CRANFIELD UNIVERSITY

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Defence College of Management and Technology

Investigations into the Optimisation of Sound Suppressor Geometry

PhD Thesis

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ENGINEERING SYSTEMS DEPARTMENT

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Academic Year 2006 – 2007

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Investigations into the Optimisation of Sound Suppressor Geometry

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September 2006

Abstract

Health and Safety regulations are becoming ever more stringent in order to protect us in all aspects of our daily lives to prevent noise pollution and damage to hearing. For those in the military and some areas of civilian life working with firearms there is a definite need to reduce the sound levels from them. In order to do this a working knowledge of sound moderators and suppressors is considered vital in order to assess their capabilities and optimise their performance.

The project looks at a theoretical model of an integral suppressor for a modified 12 bore shotgun. The model was used to determine the area of holes through the barrel, allowing gas into the suppressor, has the greatest effect on the pressure within the suppressor. It was found that the volume of the suppressor and position of the hole through the barrel did not have such a significant effect on the pressure.

The theoretical work was supported by experimental trials which confirmed the barrel hole size has a significant effect on the pressure. The experimental work also showed for the low pressure system the hole size through the baffles did not have a significant effect on the pressure.

Work was carried out to establish whether current practice for proofing suppressors was sufficient. The results show that proof rounds give a lower pressure in an external suppressor than standard ammunition. Tests on improvised suppressors showed they are effective and allowed a visual analysis on suppressors. Baffles were shown to be advantageous in a suppressor configuration.

Acknowledgments

The author would like to thank Dr D.F. Allsop for his help and guidance with the project.

The author would also like to thank:
Mr D. Miller, Mr S. Champion and Mr J. Harbour for their help on the range.

Dr B. Lawton for his time modifying his program for use with the project.

Mrs S Turner for her advice on pressure transducers.

Mr M. Tawell, Mrs S. Lister, Mr S. Gilby, Mr S. Thomson and Mr J. Knowles for their help with written work.

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Glossary

a – co-volume

l – length

m_c – mass of propellant in kg

p – pressure (in bar unless otherwise stated)

r – radius

R – Gas constant

T – temperature (in K unless otherwise stated)

V – volume (in m3 unless otherwise stated)

EPVAT – Electronic Pressure Velocity and Action Time

HDPE – High density polyethylene

PET – Polyethylene Terephthalate

SPL – Sound Pressure Level

Chapter 1

Introduction

1.1 What is Sound?

Sound is a disturbance propagated through a medium by longitudinal waves as shown in Figure 1

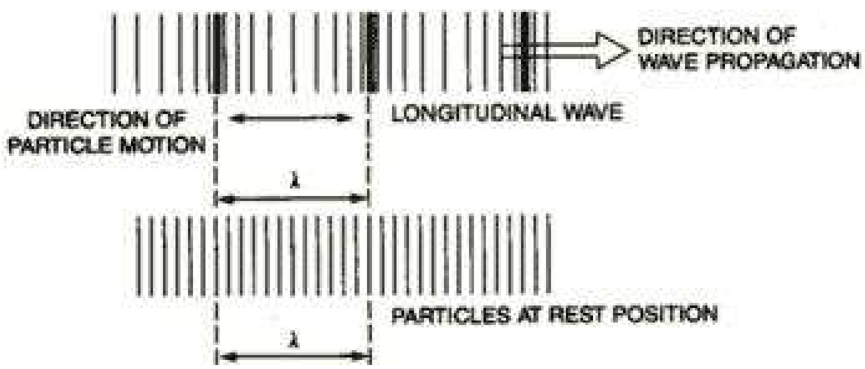


Figure 1 Sound wave propagation

Technically the term applies only to those waves that are audible to the human ear, i.e. with frequencies between about 20 and 20 000 hertz (HZ) **(1)**. Sound travels at approximately 340 metres per second through air at 20^{o}C **(2)** and is measured in deciBels (dB). The simplest form of sound is a sinusoidal wave as shown in Figure 2.

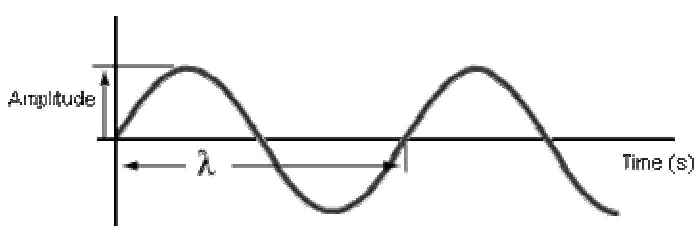


Figure 2 Simple Sound Wave

There are several terms that may be used when referring to sound. These include; wavelength, frequency, pitch and amplitude.

Wavelength is the distance between 2 peaks of the wave and is measured in metres (λ in Figure 2.)
Frequency is of the number of cycles per second and is measured in Hertz (Hz). Frequency is linked to the pitch of the sound - whether a sound seems high or low. As the frequency increases the pitch of the sound increases. **(3)**
The height of the sound wave provides a measure of sound pressure or amplitude.

The technical measurement of sound is in Pascal's (Pa) however deciBels (dB) are generally used for everyday measurements. Pascal's measure in a linear scale where as the deciBel scale is logarithmic. The quietest sound that can be perceived by the average human ear is 20 μPa (0dB) and an unsuppressed .22 rimfire rifle typically produces 200,000,000 μPa (140dB.) **(3)** The logarithmic deciBel scale is much easier to work with and is calculated as a ratio between the measured sound pressure and a standard reference level - 20μPa – the threshold of hearing.

$$SPL = 20\log_{10}\left(\frac{p_1}{p_2}\right)$$

Equation 1 Sound Pressure Level

where SPL is the sound pressure level in dB, p_1 is the measured sound pressure in μPa and p_2 is 20μPa. The ear also hears in a logarithmic scale which makes the use of the dB scale much more common. For comparison purposes Table 1 shows details of everyday noises.

Example sounds	Noise level (dB)
Airbag in car	170
Air raid siren (1m)	140
Thunderclap	130
Car Horn (1m)	120
Fireworks	100
Petrol Lawnmower	90
Alarm Clock (1/2m)	80
Main road traffic	70
Conversational speech	60
Bedroom	40
Whisper	30
Near audible	10
Near total silence	0

Table 1 Comparison of everyday noises (4)

1.2 The Sound of a Weapon

There are three sources of sound that a weapon makes when it is fired. These are from the projectile, the working parts and the expansion of propellant gases from the barrel. If a weapon is to be totally suppressed all these areas must be considered.

1.2.1 The Projectile

A bullet travelling at super-sonic velocity (i.e. greater than $340ms^{-1}$ at sea level) creates the characteristic 'crack' as it breaks the sound barrier. It is impossible to reduce this noise without the use of a sub-sonic round and this crack is the dominant sound heard from the weapon system when firing a supersonic round. An additional sound will be heard on most occasions when the projectile makes impact with the target. This sound of bullet on target can be considerable but this study will not look at terminal ballistics.

1.2.2 The Working Parts

When the trigger is pulled there are many parts of the weapon which move in order for the bullet to be fired. The noise can be reduced by the use of an electrical firing system. These systems have previously been investigated and have proved very successful. One such system has been used for the modification of a shotgun suitable for use when tranquillising animals **(5)**. However much of the noise emanates from the cycling of the operating system of the weapon for reloading it. For single shot weapons this is not a problem but for multi-shot weapons the noise from the operating system can be considerable, especially for self-loading weapons.

1.2.3 The barrel

The noise heard from the barrel is created by the rapid expansion of superheated, high-pressure propellant gas as it is expelled into the much cooler atmosphere. When a shot is fired the gas created from the burning propellant creates a build-up of pressure within the barrel and then forces the bullet from the barrel. The gas is subsequently released from the barrel into the atmosphere producing a shockwave behind the projectile. This creates sound, because a pressure fluctuation has been created as the projectile was released. This noise signature can be reduced by introducing a silencer or suppressor onto the weapon which will allow the expansion of exhaust before being released into the atmosphere. The name ‘silencer’ was used for devices intended to reduce the sound signature of firearms until the Vietnam War when the more accurate term ‘suppressor’ was used. **(11)**

When considering these three factors, suppressors are more often used on subsonic weapons as they have the greatest effect on the overall sound produced by the weapon. Suppressors can be used for rounds which are borderline supersonic, as the suppressor reduces the velocity of the round to below the sound barrier. This is due to holes drilled into the barrel which bleed off the gas from behind the round. This in turn reduces the pressure acting on the base of the projectile reducing the velocity of the round as it exits the barrel.

Another approach which the Russians have developed in order to combat the propellant gas escaping is the use of a gas sealed cartridge in which all of the propellant gas is contained within the cartridge case. The propellant gas forces a piston over a short distance – the length of the cartridge – in which time the projectile is accelerated to the required velocity. This requires very special projectiles, cartridges (which are expensive) and a special gun. Muzzle energy is also low and there are environmental and practical problems when it comes to disposing of the fired pressurised cartridge cases.

1.3 Why use a suppressor?

A suppressor reduces both pressure and velocity of the gas on exit from the barrel by providing a large volume for the gas to expand into. The suppressor also enables a slow release of the gas into the atmosphere. This controlled, slower release at a lower pressure results in a lower sound signature. The sound can only be eliminated completely by reducing the gas from the firing right down to atmospheric conditions which is virtually impossible to create. It would require an oversized contained chamber which would allow the expansion of the gas detracting from the main role of the weapon.

Daily use of a weapon can lead to permanent hearing loss if good ear protection is not used. Paulson **(3)** compiled two tables (not included). The first one lists various sound sources and their maximum SPL (dB) similar to Table 1 and Table 2. The second details the maximum duration per day to which a person should be subjected to a SPL without permanent damage to their hearing. A 12-gauge shotgun measured a SPL of 156dB upon firing but the exposure time is not available. However the exposure time (unprotected) for a SPL of 139dB(A) is only 0.11 seconds suggesting the use of such a weapon even over a short period of time would result in hearing loss. The fitting of a suppressor will help reduce the SPL and would either extend the time the weapon can be used with ear defence or reduce the need for hearing protection resulting in more effective training between an instructor and pupil to take place, as they would be able to communicate more effectively.

Table 2 shows other common military weapon sound levels. It can be seen again that the high sound levels can cause damage during intensive military training.

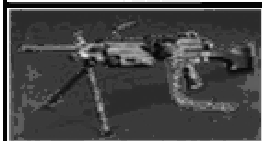
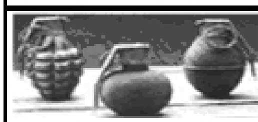
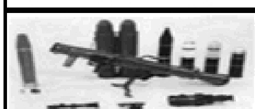
Photo	Model	Name	Location	Sound Level dB(P)
	M16A2	5.56mm rifle	Shooter	157
	M9	9mm pistol	Shooter	157
	M249	5.56mm Squad Automatic Weapon (SAW) fired from a vehicle	Gunner	159.5
	M60	7.62mm machine gun fired from a vehicle	Gunner	155
	M2	0.50 caliber machine gun fired from a vehicle	Gunner	153
	MK 19 Mod 3	machine gun fired from a vehicle	Gunner	145
	M26	Grenade	At 50 ft	164.3
	M3	MAAWS recoilless rifle	Gunner	190
	M72A3	Light Antitank Weapon (LAW)	Gunner	182

Table 2 Sound Levels for various military weapons (6)

The use of a suppressor has additional benefits when used near animals especially when darting for veterinary purposes. When a weapon is fired the unusual sound of a gunshot causes animals to use their instinctive flight/fight response. The flight/fight response causes stress levels in animals to increase dramatically and this can create problems when combined with possible sedatives that may be used in treatment, resulting in permanent harm to the animal. In addition when the animal runs away it may travel several hundred metres into what could be difficult terrain for vehicles to travel and therefore extra time has to be spent reaching the animal. This reduces the time the animal can be treated. With the use of a suppressor the stress inflicted on a darted animal by tranquillising can be reduced and the process can be made much easier for all involved.

Suppressors are also advantageous in covert operations. The benefit of using a suppressor is not just a reduction in sound. It can reduce the swirl of gas which leaves the gun which could disturb the ground and vegetation being used to camouflage the shooter. The elongated time that the gas takes to travel out of the barrel also reduces the muzzle flash which is caused by the gas escaping, coupled with the previously un-burnt propellant combusting. This, along with the noise reduction makes a shooter more difficult to locate, something which is very important in the world of clandestine operations.

It has been found that suppressors lower the noise signature of the weapon significantly enough so that people down range of the weapon turn their attention 45^o to 180^o away from the shooter with confusion over the location of the shooter. This extreme effect only works in a 150^o arc in front of the shooter. This is shown in Figure 3. The three factors which contribute to this effect are the bullet velocity, distance between the observer and shooter and the distance from the observer to the bullet. Witnesses behind the shooter can easily locate them due to the sound of the mechanical working parts.

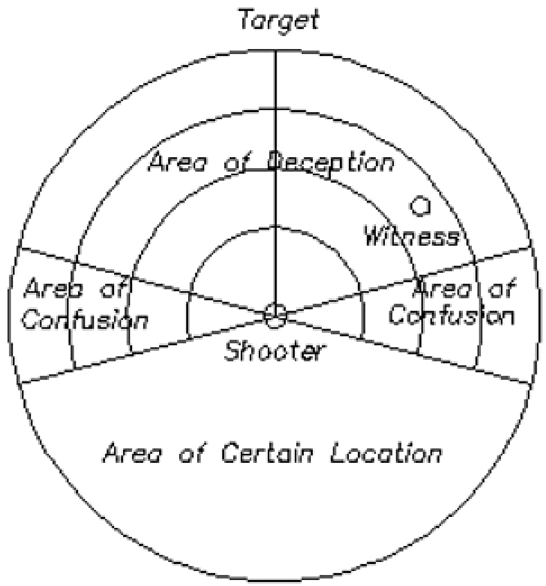


Figure 3 Areas of Deception and Confusion (7)

The Environmental Protection Act 1990 – Part III/Noise Act 1996 Statutory Nuisances: Noise **(8)**, deems the sound from the shot of a weapon is able to be classed as a statutory nuisance. This can cause problems when organising a shoot or similar target practice. There is no fixed sound level for determining when a shot becomes a nuisance as it can depend on the number of shots fired, the duration of the firing and the frequency of shots being fired through the day and year. The official classification of the noise as a nuisance can lead to large fines and removal of equipment. Therefore it is important to reduce the level of sound produced by the weapon being used, which can be achieved by using a suppressor. Military ranges are coming under increasing pressure over the sound levels. Some ranges are situated in conservation areas **(9)** and local populations and conservation groups have concerns over the noise pollution caused by training carried out in these areas. Increased public pressure may force the closure of some ranges or place restrictions on the times and conditions of use, the use of a suppressor on weapons can reduce this problem. The Army is committed to reducing the noise produced by weapons under The Control of Noise at Work Regulations and has practices in place which measure the impulse noise produced by weapons **(10)**. However current issue small arms do not include suppressors.

By using a suppressor there is a reduction in recoil from a weapon. This recoil stems from Newton's Third Law "every force produces and equal and opposite reaction" **(11)** therefore the force of the gas leaving the muzzle will create an equal and opposite reaction on the weapon to the firer. The lower the force of the gas leaving the barrel, the less the recoil of the weapon. There will of course be a force produced by the bullet, this force will not be effected by the use of a suppressor. This can help prevent injury to the shooter and also can help accuracy when more than one shot is fired because the weapon's aim will not have deviated very far from the target after the shot allowing the weapon to be brought back on target more readily. This is particularly important with automatic weapons which have a tendency to drift off target to high right due to recoil force on the shoulder during firing. In this case the use of a suppressor can enable more accurate shooting as the additional weight of the suppressor reduces the recoil force.

There are however certain disadvantages with using a suppressor. The positioning and additional weight may upset the balance of a gun which is initially designed to be balanced when held in the correct manner. Adding a suppressor shifts the centre of gravity of a weapon causing it to be uncomfortable and difficult to use. Weapons also become more bulky when a suppressor is attached and they therefore can be more awkward to transport and use on the move, especially if the suppressor is externally attached to the end of the barrel, rather than integrated in the weapon design.

Attachment of a suppressor to the end of the barrel also shifts the mean point of impact of the weapon. This is not a concern if the attachment is permanent but may raise problems if the weapon is used both with and without the suppressor.

1.4 Background of a suppressor

The designer of the first successful machine gun, Hiram Maxim, a Mechanical Engineer, also designed the first commercially successful suppressor in 1910 **(3)**. He patented a device which could be attached to the end of a barrel which reduced the sound signature of the gun. This external or muzzle suppressor, an example of which is given in Figure 4 is the most common type as it can be attached and removed easily from the barrel by threads or a coupling device. Many problems are caused by an improperly mounted suppressor or one that loosens during repeated use. This causes the suppressor to lose alignment with the bore, possibly resulting in baffle contact with the round which can lead to catastrophic failure. This problem is particularly prevalent with right hand threads which are used to attach suppressors onto barrels. These tend to loosen with continual use of the weapon due to the right hand rifling twist that is found in a large majority of barrels **(12)**.

Figure 4 CAC9 9mm with external suppressor (13)

The alternative is an integral suppressor as shown in Figure 5 which attaches around the barrel. The barrel generally has holes drilled into it in order to bleed gas into the body of the suppressor. This method has its advantages and is useful when rounds are marginally supersonic because the velocity can be reduced to prevent the supersonic crack occurring. In addition, integral suppressors usually extend only a short distance beyond the muzzle, which is an advantage when the weapon is to be used in confined spaces and during transportation. The disadvantage however is that the weapon is permanently dedicated to having a suppressor once it has been modified because holes will have been drilled in the barrel itself. The De Lisle carbine is an example of a weapon with an integral suppressor and was designed with a short section of the barrel that has no holes in it to prevent the projectile becoming un-balanced due to the venting of the gas behind it. However it has been found that properly designed ports will prevent any deviation of the bullet because they reduce the gas pressure pushing against the rear of the bullet as it exits the barrel. **(12)**

One problem which is common with integral suppressors is the fouling within the suppressor by un-burnt propellant. A large build up can cause spontaneous combustion during a firing and can have a lethal effect.

Figure 5 FAMAS S.A.F with integral suppressor (14)

Suppressor designers are constantly trying to optimise the balance between size, weight and noise reduction, which is why there is a wide variety of designs available.

During testing carried out for British Association for Shooting and Conservation (BASC) on various shotguns and ammunition it was found that a suppressor can reduce the noise produced by a weapon using standard and subsonic ammunition as shown below in Figure 6.

Gun and Ammunition	dB
12 Bore + No Suppressor + 28g 7.5	150.3
12 Bore + Suppressor + 28g 7.5	147.1
12 Bore + No Suppressor + Subsonic 28g 7.5	144.6
12 Bore + Suppressor + Subsonic 28g 7.5	138.3

Figure 6 Comparison of deciBel levels for a weapon with and without suppressor

This testing was carried out at a position 5 metres away perpendicular to the gun muzzle. The tests were to determine the sound levels produced by a double barrelled shotgun which had been fitted with a sound suppressor, a difficult application due to the geometry of the gun. The gun had been designed with a suppressor to help reduce sound pollution on shooting grounds.

