenaltyT)
       Cvent=1.95;
    end
   Q=EN*PTank*Cvent*(1-Ratio/(3*MaxRatio))*sqrt(Ratio/(Gg*T*Z));
   q(n)=Q;
   NBarrel=NBarrel+Q*t;
   nbarrel(n)=NBarrel;
   NTank=NTank-Q*t;
   ntank(n)=NTank;
   PTank=((R*T*NTank)/(VTank*Ave-B*NTank))-A*(NTank/(Ave*VTank))^2;
   ptank(n)=PTank;
   PBarrel=((R*T*NBarrel)/(VBarrel*Ave-B*NBarrel))-A*(NBarrel/(Ave*VBarrel))^2;
   pbarrel(n)=PBarrel;
   a=(ABarrel*PBarrel-ABarrel*Patm-f)/m;
   acc(n)=a;

   v=v+a*t;
   vel(n)=v;

   x=x+v*t+0.5*a*t^2;
   dist(n)=x;

   VBarrel=VBarrelgap+ABarrel*x;
   vbarrel(n)=VBarrel;
   Ratio=(PTank-PBarrel)/PTank;
   ratio(n)=Ratio;

   tid(n)=Tid;
   n=n+1;
end
figure(1);
 plot(tid, acc, "red")
 title("Projectile Acceleration")
 xlabel("Time [s]")
 ylabel("Acceleration [m/s^2]")
 grid on

 figure(2);
 plot(tid,vel,"red")
 title("Projectile Velocity")
 xlabel("Time [s]")
 ylabel("Velocity [m/s]")
```

```
grid on

figure(3);
plot(tid, dist, "red")
title("Travel Distance")
xlabel("Time [s]")
ylabel("Distance [m]")
grid on

figure(4);
plot(tid, ptank/(10^6), "red")
title("Tank Pressure")
xlabel("Time [s]")
ylabel("Pressure [MPa]")
grid on

figure(5);
plot(tid, pbarrel/(10^6), "red")
title("Barrel Pressure")
xlabel("Time [s]")
ylabel("Pressure [MPa]")
grid on

figure(6);
plot(tid, ((acc)/9.81), "red")
title("Projectile Acceleration Expressed in G;s")
xlabel("Time [s]")
ylabel("Acceleration in amount of G;s")
grid on
```

Appendix G - MATLAB code, valve based model

```
clc
% Calculation parameters
f=100;                  % friction [N]
m=0.15;                 % mass of projectile [kg]
dragcoeff=1.3;          % drag coefficient of projectile, [unitless]

% Volumes of gas at the start of the launch
V_vessel=0.3*pi*(0.1/2)^2;      % volume of the gas vessel/tank [m^3]
Area_barrel=pi*0.02^2;          % cross sectional area of barrel [m^2]
V_disks=0.02*Area_barrel;       % volume between the rupture disks [m^3]
V_barrelstart=0.02*Area_barrel; % volume between the downstream rupture disk and the projectile [m^3]

% Operational starting values, pressures and temperatures
P_vessel=40*10^6;           % Pressure in the vessel, controlled by the operator [Pa]

P_disks=P_vessel/3;         % Pressure of the gas between the rupture disks when they break, note that this is
an assumed pressure! [Pa]

Patm=101.325*10^3;          % Atmospheric pressure [Pa]

P_barrelstart=Patm;         % Pressure of the gas between the downstream rupture disk and the projectile [Pa]

T=300;                      % The temperature is assumed to be the same for all bodies of gas [K]

% Gas constants and gas values for air
R=8.314462618;              % Gas constant [J/(mol*K)]
Ave=6.02214076*10^23;       % Avogadro's constant [1/mol]
Molm=28.97*10^-3;           % Molarmass of air [kg/mol]
vdw_a=1.374*10^-1;          % Van der Waals constant [Pa*m^6/mol^2]
vdw_b=3.55*10^-5;           % Van der Waals constant [m^3/mol]
gam=1.4;                    % Ratio of specific heat for air, in reality a function of temperature and pressure
[unitless]

% Starting calculations, find the toltal number of moles and total volume
N_vessel_poly=[1 -(Ave*V_vessel/vdw_b) ((Ave*V_vessel)^2)*(vdw_b*P_vessel+R*T)/(vdw_a*vdw_b)
-P_vessel*((Ave*V_vessel)^3)/(vdw_a*vdw_b)];  % Van der Waals equation, rearranged to obtain a
polynomial for N in the vessel [Molecules]

N_vessel_roots=roots(N_vessel_poly);                                       % To
solve for N, the roots of the polynomial are obtained [molecules]