1.5 Principles behind a suppressor

There are three principles behind a suppressor which can be combined to create the most effective model for the situation.

1.5.1 Energy Absorption

Energy absorbing devices such as wire wool, work on the principle of heat transfer from the hot propellant gas to the cooler metal of the sound suppressor and its contents. This heat transfer reduces the energy of the gas and therefore its ability to do work and in turn lowers it the sound emitted. Maximum heat transfer is achieved by maximising the surface area and also using a heat sink.

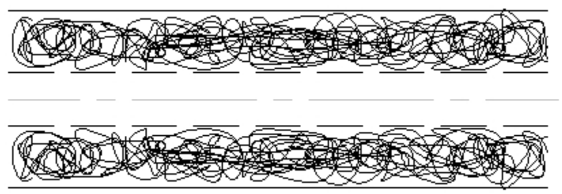


Figure 7 Energy Absorption Schematic

As can be seen from Figure 7 the gas is allowed to escape from the barrel into the chamber where wire wool absorbs the heat of the gas. Reducing the temperature of the gas reduces its pressure and thus the sound levels.

1.5.2 Energy Dissipation

Dissipative devices make the gas do work, reducing the overall energy of the gas before it is released into the atmosphere. The work can take place in many different ways for example in the form of viscous shear on channel walls or by moving a device such as a rotor. This method has its disadvantages as it is complicated to design and manufacture and can also create a turning moment for the weapon.

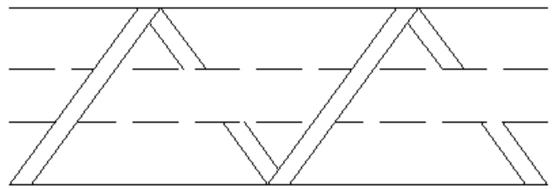


Figure 8 Energy Dissipation Schematic

Figure 8 shows gas is allowed to escape from the barrel and is directed by spirals along the suppressor. The gas constantly changes direction and thus energy is transferred.

1.5.3 Energy Containment

Containment devices consist of chambers in which the gas can expand. This expansion of the gas reduces the energy concentration and allows the gas to escape at a reduced pressure and velocity thus reducing the sound heard.

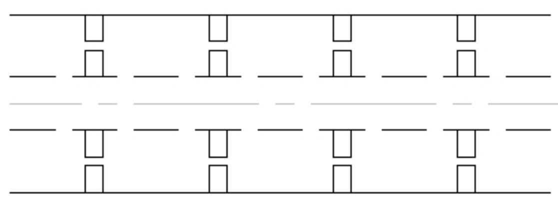


Figure 9 Energy Containment Schematic

Figure 9 shows gas allowed to escape from the barrel into chambers where the gas expands before being released.

It was initially believed when designing silencers that many baffles with a narrow spacing were needed to achieve maximum performance, however designs have changed and now small baffles with wider spacing is possible due to complex asymmetric designs. **(12)**

1.6 Literature Review

There have been many designs formulated for reducing the sound profile of a weapon over the years. Many of the early developments were made in the 1970's and this was mainly empirical in nature termed a "cut and try" approach. Very little work was done using a scientific approach using gas laws and thermodynamics. However Paulson in addition to other literature reviews detailed below, show that calculations for modelling fluid dynamics seem to apply when designing systems with a steady state pressures. However they do not apply when dampening the impulse sounds generated by the firearm **(12)**. There has been very little work done with gas modelling as most established algorithms assume steady state fluid dynamics rather than the intense single impulse of gas flow when the gun is fired. Those that are able to consider the complex flows have been unsuccessful when compared to experimental data **(15)**.

Schmidt **(16)** investigated many different muzzle devices including suppressors. His investigations in 1973 compiled all the research that had been done to date concerning the use of muzzle devices by various authors. He found that several models had been created to predict the gas expansion at the muzzle upon firing. These were generally scaling models from contained conventional explosives. However Schmidt found that the analysis of the effect of muzzle suppressors on the blast was not extensive and only containment principle based devices had been looked at in any detail.

Bixler et al **(17)** studied containment devices in more detail both theoretically and experimentally in three approaches:-

- acoustic theory
- blast theory
- quasi-one-dimensional flow theory

Each approach made many assumptions making the results invalid when compared to the experimental results. The acoustic theory assumed linear motion which is not applicable to the strong non-linear muzzle blast. The blast theory relied on assumptions which are not applicable to the situation by implying that once the blast wave had travelled into the chamber it remains frozen, this does not occur in a suppressor. Bixler's final theory did not account for reflections of the blast wave in the chambers of the suppressor. In addition it did not account for the projectile and on comparing the equations with experimental results showed the theory to be inappropriate.

Conclusions were drawn that no theoretical model would be able to handle the complex gas dynamics or muzzles and muzzle devices and Schmidt resorted to investigating the experimental measuring of muzzle blast.

Bixler et al **(17)** were found to be the only ones who had conducted a detailed experimental investigation into the attenuation of a weapon by varying the number and spacing of the baffles. It was found that the blast attenuation was seen to increase rapidly with the number of baffles before maximum attenuation was achieved and a gradual decline can then be seen in Figure 10. Limited trials at Cranfield University confirmed these results **(7)**.

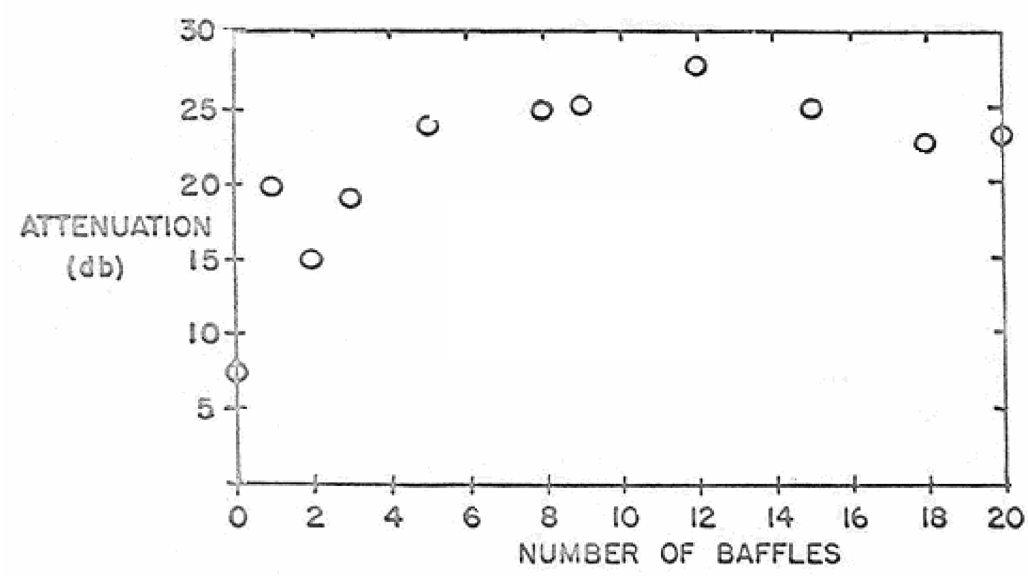


Figure 10 Attenuation of constant length suppressor (17)

Townend and Yendall **(18)** investigated the use of suppressors for blast alleviation for Light Anti-tank Weapon (LAW) style weapons. They assembled equations by Mori et al **(19)** which could determine the pressure ratios before and after a choked orifice. However these equations, when applied to multiple baffles, did not fully consider the recoil of the pressure wave from the surface of the baffle and so these equations therefore do not fully represent the situation and the equations cannot be applied to mutli-stage suppressors.

Skochko and Greveris **(20)** calculated that with maximum heat absorption in a suppressor the attenuation for a typical suppressor would be approximately 6 deciBels. This is supported by a simplified fundamental principle

$$\frac{p}{T} = \rho R = k$$

Equation 2 Ideal Gas Equation

and if a mass of gas is trapped for a short time in a given volume, its density (ρ) remains constant so

$$p \propto T$$

Equation 3 Simplified Gas Equation

where p is the pressure of the gas and T is the temperature of the gas.

This suggests that it would be advantageous to use a material which has high heat capacity and mass when designing a suppressor to maximise the attenuation. Nylon 6 has been used by Smith for the housing of the Short Recoil Locked Breech (SRLB). It has been found that this synthetic material reduces the weight of the suppressor and reduces the sound pressure level because it does not resonate like an aluminium housing **(12)**. However this material has its limitations as it cannot be used in high temperature situations.

Some designs include parts such as wipes. These are generally rubber disks fixed inside a suppressor with a small hole (often smaller than the bullet) to allow the bullet to pass through but limit the amount of gas allowed to follow through. They are no longer commonly used for suppressors as they have a limited life span due to the wear created by projectiles passing through the rubber or plastic baffles. Expandable or frangible bullets will also expand or fragment on contact with wipes. This will affect the accuracy of the round as well. However wipes do have benefits as they produce a relatively low frequency sound signature which is perceived as less of a typical gunshot noise. Also if wipes are used in a suppressor the overall dimensions can be reduced for the same attenuation **(12)**.

As a continuation of the literature review an investigation was carried out into vehicle exhaust suppressors. Vehicle suppressors can use the same principles as a weapon suppressor, a chamber in which the gas can expand before being released. A material insert is also often used to cause entrapment making the literature applicable to the project.

There are many papers available on the subject of vehicle silencers and some have covered models produced to predict the noise attenuation of common simple types of silencers, a few examples are shown below. However it was found with all the models investigated that there were limitations which made the models ineffective for the work being carried out in this project.

Kirby **(21)** noted that both Boundary Element Method and Finite Element Analysis have both been used as tools to model the gas flows in exhaust suppressors and "require numerical techniques in order to obtain sufficiently accurate predictions." Kirby also formulated a low frequency algorithm which gave "good correlation between both experimental measurements and also more advanced Finite Element techniques" however he found it unsuitable for medium to high frequencies, which are produced during gunshots.

Cummings suggests that computational methods require considerable effort and can be difficult to track **(22)** and other mathematical models are also reliant on very low Mach number velocities, which is not applicable to the situation being investigated **(23)**.

1.6.1 Conclusion

There are many methods of moderating the sounds produced by the gas emitted from the barrel which have been developed from trials. There are large amounts of literature describing the designs of market suppressors however work concerning modelling and predicting the effect within a sound suppressor has been un-successful due to the complex nature of the gases within the suppressor. Comparisons between vehicle silencers do not equate for the high frequencies produced from a shot.

1.7 Aim

To date there has been little research into factors which improve the performance of a suppressor. This project aims to determine which factor has the greatest effect on the pressure within a suppressor in order to achieve maximum sound attenuation for the weapon. The project will use a theoretical model to determine whether modification of the internal dimensions within a suppressor will affect the pressure. These theoretical results will then be quantified by experimental measurements. The project will allow a greater understanding of a suppressor and its performance.

1.7.1 The weapon

A 12 bore shotgun modified to fire tranquilliser darts **(5)** was used in this project. There is a commercial demand for this type of weapon to be suppressed. When tranquillising animals for example, noise must be kept to an absolute minimum to prevent any additional stress caused to the animal and this is an important consideration.

The chamber of the shotgun to be used has been shortened to accommodate the darting cartridge system and the overall length of the barrel reduced to 18" (457.2mm) for practical reasons. The cartridge that the dart is fired from has also been modified to provide a subsonic round. The cartridge consists of a primed 0.357 magnum cartridge which has been shortened, filled with 0.25g of greendot smokeless powder, topped with ballistic wadding and crimped shut. In order for this to fit in the chamber it was fitted within an adaptor. The plastic "dumb" dart is then inserted into the adaptor and then into the chamber. The dumb dart used for this application was a 50mm long piece of Nylon 66 Bar with a diameter 18.4mm, this prevents the wastage of expensive darts during experimentation. These adaptations were made to the weapon as part of a degree project **(24)** and the decision was made by the University that this weapon would be used for the project.

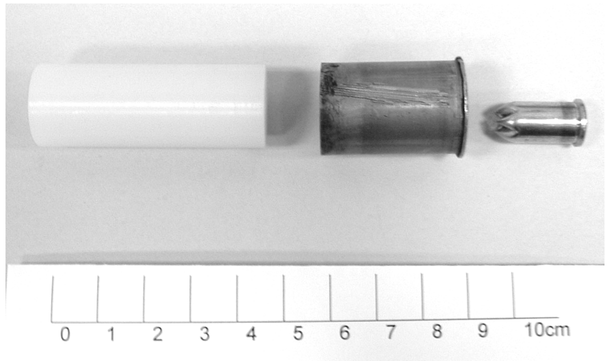


Figure 11 Arrangement of the cartridge showing from left to right the dumb dart, adaptor and 0.357 crimped cartridge

Other weapons such as pistols could be used for this project, as they also fire sub-sonic rounds, or alternatively a standard shotgun. However the results obtained will be generic and applicable to every weapon.

Chapter 2
Theoretical Work

2.1 Factors affecting attenuation

There are many factors which affect the sound attenuation of a weapon. One of these considerations is the initial pressure produced by the gas when it is fired. A lower firing pressure reduces the difference between atmospheric pressure and the pressure in the barrel thus leading to a lower sound pressure level on exit. One simple solution to this would be a reduction in the amount of propellant used, reducing the amount of gas produced. This not a feasible solution for the selected weapon as the cartridge and round have been designed for a specific task with a specific charge and flight velocity.

The size and volume of an attached suppressor is another consideration. As the size of the suppressor increases so does the volume available for the gas to expand into, thus reducing the overall pressure of the gas. The noise signature of the weapon will be reduced but the weapon must be portable and also easy to use. This can limit the size and weight of the suppressor.

The number of holes and their diameter are believed to have an important impact on how the gas enters the suppressor. Many large holes allow the gas to leave the barrel easily. However, for integral suppressors barrel is machined away causing a reduction in the overall length of the barrel and thus reduces the velocity of the projectile. This is a major consideration, as the holes need to be of a size and frequency to allow the gas to escape without overly compromising the performance of the weapon.

The material that the suppressor is made from can also affect the performance of the suppressor. As mentioned in Chapter 1 the suppressor should be made from a material which has a high heat capacity. However it is also thought that a material which has a high diffusivity rate would be beneficial. Therefore the heat can be extracted quickly from the gas and transferred swiftly through the material allowing more heat to be transferred.

All these factors and the practical application for the suppressor are design considerations. Whilst some may have a significant impact on the sound attenuation others may have little effect.

2.2 Modelling Gas flow

2.2.1 Computational Fluid Dynamics

In order to determine what was the greatest factor affecting the attenuation of sound on firing, it was considered best to model the flow of pressure in a gun barrel and suppressor. These factors could then be evaluated and an optimised suppressor produced from these tests.

The use of Computational Fluid Dynamics programs were investigated. One program that it was thought could be used was FlexPDE3. The program was found to be difficult to use as many assumptions had to be made about the conditions in the barrel, such as whether the situation was steady state or time dependant. The equations and meshes that were needed to be formed were found to be very complex and simplifications would make the results meaningless. This is because the fluid flow problem is one that is transient and 3 dimensional, including supersonic flow through complex geometry. Coupled with this is a complex heat flow problem involving heat absorption, conduction, convection and radiation. The use of this program was therefore dismissed.

The use of other programs was then considered and a suitable program, Fluent, was found. However this program was discovered to be far more complex than the one previously considered and a background in Computational Fluid Dynamics (CFD) was imperative. It was estimate that to acquire a working knowledge of the program would take 3-4 months and the time required to write a program for its application would take a similar amount of time. The idea of modelling the gas this way was therefore abandoned due to lack of time available.

2.2.2 Pressure Displacement Modelling

After due consideration and consultation it was decided to use HMSOV a computer program which determines the pressure in the barrel in relation to shot travel down the barrel. The program selected was HMSOV, an internal ballistics model that predicts the pressure/displacement for conventional weapon systems. The program was developed at Royal Military College of Science for the Ministry Of Defence. It runs in Matlab and is pre-programmed to enable modifications to suit the weapon used. This enabled the pressure distribution to be analysed and a suitable design to be developed which would take into consideration the pressure levels generated in the barrel.

The various parameters for the cartridge and gun were determined and then entered into the program. The initial results that were gained were inappropriate as the muzzle velocity of the projectile was too fast compared with the known velocity, determined during experimental trials when developing the tranquilliser darts **(24)**. The various parameters such as the propellant (greendot powder) were then edited to achieve a realistic muzzle velocity. However it was found that some parameters such as the burning rate were now un-realistic (see Figure 12 and Figure 13) because greendot powder burns at a lower rate in reality.

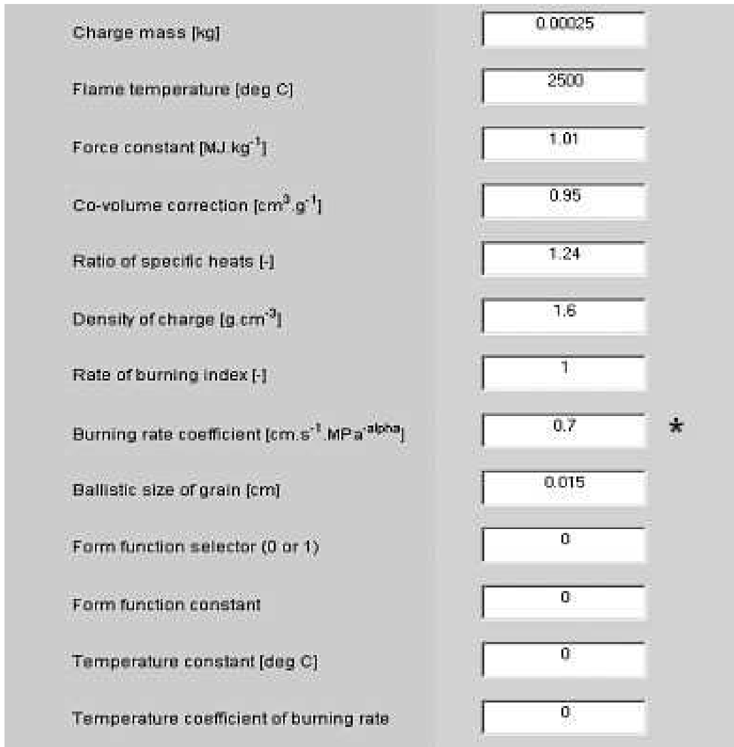


Figure 12 Data entered in HMSOV relating to charge characteristics.

(✱ Note large burning rate coefficient.)

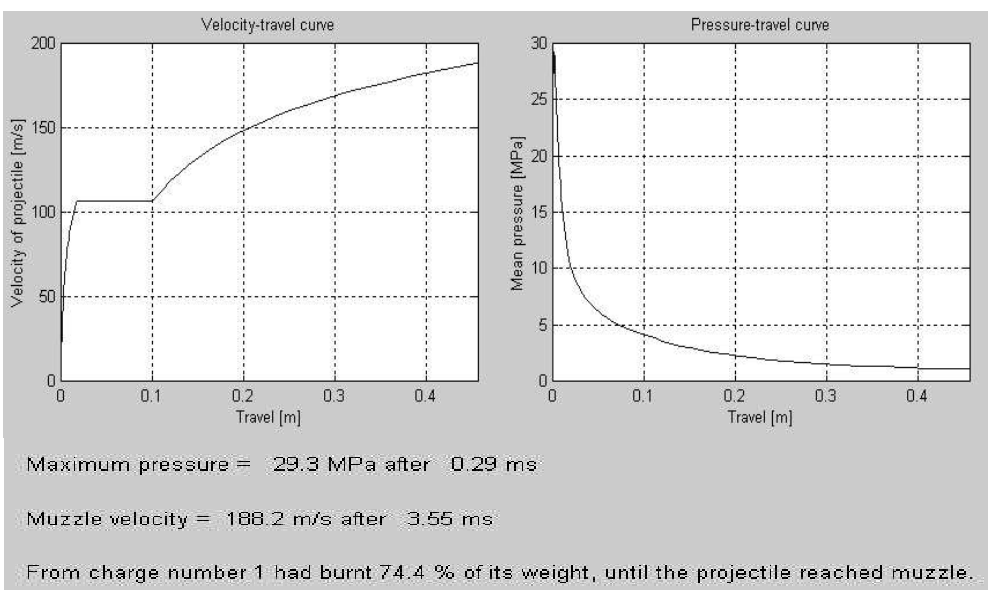


Figure 13 Velocity and Pressure – Travel results. Note approx 25% of propellant is un-burnt which is not realistic.

The underlying problem behind the results was found to be the unusual configuration of the cartridge that had to be used. It consisted of a blank cartridge fitted inside the main cartridge as shown in Figure 14. The end of the blank cartridge was crimped to ensure there was sufficient start pressure to ensure consistent internal ballistic results. In addition there was a restriction in the end of the cartridge to keep the pressure high for the same reason. It was not possible to take account of these factors in the HMSOV program and therefore the results gained were not an accurate representation of the firing.

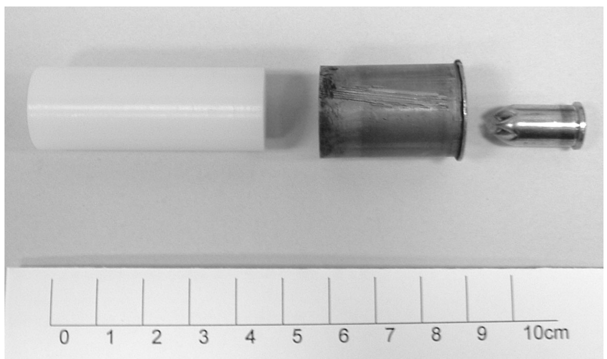


Figure 14 Arrangement of the cartridge showing from left to right the dumb dart, main cartridge and blank cartridge (identical to Figure 11)

A further program was tried which did not rely so heavily on the chamber size of the cartridge. This program (Guntemp7.exe developed by a Cranfield University Lecturer for an undergraduate practical) modelled the barrel heating during the firing of shots but also gave results with reference to the velocity of the projectile. It was written to determine barrel wear during firings. However results were not comparable to the known experimental data which had been gained during previous trials when developing the tranquilliser darts .

2.3 Suppressor Emptying and Filling Gas Modelling

After resorting to experimental methods to obtain results it was later found that a program written by a Cranfield lecturer **(25)** could be modified to allow use in the situation being considered. This program was originally developed to analyse the design of fume extractors on large calibre guns and was based on equations which take into account the energy, gas laws, continuity equations, volumes, mass flow rates, equations of motion and heat losses in the system as detailed in Appendix B. The program was written using the word silencer instead of suppressor, this will be continued through out the chapter. The program allows an iterative calculation which detailed the pressure in the chamber, barrel and silencer along with the velocity at time steps. This program permitted the alteration of the position of the silencer, the changing of the dimensions and size of holes in the barrel and also the size of the chamber of the silencer. The program was written to allow each factor to be modified independently and the effect on the pressure in the silencer and the velocity drop to be established. Simulations would first establish the pressure distribution along the barrel. A comparison with measured experimental data would establish the validity of the program. Simulations could then take into account the addition of a silencer. The factors that were investigated were:

- moving the position of the port from the barrel into the silencer
- changing the size and therefore volume of the silencer
- changing the area of the ports from the barrel to the silencer

A schematic of the system can be seen in Figure 15. Each factor can be changed to and should allow the effect on the pressure in the silencer and evaluate the velocity drop. From this it is anticipated that the program can be used to establish which of the variables produces the most desired effect. The inputs for the silencer program can be seen in Table 3.

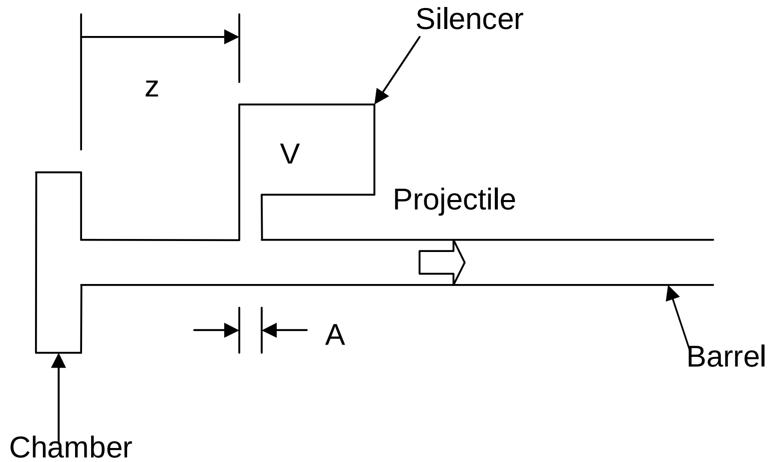


Figure 15 Schematic of System modelled

z - Position from chamber to silencer (0.04m – 0.30m within range of experimental equipment)

A - area of silencer hole ($1.00x10^{-6}$ - $5.00x10^{-3}$ m^2 within range of experimental equipment)

V - Volume of Silencer ($4.00x10^{-5}$ – $8.00x10^{-4}$ m^3 within range of experimental equipment)

Parameter	Input Data	Units
Propellant Energy	3600000	Jkg^{-1}
Co-volume	0.001	m^3kg^{-1}
Web Thickness	0.00002	m
Specific Heat	1700	Jkg^{-1} K
Propellant Density	1600	kgm^{-3}
Linear Burn Rate Co-eff.	$1.10x10^{-9}$	ms^{-1} Pa^{-1}
Charge Mass	0.0003	kg
Form Function	-0.172	
Loading Density	950	kgm^{-3}
Calibre	0.0185	m
Shot Travel	0.458	m
Silencer Hole Position **(z)**	0.02	m
Initial Shot Position	0	m
Silencer Volume **(V)**	0.0000299	m^3
Silencer Area (Charging) **(A)**	0.0	m^2
Silencer Area (Discharging) **(A)**	0.0	m^2
Chamber Inlet Area	$3.14x10^{-8}$	m^2
Shot Start Pressure	3650000	Pa
Shot Mass	.0015	kg
Time Step	0.0000001	s
Run Time	0.02	s
Time steps / Print	100	
R – 0 to stop at shot exit	0	
Igniter Mass	0.000002	kg

Table 3 Input data for Silencer Program

2.4 Theoretical Modelling Results

2.4.1 Simulation – Barrel only (no silencer)

z = 0m

A = 0m^2

V = 0m^3

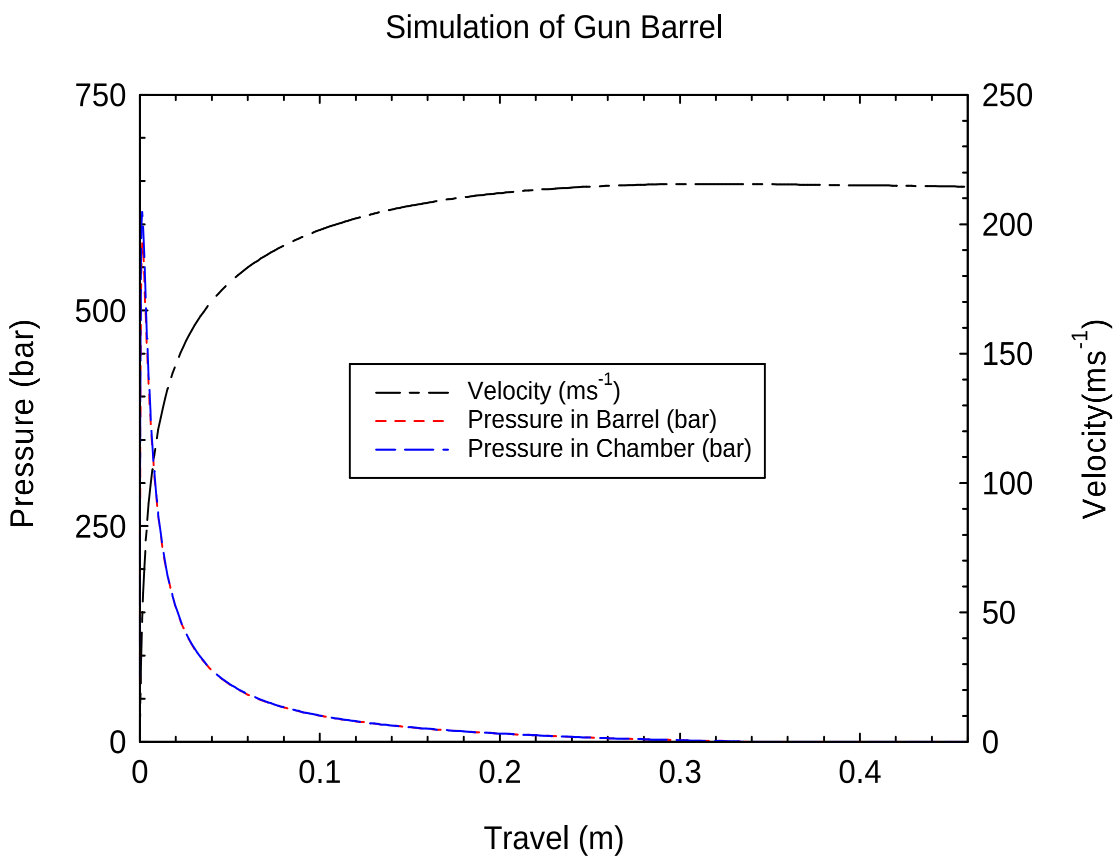


Figure 16 Graph showing pressure in the chamber and barrel and velocity against projectile travel

Figure 16 shows that the predicted chamber pressure fell very rapidly from an initial peak value of 614bar. The pressure dropped to just 10% of the peak pressure in 50mm travel of the projectile. During this 50mm of travel the projectile accelerated to 150ms^{-1} and reached a peak velocity of 214ms^{-1} after 180mm of travel. The measured pressure profile was one of pressure against time rather than pressure against projectile displacement so that it was not possible to compare exactly the predicted curves against the measured curves but peak values and general trends could be compared.

Peak predicted and peak measured values were extremely close to the readings recorded with a recorded velocity between 180-200ms^{-1} (mean 182.5) and pressure of 660bar. The slight difference in the chamber pressure was possibly caused by the unusual configuration of the cartridge which was difficult to model in the program due to the crimping of the loaded cartridge and the way it was held in the adaptor. The difference in the velocity was accounted for by the photo optical chronographs measuring the velocity around 6m away from the muzzle of the gun. Thus the velocity is not the muzzle velocity but a lower one due to the aerodynamic drag on the projectile. It was determined from the graph that the velocity stabilised at 0.18m down the barrel, there was a slight drop of around 1ms^{-1} from the maximum velocity due to the loss in velocity due to friction from the round contact with the barrel.

A difference of 35bar was noted between the predicted chamber and barrel pressure at the start of the shot. This again was due to the unusual configuration of the cartridge within the chamber.

Due to a rapid drop to 10bar within the barrel only 70% of the powder was burnt during combustion. This is realistic but shows that regular cleaning and servicing is essential to prevent the spontaneous combustion of the propellant.

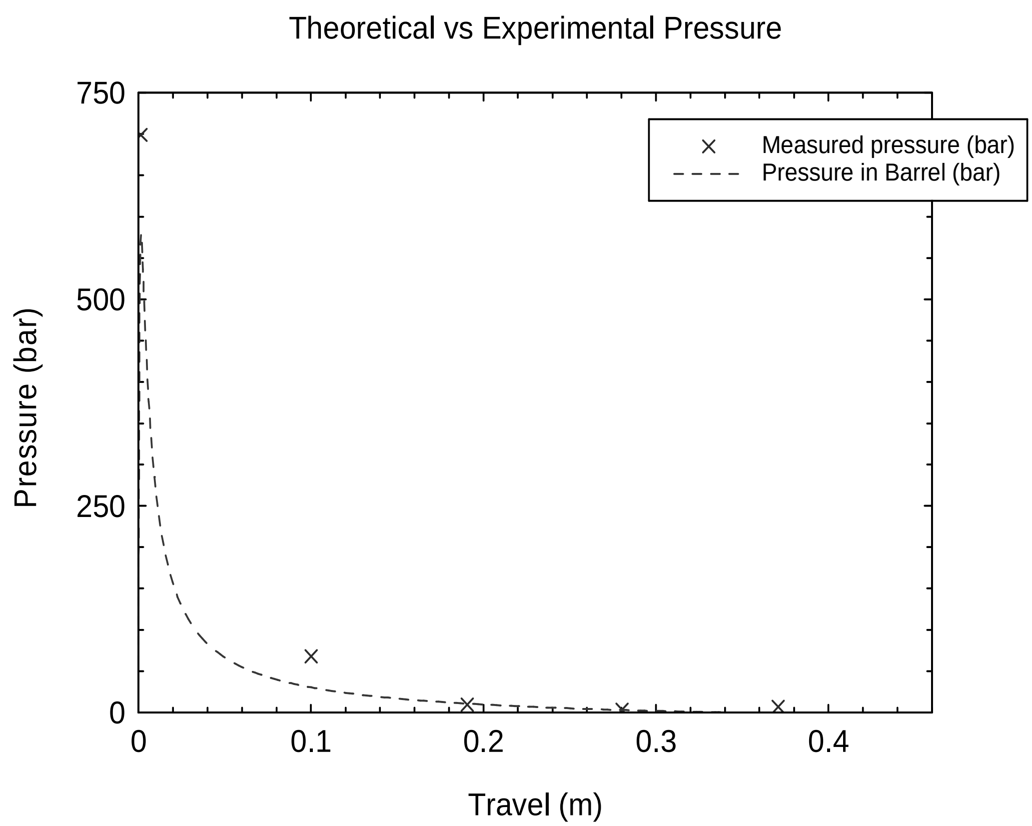


Figure 17 Theoretical vs Experimental Pressures

A comparison in Figure 17 between results carried out in Chapter 3 with initial testing suggests the results to be of the correct magnitude. The high recorded pressure shown at 700bar was measured in the chamber. This pressure is 100bar greater than the maximum calculated pressure in the chamber (not shown in Figure 17 for ease of viewing) the error with this result was expected due to the un-usual configuration of cartridge and chamber.

This comparison suggests that the program can establish results which will be applicable to the experimental work.

2.4.2 Simulation – Silencer, Changing Silencer port position down barrel.

$z = 0.04m – 0.30m$

$A = 2.90x10^{-5}m^2$

$V = 2.90x10^{-5}m^3$

The port position was changed from a minimum of 20mm to a maximum of 0.3m at regular intervals. All other factors were kept constant

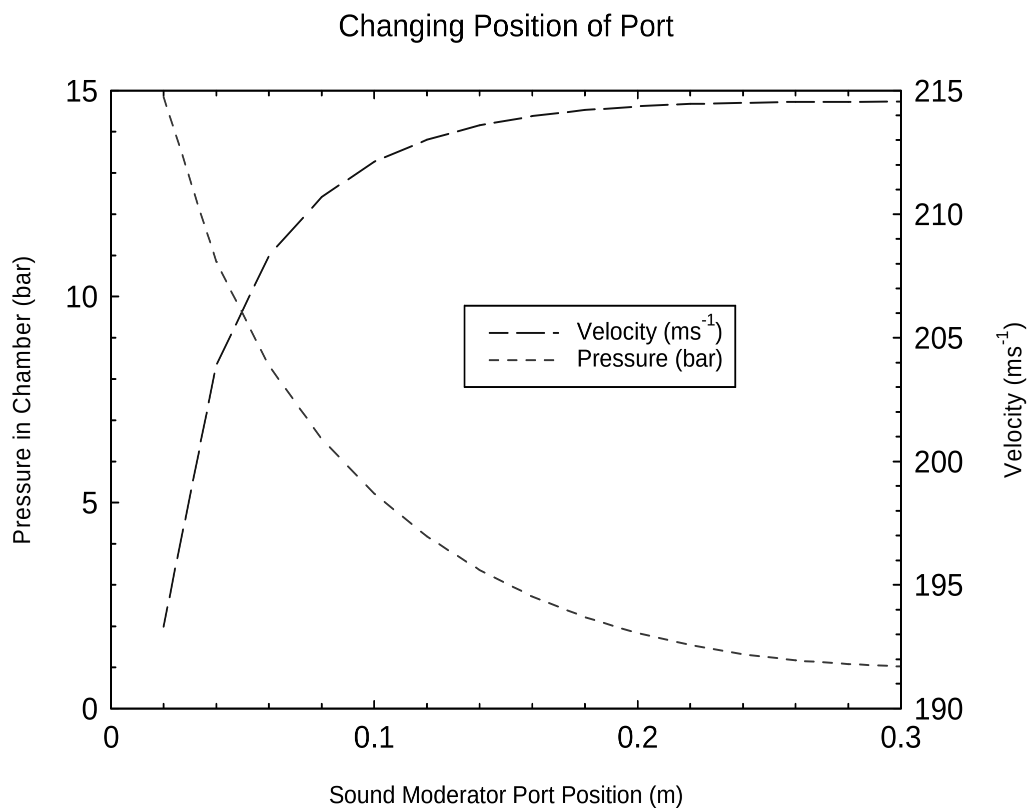


Figure 18 Effect of changing the silencer port position on the silencer pressure and round velocity

Figure 18 indicates that as the position of the silencer port moved further down the barrel the pressure that was measured in the silencer decreased. This decrease was from a maximum pressure of approximately 15bar to just over 1bar (atmospheric pressure.) After 0.2m down the barrel the conditions had reached near atmospheric.

It can also be seen that whilst porting off the gas very close to the chamber (0.02m) reduced the velocity of the projectile it did not reduce the velocity below the level expected of the ammunition (185ms^{-1}).