N_vessel=N_vessel_roots(imag(N_vessel_roots)==0);
% The root without an imaginary component is chosen [molecules]

n_vessel=N_vessel/Ave;                                                      % Converting
molecules into moles [moles]

N_disks_poly=[1 -(Ave*V_disks/vdw_b) ((Ave*V_disks)^2)*(vdw_b*P_disks+R*T)/(vdw_a*vdw_b)
-P_disks*((Ave*V_disks)^3)/(vdw_a*vdw_b)];     % Van der Waals equation, rearranged to obtain a
polynomial for N between the disks  [Molecules]
```

```
N_disks_roots=roots(N_disks_poly);                                          % To solve for N, the roots of the polynomial are obtained [molecules]

N_disks=N_disks_roots(imag(N_disks_roots)==0);                              % The root without an imaginary component is chosen [molecules]

n_disks=N_disks/Ave;                                                        % Converting molecules into moles [moles]

N_barrelstart_poly=[1 -(Ave*V_barrelstart/vdw_b)
((Ave*V_barrelstart)^2)*(vdw_b*P_barrelstart+R*T)/(vdw_a*vdw_b)
-P_barrelstart*((Ave*V_barrelstart)^3)/(vdw_a*vdw_b)];   % Van der Waals equation, polynomial for N [Molecules]

N_barrelstart_roots=roots(N_barrelstart_poly);

N_barrelstart=N_barrelstart_roots(imag(N_barrelstart_roots)==0);

n_barrelstart=N_barrelstart/Ave;

n=n_vessel+n_disks+n_barrelstart;                     % Total number of moles once the all the gases are combined [moles]

V=V_vessel+V_disks+V_barrelstart;                     % Total volume of the gas, once combined [m^3]

Pgas=((n*R*T)/(V-n*vdw_b))-vdw_a*(n^2)/(V^2);         % The resulting pressure, once all the gases are combined [Pa]

fv=1-(2*n*vdw_a)*((V-n*vdw_b)^2)/(R*T*V^3);           % Calculating the value of fv [unitless]

G=fv*(gam-1)+1;                                       % Calculation of the factor [unitless]

C1=(Pgas+vdw_a*(n^2)/(V^2))*(V-n*vdw_b)^G;            % Calculation of constant 1

C2=T*(V-n*vdw_b)^(G-1);                               % Calculation of constant 2

% loop parameters and introduction of vectors
i=1;
t=1*10^(-6);        % Size of timestep
time(i)=0;
x=0;                % Distance travelled by projectile in barrel [m]
travel(i)=x;
v=0;                % Projectile velocity [m/s]
velocity(i)=v;
a=0;                % Projectile acceleration [m/s^2]
acceleration(i)=a;
pressure(i)=Pgas;
Temperature(i)=T;
fvvec(i)=fv;
gvec(i)=G;
```

```
for Time=0: t: 3*10^(-3)
  i=i+1;

  a=(Area_barrel/m)*(Pgas-Patm*dragcoeff)-f/m;
  acceleration(i)=a;

  v=v+a*t;
  velocity(i)=v;

  x=x+v*t+0.5*a*t^2;
  travel(i)=x;

  V=V+Area_barrel*travel(i);

  T=C2/((V-n*vdw_b)^(G-1));
  Temperature(i)=T;

%     fv=1-(2*n*vdw_a)*((V-n*vdw_b)^2)/(R*T*V^3);
%     G=fv*(gam-1)+1;

  Pgas=(C1/((V-n*vdw_b)^(G)))-vdw_a*(n^2)/(V^2);

  pressure(i)=Pgas;

  time(i)=t*(i-2);
End

figure(31)
plot(time, acceleration/(9.81), "red")
title("Projectile acceleration expressed in G;s")
ylabel("Acceleration in amount of G;s")
xlabel("Time [s]")
grid on

figure(32)
plot(time, velocity, "red")
title("Projectile Velocity")
ylabel("[m/s]")
xlabel("[Milliseconds]")
grid on

figure(33)
plot(time, travel, "red")
title("Distance Traveled by Projectile")
ylabel("[m]")
xlabel("[Milliseconds]")
grid on

figure(34)
plot(time, pressure/(10^6), "red")
title("Pressure of Gas")
```

```
ylabel("[MPa]")
xlabel("[Milliseconds]")
grid on
hold on
figure(35)

plot(time, Temperature, "red")
title("Gas Temperature")
ylabel("[Kelvin]")
xlabel("[Milliseconds]")
grid on

figure(36)
plot(travel,acceleration, "red")
title("Acceleration over travel distance")
ylabel("Amount of G;s")
xlabel("Projectile travel distance [m]")
grid on
```

Appendix H - Gas tank drawing