2.4.3 Simulation – Silencer, Changing silencer volume

z = 0.02m

A = 2.90x10^{-5}m^{2}

V = 4.00x10^{-5} – 8.00x10^{-4}m^{3}

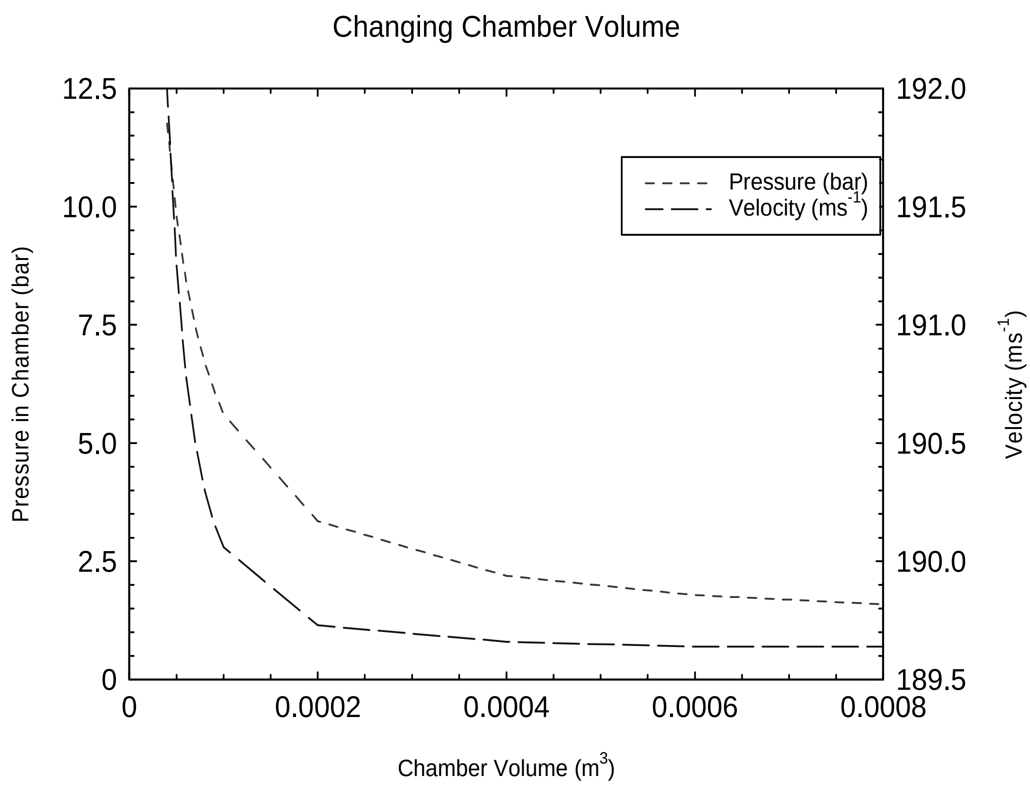


Figure 19 Effect of changing the silencer volume on the silencer pressure and round velocity

The volume was changed from a minimum of 3.0x10^{-5}m^{3} to a maximum of 8.0x10^{-4}m^{3} at regular intervals. All other factors remained the same.

It can be seen from Figure 19 that as the volume of the silencer increased the pressure within the silencer and the muzzle velocity dropped. The pressure dropped from a maximum of 12.5bar with a very small chamber to just over 1bar with a volume of $8.0x10^{-4}m^3$. The pressure drop was very rapid from $3x10^{-5}m^3$ to $2x10^{-4}m^3$ where it dropped to just over 3bar when it then became less rapid. The drop in pressure within the silencer as the volume increased was to be expected as there was more room for the gas to expand within.

The velocity drop over the volume range was only just over $2ms^{-1}$. There was a steep drop in velocity from $3x10^{-5}m^3$ to $2x10^{-4}m^3$ from $192ms^{-1}$ to $189.7ms^{-1}$ and from $2x10^{-4}m^3$ to $8x10^{-4}m^3$ it was only $0.5ms^{-1}$.

2.4.4 Simulation – Silencer, Changing the size of the ports through the barrel

z = 0.02m

A = 1.00×10^{-6} - $5.00 \times 10^{-3} m^2$

V = $2.99 \times 10^{-5} m^3$

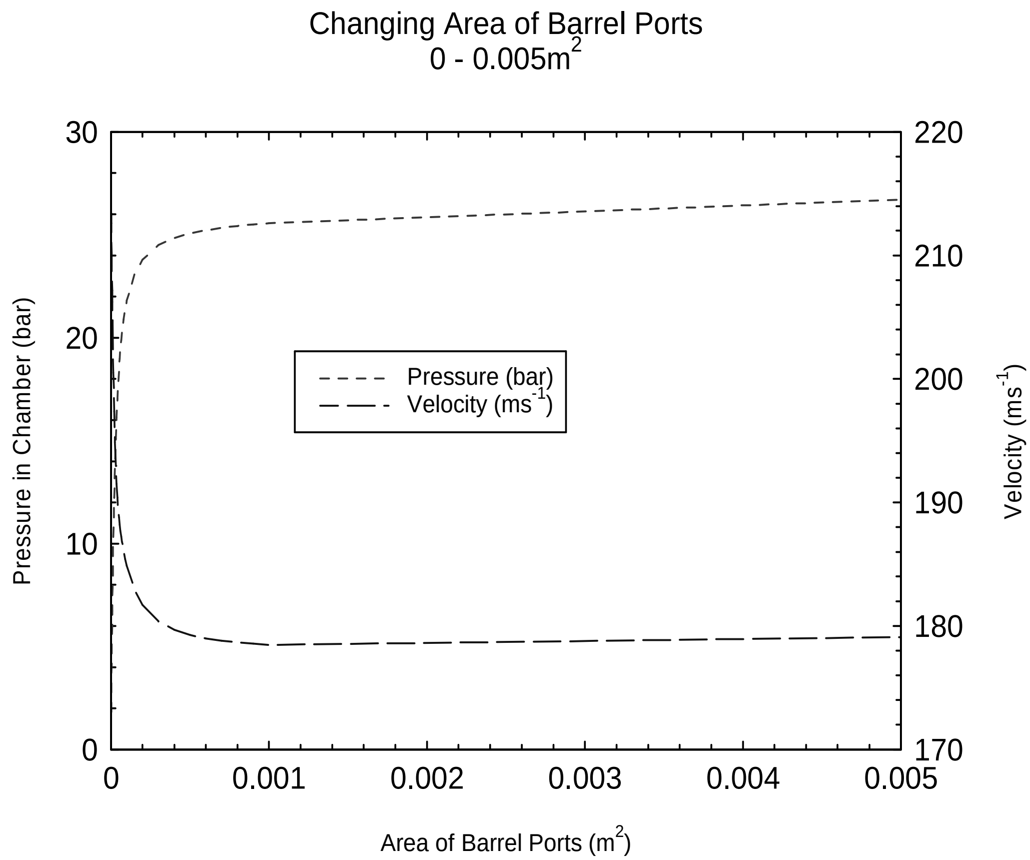


Figure 20 Effect of changing the area of silencer ports on the silencer pressure and round velocity

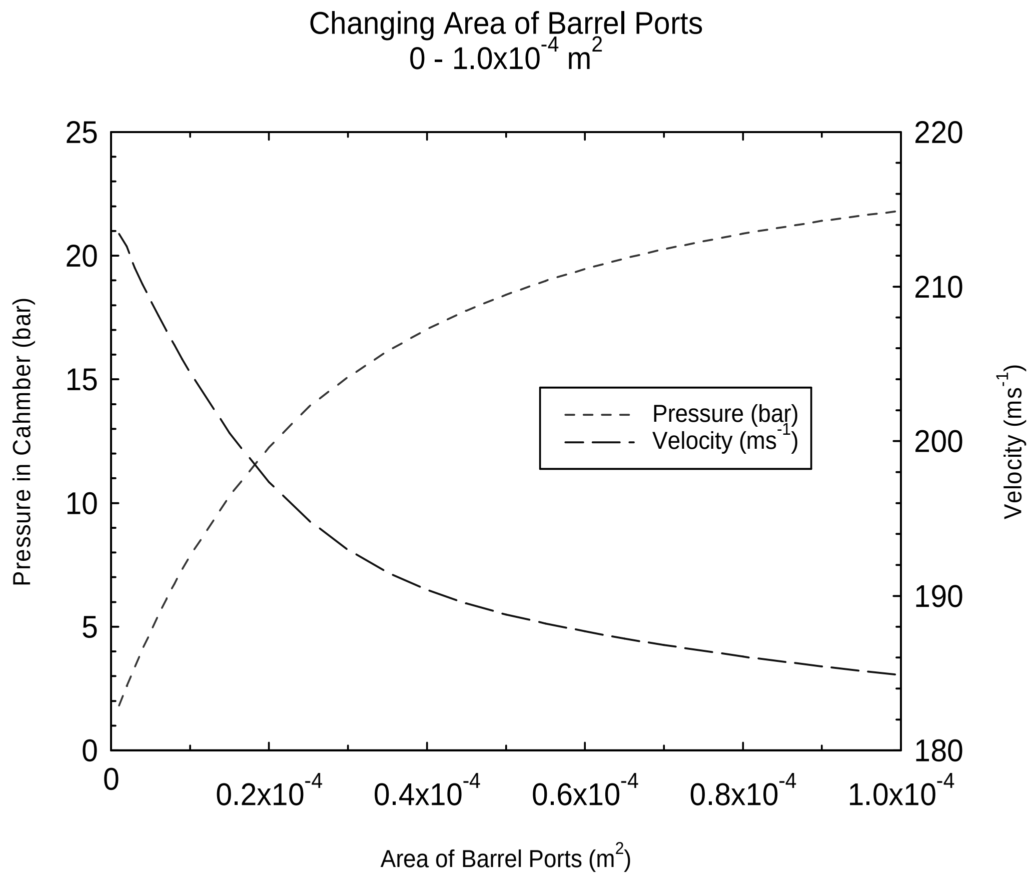


Figure 21 Effect of changing the area of silencer holes on the silencer pressure and round velocity. Expanded First section

The size of the total area of the ports was changed from $1x10^{-6}m^2 – 5x10^{-3}m^2$. Above $5x10^{-3}m^2$ the size of the holes would be greater than the wall circumference (i.e. more hole than barrel.) The silencer volume was set at $3.0x10^{-5}m^3$. Figure 20 shows the full range of the data acquired. Figure 21 shows the section from 0 to $1x10^{-4}m^2$.

Figure 20 shows that as the port size increased the velocity of the projectile decreased. There was a very sharp fall over the first part of the graph up to $1.0x10^{-4}m^2$ where the velocity fell from $214ms^{-1}$ to $185ms^{-1}$. This was to be expected as the combustion gas was being vented off resulting in less force behind the projectile. This effect was magnified because this would cause a reduction in propellant burning rate. Whilst the velocity drop was nearly

$30ms^{-1}$ it could be suggested this is not an insignificant drop as the variation in velocity due to the loading of the cartridges could be as great as $\pm 25ms^{-1}$.

The pressure in the silencer increased as the area of the ports increased. There was a distinct pressure rise that can be seen between 0 and $1x10^{-4}m^2$ which results in the pressure rising from 2bar to 22bar. This was to be expected because more gas is able to flow into the silencer with increasing port area. After $1x10^{-4}m^2$ the pressure rise was less pronounced.

2.5 Theoretical Modelling Discussion

2.5.1 Changing silencer port position down barrel.

The results suggest that gas should be vented off near the breech of the barrel rather than further along the barrel where the silencer would be ineffective. This suggests for this application that porting off the gas at any point along the barrel would be acceptable with little loss in velocity. It should be noted that this is applicable for this situation i.e. low chamber pressure and velocity and might not be applicable to high pressure systems. Further simulations would be needed to confirm this.

2.5.2 Changing silencer volume

The results suggest that the larger the volume of the chamber, the lower the pressure. This is to be expected when the gas has more room to expand into thus allowing an overall drop in pressure. The results also suggest the volume of the silencer had little effect on the velocity of the projectile. The little effect it had was only noticeable with small chamber volumes and the effect was not so pronounced with larger volumes. The variation in velocity is within experimental error for the cartridges.

2.5.3 Changing the size of the ports through the barrel wall

The results suggested that the greater the area of holes in the barrel, the greater the pressure in the silencer and in addition it was seen that the projectile travelled slower along the barrel. This is due to the greater hole size allowing more gas to enter the silencer which in turn creates a bigger pressure. However unfortunately what the results do not tell us is whether the area should be made up of lots of small holes or several larger holes.

Several factors would have to be considered. An increase in holes will create a greater sharp edge area. Therefore a drop in velocity of the gas would occur due to friction and this would lead to a greater drop in the pressure within the silencer. However small holes would cause a cumulative increase in the vena contractor effect of the gas flow through the hole and therefore reduce the area of the hole shown in Figure 22. Smaller holes would be more prone to being blocked by carbon deposits from firing and thus affect the performance of the silencer.

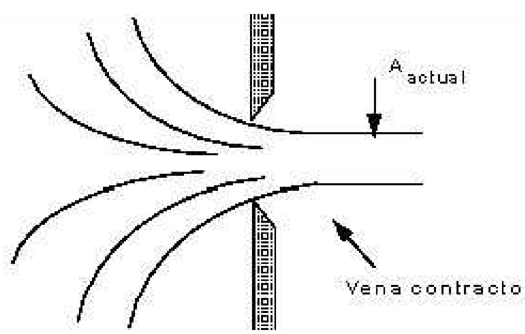


Figure 22 Reduction in the area of a small hole due to the Vena Contractor effect (26)

Increasing the diameter of the holes would reduce the cumulative effect of the area loss due to the vena contractor and allow a greater amount of gas to pass into the silencer. An increased diameter would also reduce the machining time of the barrel, decreasing production time and possibly costs. The large holes may however affect the flight of the bullet as it travels down the barrel due to a possible risk of the leading edge coming in contact with a sharp edge.

2.6 Conclusion

Theoretical pressure calculations are extremely difficult to undertake for the non-standard cartridge and silencer proposed. The use of a standard cartridge would help alleviate part of this problem. However as the silencer is being designed for a real application in the field the non-standard cartridge arrangement will be used and it is therefore necessary to measure the pressure experimentally to determine the exact pressures in the barrel. Experimental results will also ascertain whether the Emptying and Filling program has correctly established the factors which have the greatest effect on the performance of a silencer.

Theory suggests that the biggest factor that will affect the pressure in the suppressor is the area of the holes in the barrel which will allow the gas into the suppressor chambers. This has the effect of producing the largest increase of pressure recorded in the suppressor chamber.

Chapter 3
Experimental Work

3.1 Pressure distribution within 18", 12 bore barrel

Although it was initially very difficult to model the pressure time curve within the system being used, any results would be validated by experimental work. A system was set up to experimentally measure the pressures within the barrel which would later be modified to accommodate a suppressor.

The two options available for measuring the pressure were strain gauges or pressure transducers attached to a barrel which would measure the pressures generated during a shot.

3.1.1 Strain Gauges

The possible use of strain gauges was investigated. Conventional gauges were not suitable for the situation due to the interference and noise created during a shot with a metal suppressor, however an alternative was available in the form of optical fibre sensors. These are used in situations where conventional strain gauges are unsuitable. These sensors are unaffected by electromagnetic fields and use Fibre Bragg Gratings (FBGs) sensory technique **(27)**. However the sampling rate of the sensors was too slow (1000Hz) and was considered unsuitable for the changes in pressures during a shot.

3.1.2 Pressure Transducers

It was therefore decided to use a pressure transducer, especially as there is a market for ballistic pressure transducers which are used for applications such as this. For the first stage of testing a Piezotron Universal Pressure Transducer, a Kistler 211B1 was used to measure the required pressures. This was selected, after discussions with a Kistler representative, to withstand the high pressure and rapid temperature rise whilst remaining within a small budget.

The use of pressure transducers required modifications to the barrel to allow them to be fitted within a suitable housing. The transducers were connected to a Nicolet digital oscilloscope via a signal cable and coupler. The pressure signal generated upon firing was recorded and saved for processing using the conversion factor supplied with the transducer. The program which was initially used for processing the results was NICDSKRD, it converted results into a format which could be manipulated in Excel. Later testing used a program called DPlot which was able to manipulate the results more effectively without having to transfer results between programs.

3.1.3 Experimental work with 211B transducer

An 18" barrel was modified to accommodate the pressure transducer at four points along the barrel as is shown in Figure 23 using the mounting data provided with the transducer. A full AutoCAD drawing is found in Appendix A. Plugs were also manufactured to allow the other positions to be blocked off during testing.

Shots were fired enabling 10 recordings to be saved at each position. Full details of the experimental procedure can be found in Appendix C. The results were then processed and the maximum pressure achieved deduced.

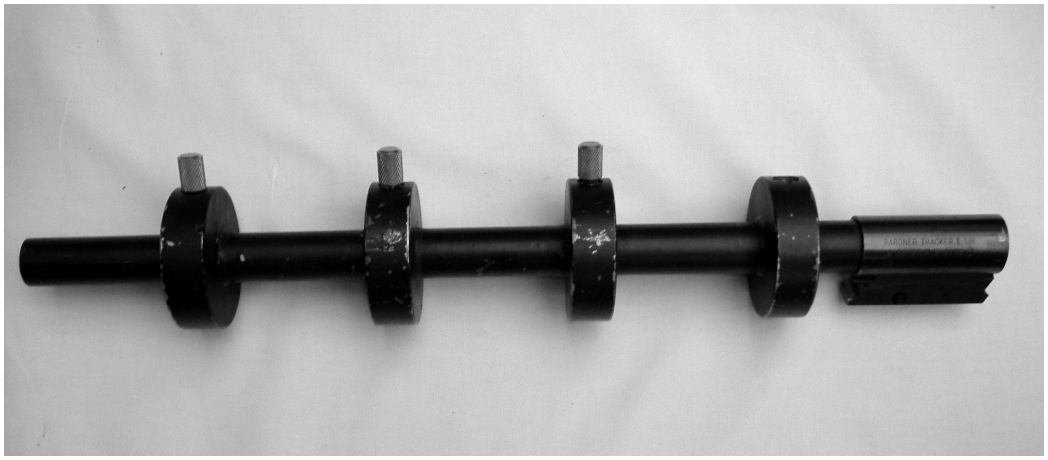


Figure 23 The assembled 18" barrel. The three plugs which seal the remaining transducer ports during testing can be seen

The maximum pressure recorded in the barrel was 239.5lb/in^2, which is 16.3bar. Using this data the volume needed for the pressure to be atmospheric (1.01bar) was determined by applying the Noble-Abel gas law.

$$p(V - am_c) = m_c RT$$

Equation 4a Noble-Abel Gas Law

Where p is the pressure of the gas, V is the volume of gas, a is the co-volume (0.001 m^3kg^{-1}), m_c is the mass of the propellant in kg, R is the gas constant and T is the temperature of the gas in Kelvin.

This can be simplified to

$$p_1(V_1 - am_c) = p_2(V_2 - am_c)$$

Equation 4b Modified Noble-Abel Gas Law

because the temperature of the gas remained constant with the use of the identical propellant in each firing. The mass of propellant used and gas constant was also uniform.

Therefore it was calculated that the volume required would be 1.80 $x10^6mm^3$. This gave a diameter of 38.0mm for the suppressor given the length was 389.5mm and the volume of a cylinder is expressed as

$$V = \pi r^2 l$$

Equation 5 Volume of a Cylinder

where V is the volume in m^3, r is the radius in m and l the length in m.

An experimental suppressor was developed and tests were carried out on various setups as detailed in Chapter 3.3. Originally testing was carried out with the Kistler 211B transducer. During the first stage of testing four different set ups were tested. For each different arrangement of components 40 shots were fired to enable 10 pressure readings to be recorded at each transducer position along the weapon. These 10 pressure readings would allow a mean pressure to be determined without bias from anomalous results. The raw data was processed using the NICDSKRD program as described in 3.1.2 before being analysed.

Due to the length of time taken completing each test it was decided to invest in more transducers. A Kistler 217C ballistic transducer had been loaned to the University. The 217C is cheaper than the Kistler 6203 and often used for similar applications as the Kistler 6203 ballistic transducer, used tests by the University. This transducer was tested alongside the 211B transducer but significant differences were observed.

Tests were therefore carried out to ascertain why different results were being obtained at the same point with the same set-up. A 12 bore shotgun proof barrel which had a pressure tapping into the chamber was used for the tests. The pressure achieved in the chamber was known for standard shotgun cartridges. The original tapping could accommodate a Kistler 6203 transducer and an additional tapping was added to accommodate a 217C transducer. It was not possible to add a further hole to accommodate a 211B transducer.

Shots were then fired and the pressures calculated for both the 6203 transducer and the 217C transducer. The results showed both the 6203 transducer and the 217C transducer gave readings in the correct area accounting for experimental error (550 – 600bar). The tests were then repeated on the proof barrel using the plastic darts and cartridge instead of the standard shotgun cartridge. The results obtained with the 6203 and 217C transducers showed a chamber pressure of 670 – 730bar which showed they were suitable for the application. This higher pressure is due to the unusual configuration of the dart and cartridge arrangement.

Tests were then carried out on an 18” barrel with four transducer positions along the barrel as shown in Figure 23 as discussed in Chapter 3.1.3. The tests were carried out with the Kistler 211B and 6203 transducers (due to limited space it was not possible to also accommodate the Kistler 217C transducer). Results at the first position closest to the chamber showed a pressure of 50 – 62bar with the 6203 transducer and of only 10 – 16bar with the 211B transducer. As the 6203 transducer had previously been tested to exhibit good agreement with the 217C transducer it was concluded that the Kistler 211B transducer would have no further role within the project. The options for transducers were either the Kistler 6203 or the Kistler 217C. To provide reliable accurate results it was necessary to have a transducer dedicated to the project. To allow swift progress with the project it was also necessary to have four transducers. 217C transducers were chosen as they were deemed to be more economically viable than the 6203 transducers.

However there were problems obtaining the transducers as they are only available in the USA and there were none available for a period of 3 months. It was decided to wait for these transducers as they would be the best for the application. Meanwhile the project deviated slightly to incorporate the testing other improvised suppressors. The details of this work can be found in Chapter 5. In addition tests were carried out on a production suppressor to see whether current proofing practices for barrels were suitable for suppressors. The details of this work can be found in Chapter 4.

3.1.4 Experimental work 217C transducer

With four 217C transducers available with up-to-date calibration certificates it was necessary to repeat the experimental work with the 217C transducers. With four transducers available, tests could be completed quicker, with fewer cartridges requiring manufacture. There were advantages of having completed the earlier tests as the set-up of the tests and the collation of the data ran smoother and all potential problems had been ironed out. It was found during this previous testing that the results had a good repeatability. It was therefore decided to reduce the number of readings needed due to the time pressure of range availability. Three pressure readings were therefore decided on. If there were problems with repeatability or anomalous results were discovered during processing further tests could then be undertaken.

Using the 217C transducers proven for this application the pressure along the 18” barrel were obtained. The experimental procedure was identical to that in Appendix C with the 217C transducer replacing the 211B transducer. The results gained are shown in Figure 24.

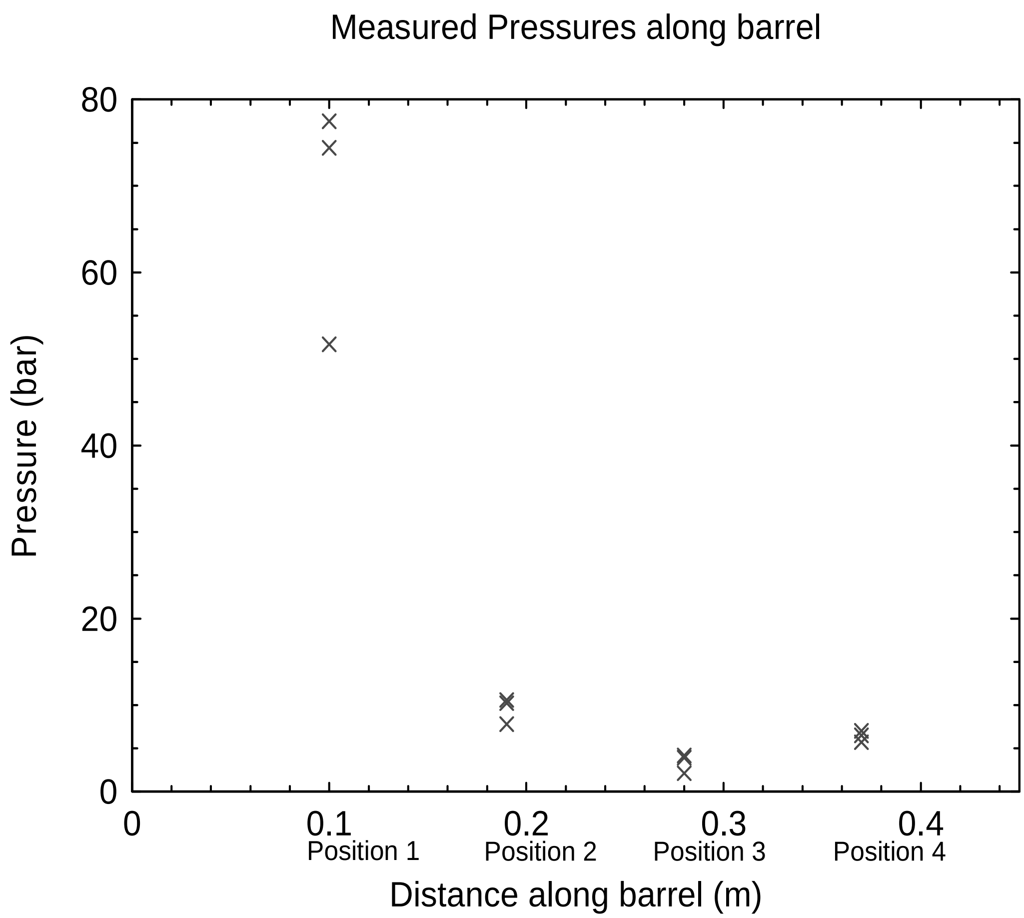


Figure 24 Pressure measured at the 4 points along the barrel

During the testing four cartridges from a new batch were used. On processing the results it was found these new cartridges gave lower readings in comparison to others, however the round velocity remained within the expected range. These new cartridges were used at position 3 shown in Figure 24 (one result did not record correctly).

It was originally thought that the different cartridges would not make a difference with the results, however the results obtained suggested otherwise. One possibility was the cartridge was of a different material and therefore the force of the gas required to un-crimp the cartridge upon firing may be different. Unfortunately the cartridge had been disposed of once it had been fired so establishing the material was not possible.

Testing was therefore repeated using cartridges from the original batch to establish the validity of the results. It was found that the different cartridges were not giving different results, and that the pressures at position 3 were lower than those at position 4 as shown in Figure 24. On further investigation it was found there was a constriction in the barrel at position 3. This drop in pressure is the same effect as seen in a venturi meter where a constriction results in a lower pressure and is a principle of Bernoulli Equation **28**. The pressure further down the barrel would not be affected by this.

Using an average maximum pressure of 67.85bar, Equation 4 and Equation 5 the volume required was found to be 1.04 x105mm^3 and the diameter of the suppressor needed would be 76.3mm. This dimension aided the selection of the outer tubing which holds the parts of the suppressor, allowing a suitable tube to be selected for the test, however tests had already been started using a tube of internal diameter of 57.6mm. As no other suitable tubing was available immediately the use of this tube was continued.

3.2 Velocity Measurement

It was vital to know the velocity of the projectile travelling down range in order to establish the effect of the suppressor on projectile velocity. The mean velocity that was obtained for the plain barrel was 182.3ms^{-1}. The velocity was measured using both Doppler Radar and Photo Optical Chronographs. The Doppler Radar however was not available for all tests so Photo Optical Chronographs were selected for all experimental trials.

3.2.1 Doppler Radar

The Doppler Radar bounces microwave radiation off a moving projectile and detects the returning waves. Due to the Doppler Effect the waves return at different frequencies. The difference between the frequencies of the out bound and in bound waves determines the velocity at which the projectile is travelling. Readings are processed and displayed in graphical form on a computer

3.2.2 Photo Optical Chronographs

Photo Optical Chronographs work by the projectile interrupting the light between a source and a photo receiver. The time taken between the set of sensors (a known distance apart) allows the velocity of the projectile to be calculated. Readings are then processed by computer to provide numerical results. During the experimental investigations the Chronographs were periodically calibrated to ensure they were giving accurate results. No discrepancies were found.

3.3 Experimental suppressor allowing pressure measurements

The most common method of suppressing a gun is the use of the containment method. As this is the simplest way to construct a suppressor and can be adapted readily, it was decided to use this technique. The 12 bore barrel would have holes drilled in it allowing the propellant gas to escape into the chambers of the suppressor. Baffles with holes to allow gas to escape between chambers would be separated along the barrel by spacers. This set up also allowed modelling to be undertaken in Chapter 2. Using this method of construction a number of different features can be investigated. These include:

- the diameter of hole in the barrel
- the size of holes in the baffles
- the number of chambers

- variation in the spacing of the baffles (e.g. many chambers at the breech end and few at the barrel exit or vice versa)

It was anticipated that studying the effect each factor had on the pressure along the barrel would allow for an optimum design to be achieved.

A new barrel was used to accommodate the new test procedures. Eight 4mm diameter equispaced holes around the circumference were milled into the barrel at regular intervals of 20mm. Gas is required to be bled off behind the bullet evenly to prevent instability of the projectile, this requires an even, equispaced number of holes along the barrel. Upon evaluating other suppressors available for purchase eight holes was the most common arrangement. The holes cannot be too big otherwise the bullet can foul on the hole causing destruction of the round, therefore for this situation a maximum of 4mm diameter hole was selected.

Figure 25 Experimental barrel showing the 4mm holes

Sleeves were produced to fit over the barrel with 2mm and 3mm holes milled so when the sleeves were placed over the barrel they would reduce the size of the barrel holes. The sleeves were produced in three lengths (18mm, 38mm, 58mm) allowing the spacing between baffles to be tested. This set up can be seen in Figure 28.

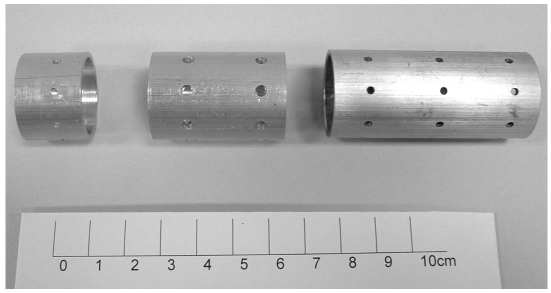


Figure 26 The sleeves in three sizes showing 2mm and 3mm holes

There were 2 batches of baffles produced with 2 and 3mm holes as shown in Figure 27. These were fitted on the barrel between spacers as shown in Figure 28.

Figure 27 The baffles showing 2mm (left) and 3mm (right) holes

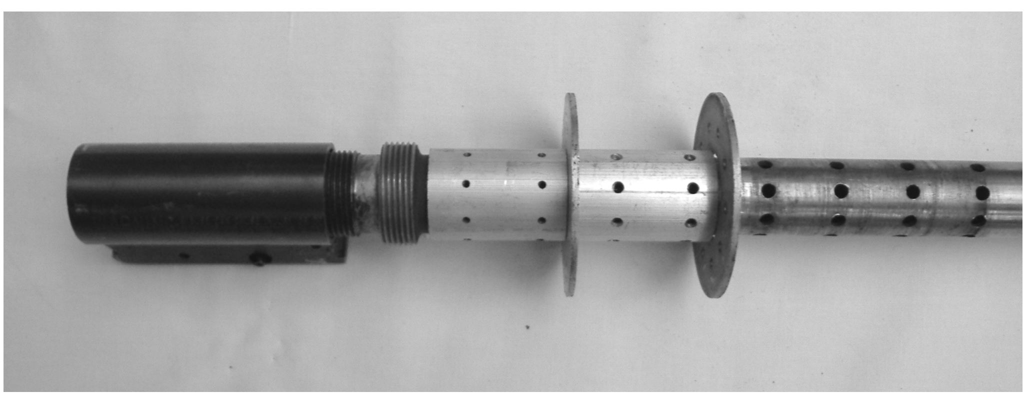


Figure 28 Close up of the barrel with an example of the mounted spacers and baffles

All the components were contained in the suppressor housing which was produced from a piece of tubing 389.5mm long with an internal diameter close to the 38.0mm diameter which was originally calculated. Four pressure tappings were required along the barrel at a distance of 30, 120, 210 and 300mm from the end of the chamber and therefore a wall thickness of 5mm or greater was needed. This allowed a comparison of pressures between an un-suppressed and a suppressed barrel as the pressure was measured at the same points along the barrel as the testing in 3.1.3. The suppressor housing with pressure tappings can be seen in Figure 29.

The only available tubing which had a thick enough wall to allow tapping for the pressure transducers was one of 57.6mm internal diameter. Original calculations suggested an internal diameter of 38.0mm whilst revised calculations with the corrected pressures suggested 76.3mm. Full AutoCAD drawings of each of the components can be found in Appendix A

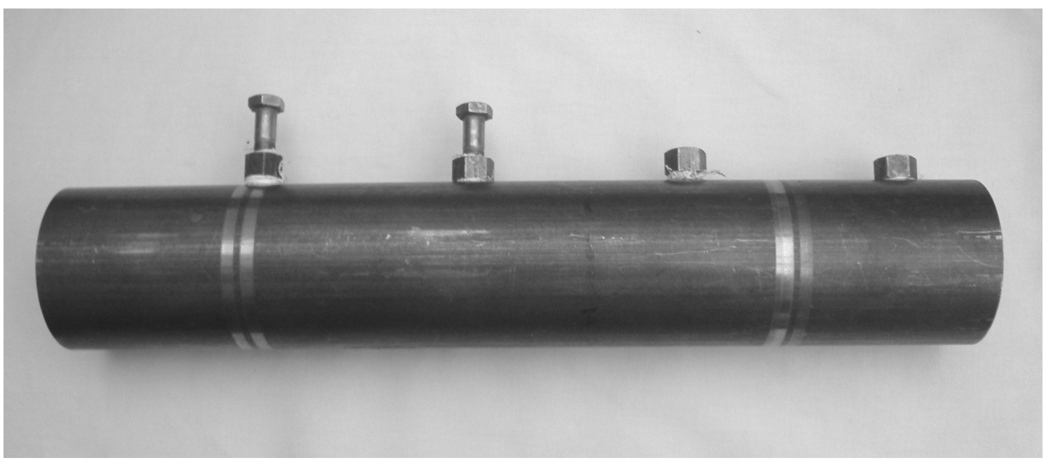


Figure 29 Suppressor housing fitted with the pressure transducer adaptors allowing pressure to be measured within the suppressor

3.4 Experimental testing of possible suppressor setups

Testing of the 18 possible set ups was undertaken.

Test	Baffle hole size (mm)	Barrel hole size (mm)	Length of spacer
1	nothing (4mm barrel holes)		
2	2	2	s
3	2	2	m
4	2	2	l
5	2	3	s
6	2	3	m
7	2	3	l
8	2	4	s
9	2	4	m
10	2	4	l
11	3	2	s
12	3	2	m
13	3	2	l
14	3	3	s
15	3	3	m
16	3	3	l
17	3	4	s
18	3	4	m
19	3	4	l

Table 4 Testing arrangements

s = 18mm, m = 38mm, l = 58mm

Extra time was available on the range after planned testing had been completed so it was decided to undertake additional firings with fewer obstructions in the suppressor. Testing was completed with the following arrangements:

20	2	4	1 baffle at mid point of SM
21	2	2	1 baffle at mid point of SM
22		4	SM blocked into 2 chambers at mid point
23		2	SM blocked into 2 chambers at mid point

Table 5 Testing arrangements

The pressure traces from each test were processed using D Plot which read converted them into graphical format.

The maximum pressure was read from the graph and a mean was taken for each position and can be seen in Table 6. Full experimental graphs can be found in Appendix E.

3.4.1 Sound Recordings

It was hoped to measure the Sound Pressure Level (SPL) from each firing during the testing to establish which configuration gave the optimum performance. Unfortunately the equipment used to measure the SPL was on loan and was recalled after the first stage of testing and it was not possible to obtain a replacement. The limited results obtained are shown in Table 7. Full details of the equipment, set up and procedure can be found in Appendix G.

3.5 Results and Discussion

The results are shown in Table 6. The pressures shown are all gauge pressure. To convert to absolute pressure add atmospheric pressure (add 1.01bar) to the results.

Test	Baffle hole size (mm)	Barrel hole size (mm)	Length of spacer	Pressure (Bar)				Mean velocity (m/s)
				Position 1	Position 2	Position 3	Position 4	
1	nothing (4mm barrel holes)			3.44	3.27	2.74	3.68	161.9
2	2	2	s	5.19	2.43	2.00	1.62	175.1
3	2	2	m	5.92	0.76	1.97	1.14	188.2
4	2	2	l	4.07	3.51	4.92	4.23	188.9
5	2	3	s	20.02	11.68	5.07	5.81	179.6
6	2	3	m	9.52	6.58	3.13	5.97	174.8
7	2	3	l	6.27	4.93	6.54	5.68	164.7
8	2	4	s	26.46	25.40	32.14	31.65	203.0
9	2	4	m	26.40	23.99	4.96	7.59	181.8
10	2	4	l	77.86	2.44	6.33	2.24	169.8
11	3	2	s	10.31	5.05	6.93	6.33	179.0
12	3	2	m	2.30	0.80	1.84	0.71	175.1
13	3	2	l	1.30	1.79	0.72		187.4
14	3	3	s	12.62	15.31	1.48	7.91	176.6
15	3	3	m	15.26	4.88	2.85	1.24	178.3
16	3	3	l	3.15	2.43	2.06	1.24	181.8
17	3	4	s	25.42	22.81	16.48	13.50	186.0
18	3	4	m	7.12	2.78	1.83	2.08	201.8
19	3	4	l	27.23	4.67*	21.06	29.13	175.8
20	2	4	1 baffle at mid	2.61	3.29	2.97	1.72	178.30
21	2	2	point of SM	1.86	1.91	2.38	1.18	172.50
22	-	4	SM blocked into 2	3.58	3.07	2.72	1.85	159.82
23	-	2	parts at mid point	2.25	2.05	1.33	1.09	165.35

Table 6 Results Table

Test	SPL (dB)
No silencer	138.51
Test 1	129.50
Test 13	126.36
Test 19	121.57
Test 20	131.86

Table 7 Sound Pressure Level Results

The discussion will begin by looking at the groupings of results and consider the variations within these groups. This part of the discussion will use test 1 as the baseline for a comparison. The discussion will then compare results within different groups against each other allowing a comparison of individual tests. In order to analyse and compare the results they were grouped according to their properties. Comparisons could then be made between the groups.

3.5.1 Test 1

The pressure within the suppressor can be seen to be even down the length of the suppressor with a slight drop at position 3. The mean pressure is 3.28bar across the suppressor.

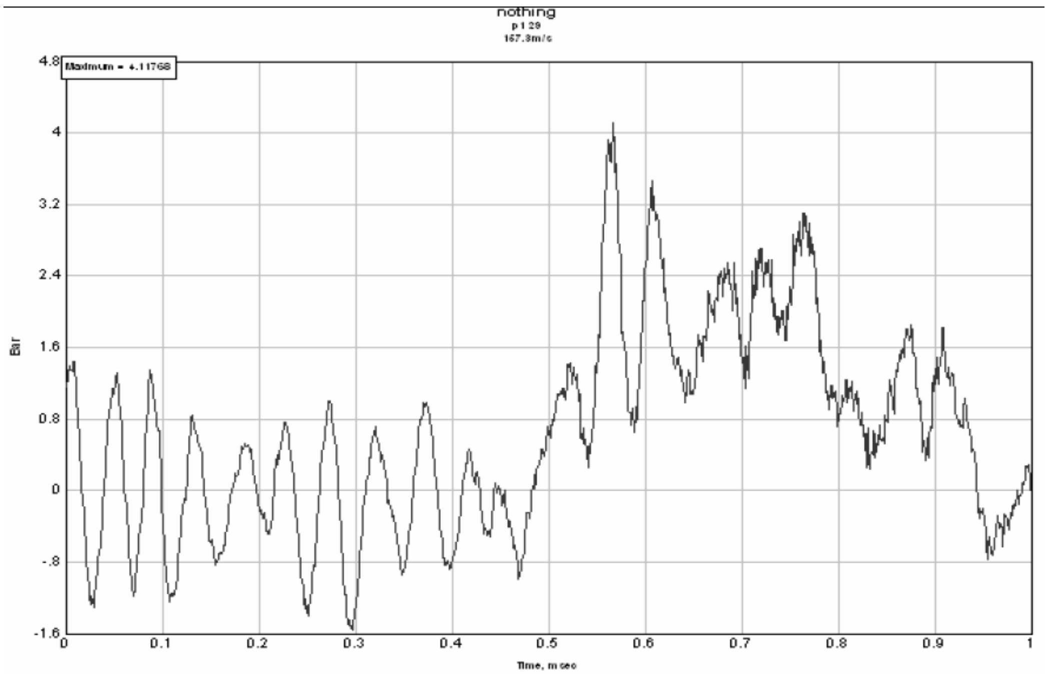


Figure 30 Sample graph Test 1, position 1

It can be seen from Figure 30 that there is a general trend showing an increase in pressure before a drop off. This is typical of all results with an increasing delay for the maximum pressure further down the suppressor. Within the general trend there is a pressure fluctuation. This pressure fluctuation becomes more spiked as it approaches the maximum pressure. It is suggested that could be this caused by more gas entering the chamber giving a mixing effect which results in a more disturbed gas. The spiked fluctuations could also be due to the reflection od he pressure waves from the walls of the suppressor. This effect was seen with all results.

All other result discussions will be using this test for initial comparison.

3.5.2 Tests 2 – 4; 2mm baffles, 2mm barrel holes with small to long spacers

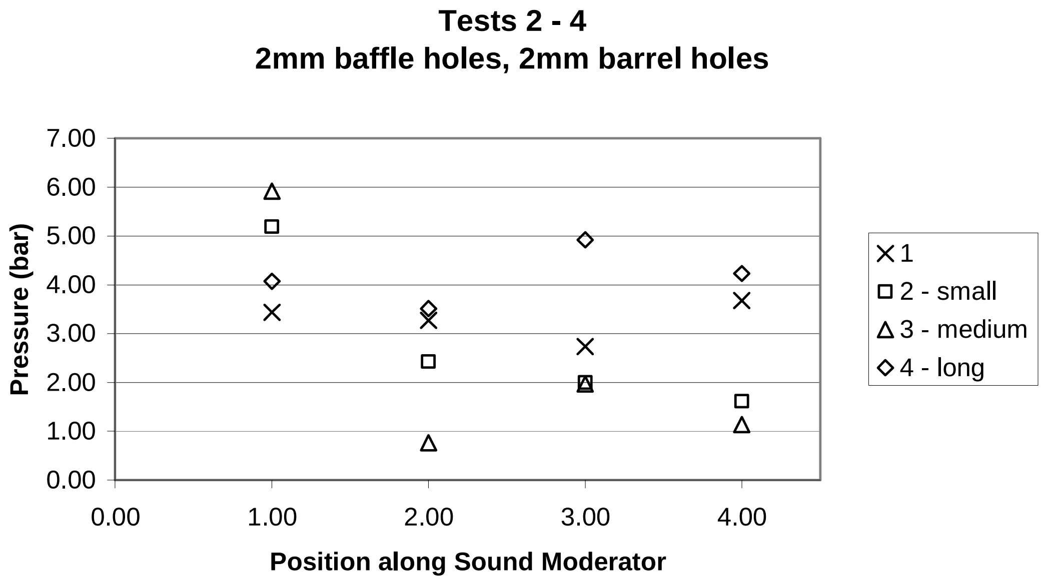


Figure 31 Graphical representation of Tests 2 - 4

It can be seen from Figure 31 that for test 2 the pressure at position 1 is higher than for test 1 with the pressures further along the suppressor being lower than those of test 1. This suggests the introduction of smaller holes and baffles has caused a higher pressure which drops off more rapidly. For test 3 by increasing the length of the spacer from small to medium, the pressure at position 1 has increased slightly. However there has been a drop in all the other pressures along the suppressor. This is a trend seen in gun barrels where by increasing the pressure created by the burning propellant causes a lower pressure further down the barrel.

In test 4 the long spacers have caused a small drop in pressure at position 1 compared to tests 2 and 3, however the pressure along the suppressor is more even at a higher value than for Test 1. It is suggested that long spacers have allowed more mixing of the gas within the suppressor causing a lower pressure than tests 2 and 3. This supports the theoretical modelling in Chapter 2 which indicates an increase in suppressor chamber volume will cause a decrease in the pressure in the chamber. This suggests that by having small diameter barrel holes and by inserting few baffles with small holes increases the pressure within the suppressor and therefore reducing the sound signature produced.

A comparison of velocities shows that the mean velocity is greater with baffles included, this suggests the suppressor is more effective with baffles without reducing the weapon performance. The velocity for test 4 however is lower than for the other two tests. This may be due to the greater amounts of gas bled off from behind the projectile with the larger barrel holes causing the round to lose velocity. This supports the theoretical work that by increasing the combined area of the holes there will be a drop in velocity of the projectile.

<u>3.5.3 Tests 5 – 7; 2mm baffles 3mm barrel holes with small to long spacers</u>

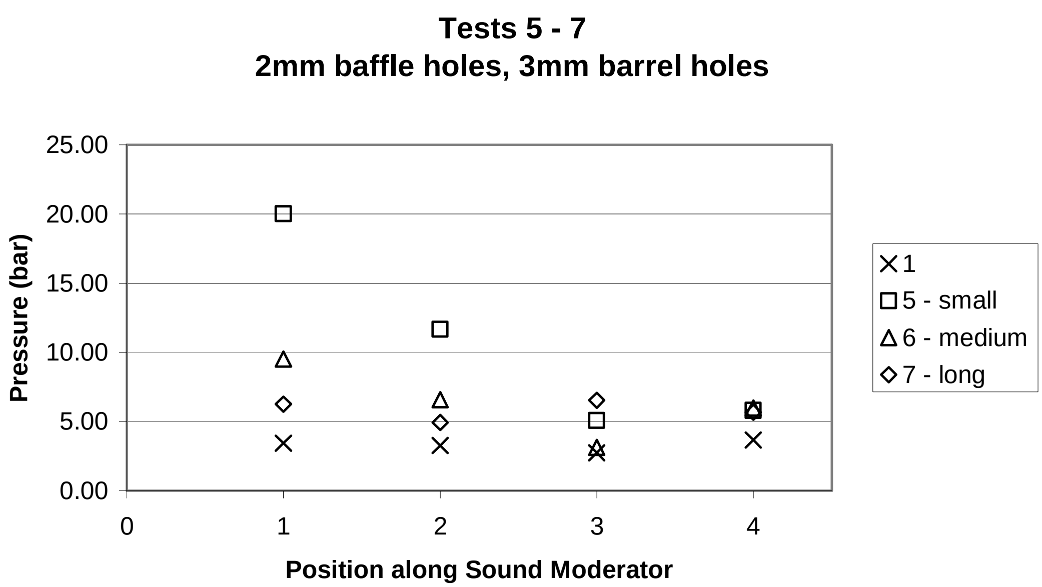


Figure 32 Graphical representation of Tests 5 - 7

In test 5 the results indicate a large pressure at position 1, in comparison to test 1. This may be due to the increased length of the sharp edges for the

4mm causing a lower pressure than for the 3mm holes. The pressure drops along the suppressor remaining greater than those for test 1. Increasing the size of the spacers from small to medium has a negative effect on the pressures reducing them by half for positions 1 and 2 with less of an effect on positions 3 and 4.

By increasing distance between baffle from medium to large for test 7 it again reduces the pressure measured in the suppressor. The longer spacers may have allowed more mixing within the chambers thus creating a lower pressure. The pressure along the barrel also levelled out along the suppressor to around 6bar. This supports the theoretical work of Chapter 2 which suggests increasing the volume of the suppressor chamber will decrease the pressure within the chamber.

The mean velocity is also greater than for test 1 suggesting an increase in performance of the suppressor without compromising on the velocity of the round. The velocity for test 7 with the long spacers is less than for tests 5 and 6 and is closer to that of test 1. This suggests that baffles improve the velocity of the projectile, a consequence of a higher projectile base pressure.

3.5.4 Tests 8 – 10; 2mm baffles 4mm barrel holes with small to long spacers

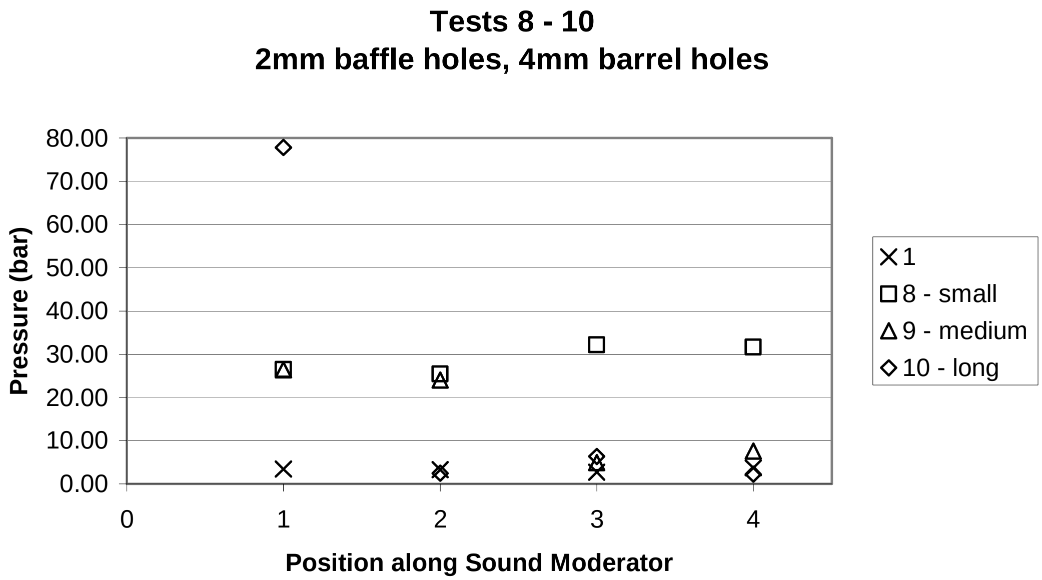


Figure 33 Graphical representation of Tests 8 - 10

A comparison between tests 8 – 10 shows greater pressures than those seen in test 1.

Small spacers in test 8, hence more baffles have increased the pressure in the suppressor to over 25bar. This may be due to the smaller volume reducing the effect for gas expansion resulting in a higher pressure. The pressure at positions 3 and 4 are also 5bar greater than at positions 1 and 2. In comparison to the other results within this group the pressures are more evenly distributed along the suppressor.

With the medium spacers in test 9 the pressures at position 1 and 2 are similar to those with the small holes. However the pressure drops dramatically to under 8bar for positions 3 and 4.

The large spacers with test 10 have a significant affect on the pressure at position 1 in test 10 with a high level compared to test 1 of 77.86bar. This pressure drops dramatically for the other positions to under 6.5bar. With the large holes large volumes of high pressure gas was able to enter the suppressor causing a high pressure reading. This gas may have been able to disperse within the large volume chambers available, dissipating some of the energy through viscous interaction.

The velocity of the projectile for tests 8 - 10 is consistently higher than that of test 1. The velocity for test 8 is significantly higher than all other tests suggesting the combination of lots of baffles with small holes and large barrel holes prevent significant velocity drop. As seen in test 7 the velocity for the long spacers is lower than others within the grouping suggesting long spacers reduce the velocity of the round. This contradicts the theoretical work that shows that the greater the volume of the chamber the lower the velocity of the projectile and ties in with the theory that the smaller area barrel holes prevent velocity loss. This in turn suggests that the barrel hole size has a greater impact on the velocity than the size of the chambers within the suppressor.

A comparison of the 2mm baffle hole results shows a general trend suggesting increasing the barrel hole size increases the pressure within the suppressor.

3.5.5 Tests 11 – 13 3mm baffles 2mm barrel holes with small to long spacers

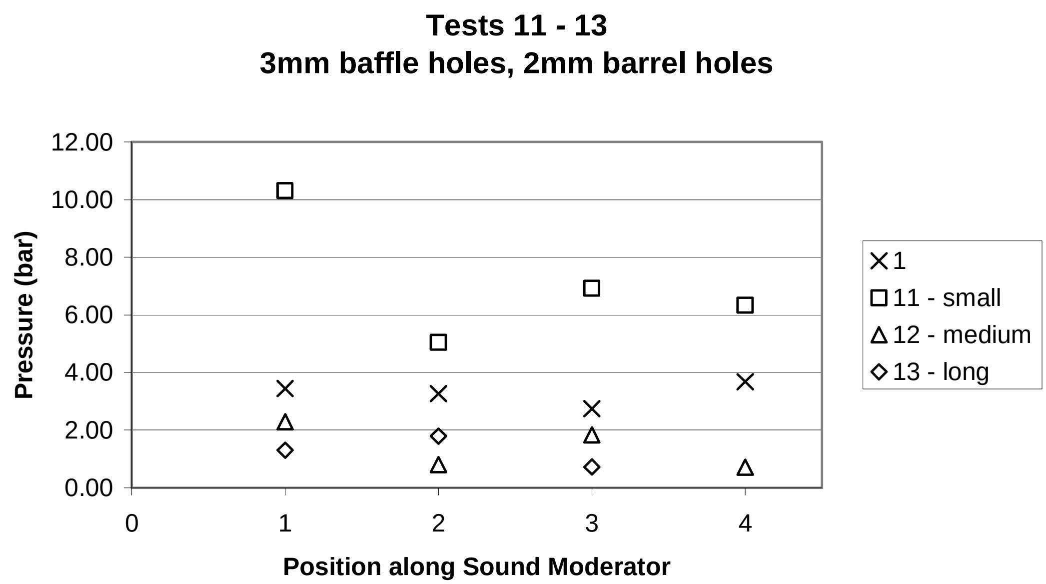


Figure 34 Graphical representation of Tests 11 - 13

Small spacers have increased the pressure along the suppressor up to 10bar at position 1 and to 5 – 7bar along the rest of the suppressor. This is a much higher pressure than for the medium and long spacers which have a maximum pressure of 2.3bar. Medium spacers have caused a pressure drop, compared with test 1, to 2.3bar and below. This may be due to the increased volume available for the gas to mix within allowing a lower pressure to be recorded. This supports the theoretical work which suggests the greater the suppressor chamber size the lower the pressure within that chamber.

The pressure with the long spacers was so low for Position 4 that a pressure change could not be detected with the Nicolet on the most sensitive setting. The pressures were only just over atmospheric for positions 1 and 2 and at positions 3 and 4 the pressure was below atmospheric suggesting the movement of the projectile down the barrel had created a vacuum in the suppressor. This would create a louder sound signature as more gas is being expelled with the projectile.

The velocity of the rounds for tests 11- 13 are all greater than the velocity of the rounds in test 1. The velocity of the long spacers test 13 is greater than that of the other two tests. Theoretical work suggests the greater the chamber volume the lower the velocity of the rounds. This however has not been seen and suggests that the barrel hole size has a greater impact on the velocity of the rounds.

3.5.6 Tests 14 – 16; 3mm baffles 3mm barrel holes with small to long spacers

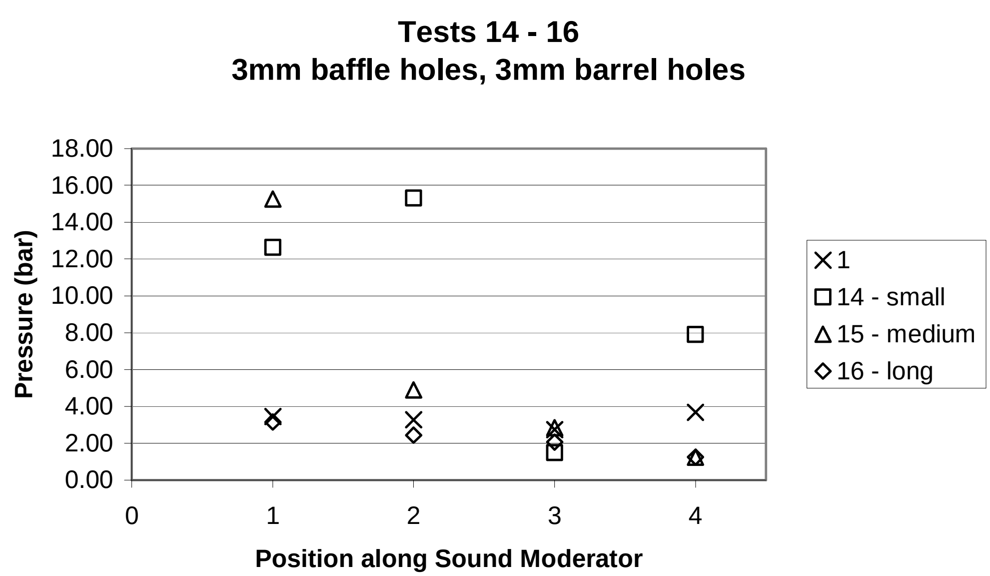


Figure 35 Graphical representation of Tests 14 - 16

Small spacers have caused a higher pressure than for test 1. The pressure at position 1 has increased to 12.62bar increasing further to 15.31bar at position 2. There is then a dramatic drop to just above atmospheric pressure before the pressure increases to just under 8bar.

Medium spacers have again increased the pressure at position 1 compared to test 1 to over 15 bar however the pressures along the rest of the barrel are lower than the pressure seen in test 1. The pressures have returned to near atmospheric by position 4.

Long spacers caused a reduction in the pressures compared to the medium and small spacers and also compared to test 1. Pressures were equalised along the suppressor at approximately 2bar. This may be due to the sharp edges reducing the pressure of the gas by viscous interaction combined with the volume the gas is able to expand into.

The mean velocity of 178.7ms^{-1} is higher that that of test 1 suggesting the use of baffles within the suppressor has prevented a large velocity loss (from 185ms^{-1} without suppressor).

<u>3.5.7 Tests 17 – 19; 3mm baffles 4mm barrel holes with small to long spacers</u>

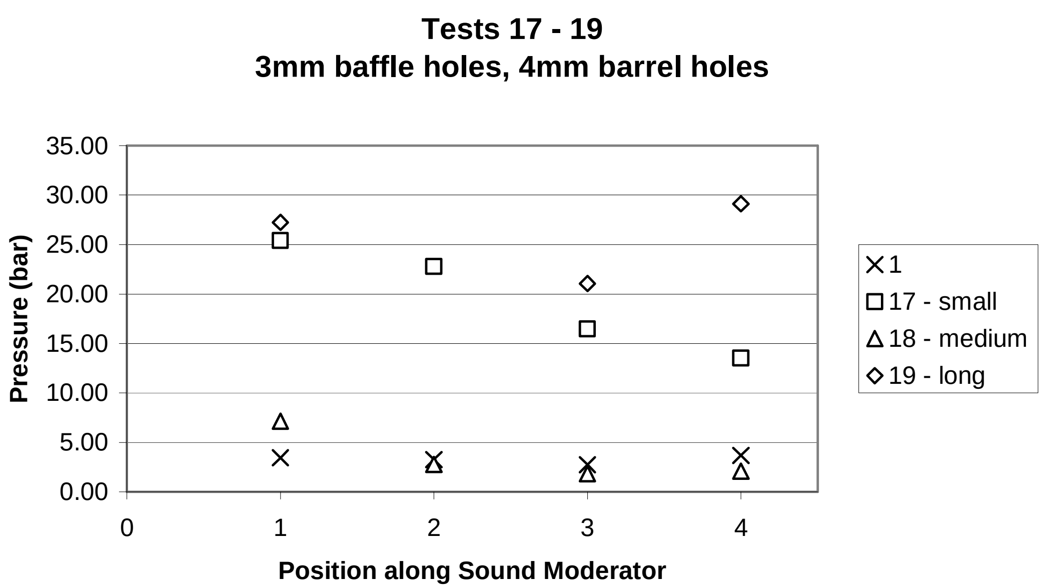


Figure 36 Graphical representation of Tests 17 - 19

Small spacers with test 17 caused high pressures in the suppressor. Pressures linearly dropped along the suppressor.

The medium spacers of test 18 however had lower pressures than for the small with 7.12bar at position 1 dropping to around 2 for positions 2 – 4 due to the volume available for the gas to expand into. The pressures have then risen for the long spacers to the high 20bar which is maintained across the suppressor with a slight increase towards the end of the suppressor. This may be due to greater hole size available for the gas to expand through into the suppressor allowing more gas to enter and a higher pressure to be reached. This supports the theoretical work suggesting the greater the suppressor chamber volume the lower the pressure within the chamber. The readings at position 2 (starred in Table 6) were distinctly lower than the others along the suppressor. The velocity readings were also distinctly lower than for the rest of the tests. Initial testing on this position was aborted after the signal cable failed. Retests with a new cable were carried out but a different batch of primers was used. The results have therefore been included but not analysed.

The velocities of the rounds going down range are all higher than for test 1. The velocity for test 19 however is lower than for the other 2 tests. This may be due to the greater amounts of gas bled off from behind the projectile with the larger barrel holes causing the round to lose velocity.

A comparison between all the 3mm baffle hole size results shows a general trend that by increasing the hole size increases the pressure within the barrel. The effect is not as pronounced as for the 2mm baffles.

3.5.8 2mm holed baffles, small spacers (Tests 2, 5 and 8)

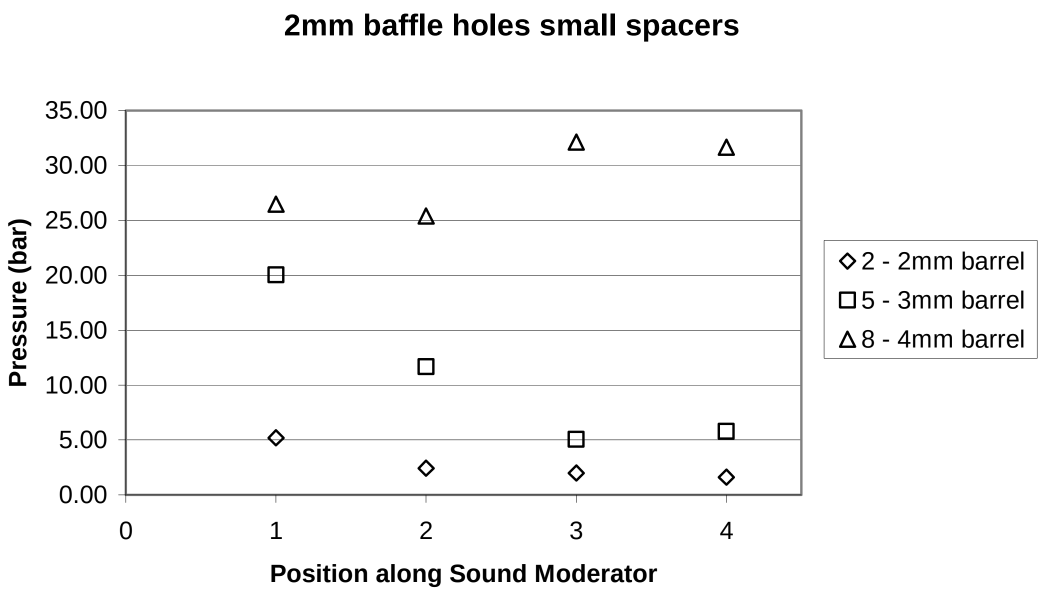


Figure 37 Graphical representation of Tests 2, 5 and 8

It can be seen from Figure 37 that as the barrel hole size increases the pressure within the suppressor increases. This is to be expected as the greater the hole size the more area for the gas to expand through into the suppressor and the more limited effect of the vena contractor. This also supports the theoretical work of Chapter 2.

Whilst the pressure within the suppressor with 2mm barrel holes was even along the barrel, pressures within the suppressor with the 3mm holes dropped off along the barrel. This is a feature seen in pressure time curves along standard barrels where pressure rapidly increases after firing followed by a decay along the barrel.

The pressures for the 4mm hole set up decreased initially before increasing along the suppressor. This may be due to the large volumes of gas able to enter the suppressor with the large holes. This pressure was then able to build up within the suppressor as more and more gas was forced into the suppressor.

The velocity of the projectiles increases as the barrel hole size increases. This goes against the theoretical work. It may be due to the reduced friction within the barrel due to less overall material in contact with the projectile allowing the bullet to accelerate to a higher velocity. Another suggestion is the gas in front of the projectile is able to disperse into the suppressor reducing the effect on the speed of the projectile.

3.5.9 2mm holed baffles, medium spacers (Tests 3, 6 and 9)

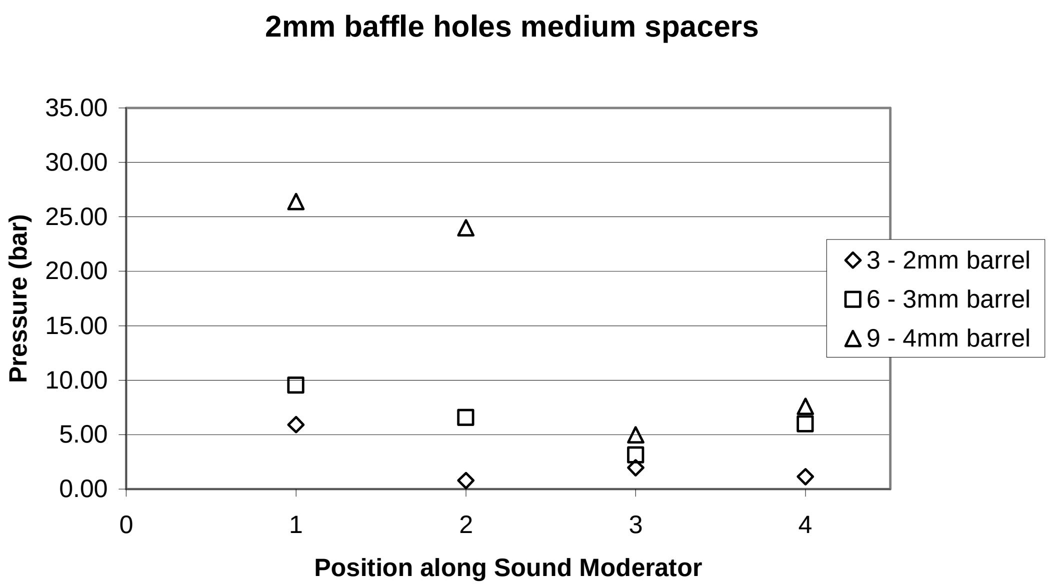


Figure 38 Graphical representation of Tests 3, 6 and 9

It can be seen from Figure 38 that as the barrel hole size increases the pressure within the suppressor increases. This is to be expected as the greater the hole size the more area for the gas to expand into the suppressor. This also supports the theoretical work of Chapter 2 which suggests as the barrel hole size increases the pressure within the chamber increases.

It was also observed that there was a large difference between pressures with the 3 and 4mm barrel holes tests at positions 1 and 2 of around 17bar. This drops to around 1.7bar by positions 3 and 4. The pressures also go up from position 3 to 4.

The velocity of the rounds is less for the 4mm barrel holes (test 9) than for the 2mm holes (test 3). This supports the theoretical work which suggests increasing the hole size will decrease the velocity of the projectile. However the mean velocity for test 6 is greater than for test 9.

3.5.10 2mm holed baffles, long spacers (Tests 4, 7 and 10)

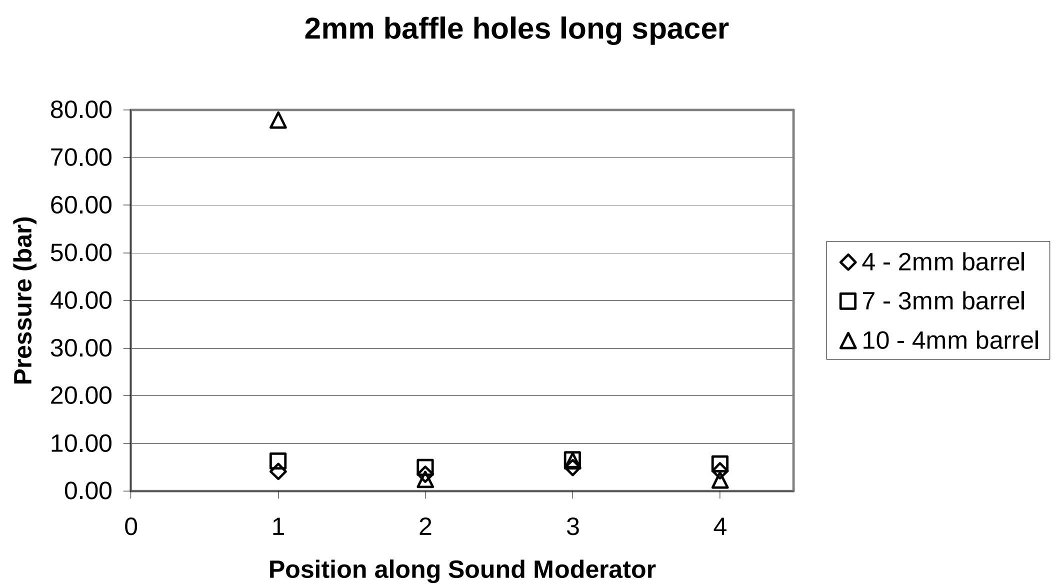


Figure 39 Graphical representation of Tests 4, 7 and 10

From the results obtained on the 2mm holed baffles, the graphs shows that 4mm barrel holes achieved a greater pressure within the suppressor than 2 or 3mm holes. This is in agreement with the theoretical work carried out in Chapter 2. Where small spacers were used the results suggest that overall a higher pressure was measures and this is in line with theoretical predictions.

Lower pressure values (<10bar) were obtained for the medium and long spacer configurations. However at position 1 the pressure peaked at 77bar. This was probably caused by the onset of a shock wave being generated from the high pressure gas expanding through the 4mm holes near to the breech end of the suppressor.

3.5.11 3mm holed baffles, short spacers (Tests 11, 14 and 17)

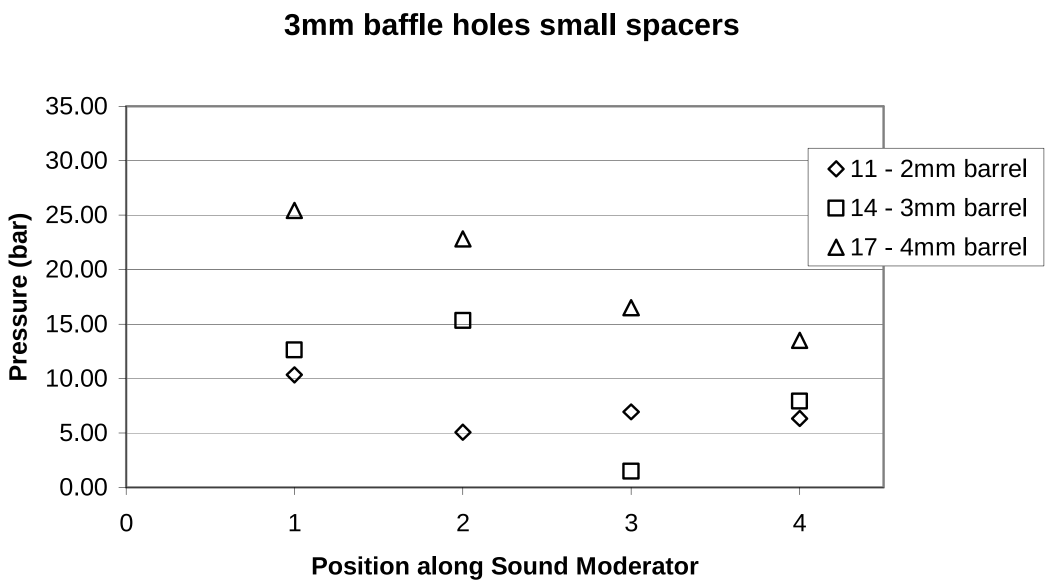


Figure 40 Graphical representation of Tests 11, 14 and 17

It can be seen from Figure 40 that as the barrel hole size increases the pressure within the suppressor increases. This is to be expected as the greater the hole size the more area for the gas to expand through into the suppressor. There is one exception to this with the 3mm barrel holes. Whilst the 2 and 4mm hole tests have a decrease along the barrel (with the exception of the slight deviation of position 2 on test 11 – 2mm holes) the 3mm barrel has erratic points across the pressure scale. The pressure begins low before increasing rapidly followed by a more dramatic drop and then an increase at position 4. This may be due to the setup. The effect of the drop for position 3 rising again for position 4 was seen in tests 4, 7 and 10. It suggests that the combination of the baffles and holes has created a pressure fluctuation within the suppressor which is enhanced by the 3mm holes.

<u>3.5.12 3mm holed baffles, medium spacers (Tests 12, 15 and 17)</u>

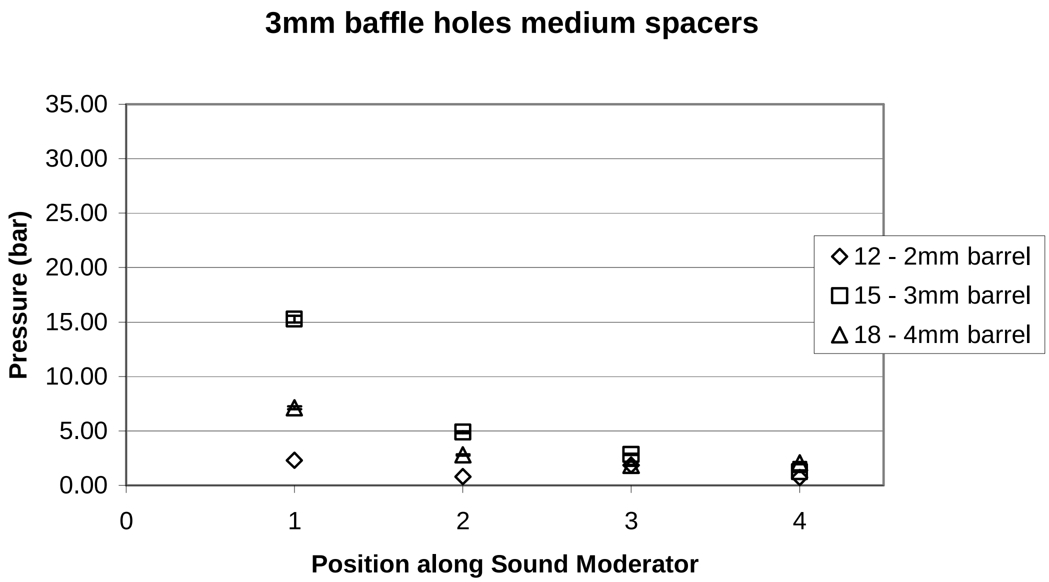


Figure 41 Graphical representation of Tests 12, 15 and 18

Figure 41 shows a progressive drop in pressure along the barrel as expected. The barrel with 4mm holes show less pressure than the barrel with 3mm holes. This may be due to the cumulative effect of the sharp edges reducing the pressure of the gas combined with the vena contractor affect of the holes slowing down the movement of gas into the suppressor. This in turn reduces the pressure within the suppressor to below that of the 3mm holes.

3.5.13 3mm holed baffle long spacers (Tests 13, 16 and 19)

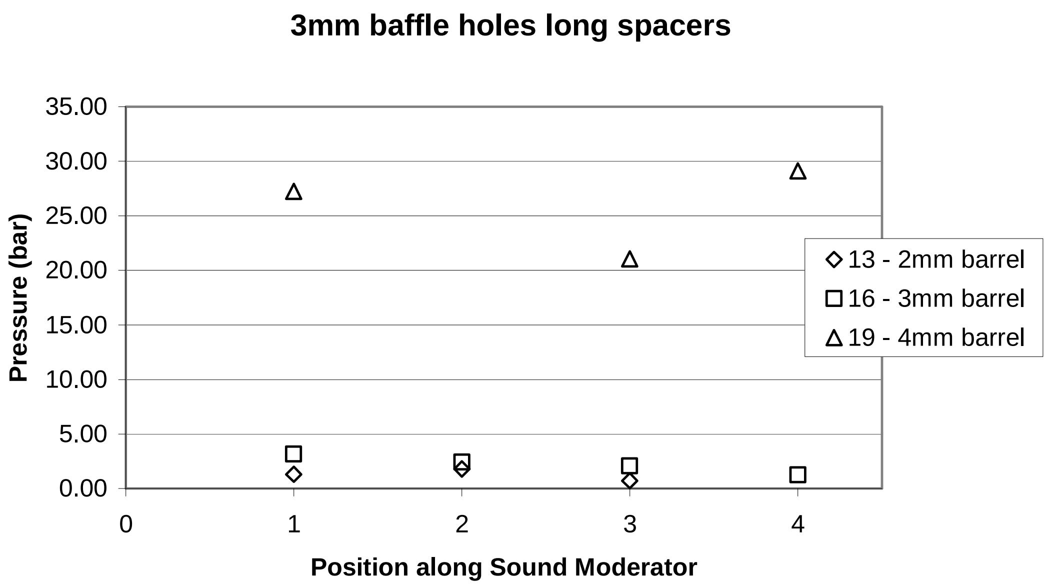


Figure 42 Graphical representation of Tests 13, 16 and 19

It can be seen from Figure 42 that as the barrel hole size increases the pressure within the suppressor increases. This is to be expected as the hole size increases the more area is available for the gas to expand into the suppressor. This finding also supports the theoretical predictions. The pressure for the 4mm holes is distinctly greater than that for the 2 and 3mm holes. The effect seen within the 3mm medium graph where the 3mm holes gave a greater pressure than the 4mm holes is not seen with the long spacers suggesting that the larger volume has a greater effect on the pressures than the hole size.

A comparison of the 3mm results (Figure 40, Figure 41 and Figure 42) suggests that with the exception of the medium spacers the larger the hole size produced a higher pressure within the suppressor showing general agreement with theoretical modelling. As with the 2mm baffle holes the shorter spacers have overall generated greater pressures within the suppressor than the medium or large spacers. This is an effect observed in the theoretical evaluation

3.5.14 Limited baffle tests (Tests 20 - 23)

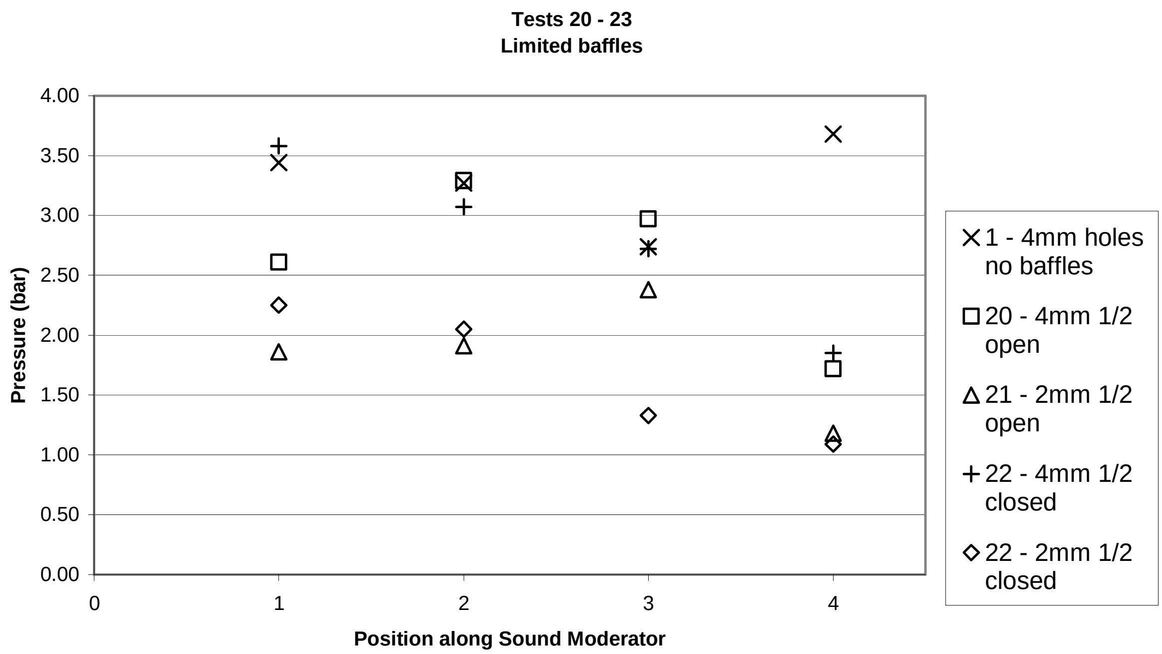


Figure 43 Tests 20 - 23

½ open is where the suppressor was separated into 2 chambers interconnected allowing gas to move between chambers.

½ closed is where the suppressor was separated into 2 chambers not connected.

It can be seen from Figure 43 that by removing many baffles from the suppressor creates a low pressure within the suppressor. The 4mm holes give a greater pressure than the 2mm holes. The result supports the theoretical work which suggests that more gas is allowed into the chamber. The introduction of 1 baffle or splitting the suppressor into 2 separate chambers has not significantly affected the pressures within the suppressor except at position 4.

For the 2mm holes at positions 1 and 2 the pressure is lower with the baffle in place than with two separate chambers. However at positions 3 and 4 the baffle has allowed gas through along the suppressor and there is a greater pressure than with two separate chambers. This suggests that the baffles produce a useful effect in a suppressor device.

3.6 Velocity measurements

To establish the validity of the results the standard deviation of all the velocity measurements was calculated. The mean velocity was 182.2ms^{-1} and a standard deviation of 11.95ms^{-1}. This is considered reasonable as velocity loss was expected due to the addition of a suppressor. A combined standard deviation was calculated as there were in-sufficient results to calculate the variance in results for each individual test. Whilst repeating shots would improve the variable , this was not possible due to the time constraint and any added improvement to the test variable was considered to have little benefit in this study.

3.7 Sound Pressure Levels

As mentioned in 3.4.1 it was hoped to measure the Sound Pressure Levels (SPL) of each firing during but unfortunately the equipment was not available after the first stage of testing. The results show that the introduction of a suppressor has decreased the sound signature produced by the weapon. By introducing holes along the barrel into the suppressor the sound level has dropped by over 9dB. The introduction of a single baffle into the system has increased the sound level.

The results allow one comparison between 2mm and 4mm barrel holes. The use of more than 1 baffle has dropped the SPL under 130dB. There is a marked difference between the 2mm and 4mm barrel holes with a SPL difference of nearly 5 dB in favour of the 4mm holes. This finding is in general agreement with the theoretical work which suggested that a greater barrel hole size would result in a greater pressure within the suppressor thus reducing the sound signature produced.

3.8 Conclusion

It was established that by increasing the pressure inside a suppressor chamber improves the effectively of a suppressor device on the SPL recorded in the vicinity of a weapon. In order to achieve this objective a number of suppressor configurations were introduced and investigated. In this study the following geometric variations were found to have a direct influence on improving the effectiveness of a silencer:

- the use of baffles
- increasing the number of baffles
- increasing the size of the holes in the barrel.

The study also found increasing the size of the baffle holes does not have a discernable effect on the pressures within the suppressor.

The results suggested a suppressor configuration with 4mm barrel holes and small spacers with 2mm holes through the baffles would achieve maximum stabilised pressure along the suppressor resulting in a quieter sound signature.

Chapter 4
Proofing a Suppressor

4.1 Introduction and Aim

Sound suppressors that are attached to the muzzle of a gun will be subjected to pressures that are dependant upon internal ballistic considerations and not necessarily the pressures developed in the chamber of the gun. A requirement for all weapons sold in the UK is that they must be sent to either the London or Birmingham Gun Barrel Proof House for testing or ‘proofing’ to ensure they are safe to use by members of the public. If a sound suppressor is fitted to the weapon then this must be tested also.

The test consists of firing a high pressure cartridge in the weapon followed by a viewing of the weapon to ensure that the weapon has withstood the higher pressure. The high pressure cartridge is loaded to generate a chamber pressure 30% greater than the mean maximum pressure for the weapon. In most instances it is not possible to increase the charge weight sufficiently to give the extra 30% pressure required so a different, often faster burning propellant is used. Whilst this may give the increase in pressure in the chamber it may also generate a different pressure/displacement profile. Therefore the pressure at the muzzle and sound suppressor may be lower than the standard service pressure rather than the 30% higher value required for the test. This part of the study was therefore carried out to investigate if a proof charge designed to give 30% greater pressure than that of a service load at the chamber also gives a 30% greater pressure than that of the service round inside the suppressor body at the muzzle end of the weapon.

4.2 Experimental Procedure

A Jackson rifle suppressor was selected for this investigation because it is a typical device that is extensively used by the shooting community. The 7.62mm x 51mm cartridge is used by the military, target shooters and by deer stalkers and so was a natural choice for a typical powerful rifle calibre firing a super sonic bullet. The sound suppressor was fitted to the barrel by Cranfield University workshops in accordance with the manufacturer's instructions. The barrel was adapted to fit within the No.3 Universal Breech housing and all firings were undertaken in the Small Arms Experimental Range, which is a fully enclosed range at Cranfield University. All firings were carried out remotely. A pressure tapping was added to the breech end of the barrel, immediately beyond the end of the chamber, to allow the chamber pressure to be measured.

The suppressor was modified to allow pressure reading to be taken from 3 different points along the suppressor. The points were chosen after the suppressor was x-rayed to determine the internal layout of the components. A damaged suppressor was also sectioned to confirm the best position to attach the pressure transducers and is shown in Figure 44. Three clamps were made up to mount the pressure transducers, the mounted clamps are shown in Figure 45 (AutoCAD drawings can be found in Appendix A). Figure 46 shows the barrel used in the work with a close up of the transducer hole drilled into the chamber.

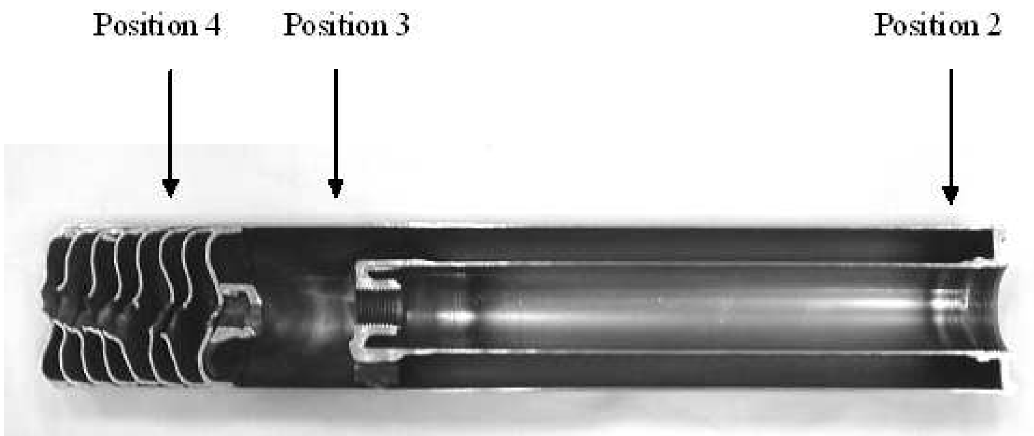


Figure 44 Cross-sectioned damaged suppressor

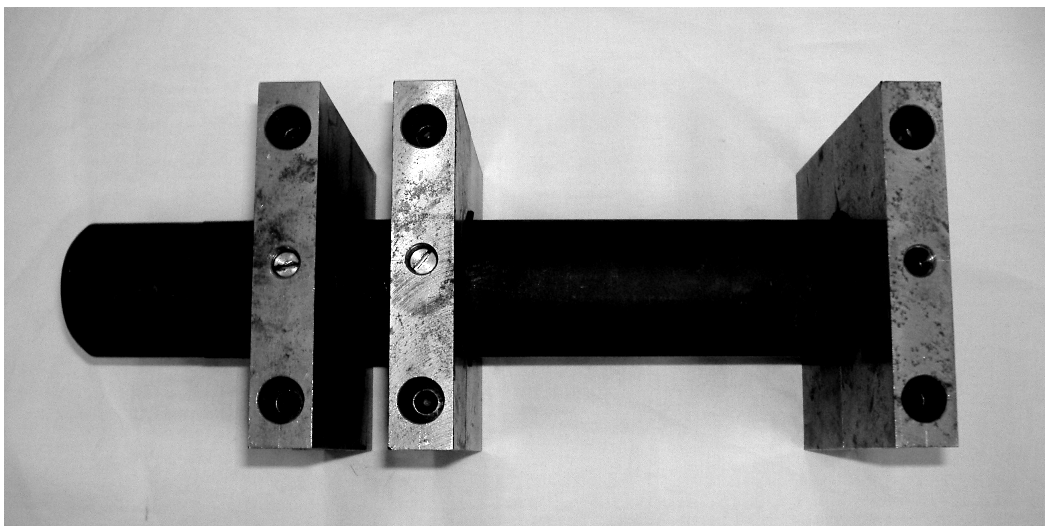


Figure 45 Pressure transducer clamps mounted on the suppressor

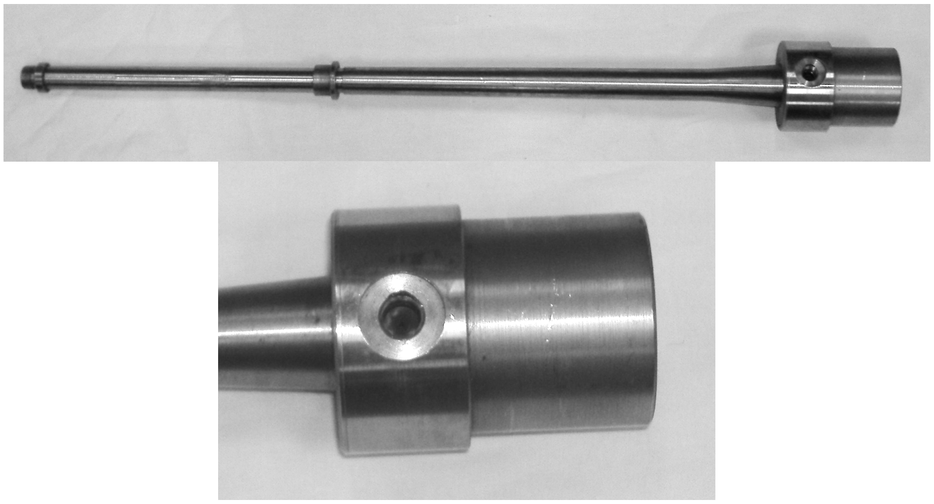


Figure 46 Barrel used with close up of chamber, position 1

Due to the limited availability of pressure transducers 10 shots were fired at each transducer position to enable 10 pressure recordings to be taken. Two types of transducer were used; a Kistler 6203 piezo electric transducer with a charge amplifier and a 217C peizotronic transducer with external power supply. Pressure/time traces were collected using a Nicolet digital recording oscilloscope. Unfortunately the 217C transducer developed a fault during testing so its use was discontinued and the results were not used. A full experimental procedure can be found in Appendix F.

Results from the digital recording oscilloscope were processed using a program called DPlot which enabled accurate peak pressure readings to be taken.

4.3 Results

The results are detailed in tabular form giving details of pressures at each pressure tapping. Position 1 is at the chamber of the barrel. Position 2 is on the suppressor at the end closest to the muzzle at the end of the blow back system. Position 3 is after the end of the muzzle of the weapon within the suppressor. Position 4 is towards the end of the muzzle of the suppressor within the baffles. These are shown in Figure 45. Full DPlot results can be found in Appendix G.

4.3.1 Firing 1

The first ammunition used was Standard Military 7.62mm Ball Radway Green ammunition and results are shown in Table 8 below.
Transducer used – 6203 Kistler.

Position along barrel	1	2	3	4
Max pressure recorded	5360.00	43.89	36.00	32.13
for each shot (Bar)	4688.00	35.78	33.09	31.65
	5132.80	32.16	35.10	31.70
	5606.40	38.19	34.18	33.30
	4049.60	34.62	32.43	30.18
	5340.80	34.45	29.42	32.91
	5161.60	35.92	33.33	31.38
	5372.80	36.61	34.70	34.59
	5596.80	32.69	31.12	31.73
		35.57		
Mean Pressure (Bar)	5145.42	35.99	33.26	32.17

Table 8 Pressures measured at the chamber and in the Johnson sound suppressor using the Kistler 6203 pressure transducer

Unfortunately not all shots resulted in a reading being recorded from the pressure transducers due to a faulty trigger to the recoding device.

It can be seen the chamber pressure is extremely high for the standard ammunition used. It was thought that this high pressure was due to the individual barrel being used rather than the ammunition. This was then confirmed when a standard EPVAT (Electronic Pressure, Velocity, & Action Time) test barrel was then used to check the pressures generated by the same batch of ammunition, the expected pressure level of 3800 Bar was recorded. This is the standard pressure as specified by the manufacturer.

Previous experience of a similar incident in which a 7.62mm x 51mm chambered barrel had given excessive chamber pressures indicated that the excessively high pressure results may have been due to the profile of the lead at the commencement of rifling. A plastic cast was made to take a profile of the lead on the commencement of rifling of both the barrel being used and a standard EPVAT test barrel. The profile of the plastic casts were displayed on a shadow graph and showed the lead of 3^{o} was missing from the chamber into the first barrel tested. Once a 3^{o} lead into the barrel from the chamber was machined into the barrel, pressure levels returned to the standard level.

4.3.2 Firing 2

The second stage of testing used the modified barrel with the 3^{o} lead and standard 7.62 Ball Radway Green ammunition.

The pressure was measured with the Kistler 6203 transducer.

The results are shown in Table 9.

Position along barrel	1	2	3	4
Max pressure recorded	3817.60	29.74	27.82	18.85
for each shot (Bar)	3886.40	28.62	25.68	15.34
	3616.00	34.43	27.98	14.35
	4060.80	29.58	25.87	14.80
	4003.20	30.80	25.10	13.28
	4049.60	30.40	24.45	15.28
	4069.60	28.96	26.29	12.80
	3299.20	29.86	26.29	12.98
	3814.40	29.22	25.31	14.05
		28.14		11.78
Mean Pressure (Bar)	3846.31	29.98	26.09	14.35

Table 9 Pressures measured for the modified barrel at the chamber and in the Johnson sound suppressor using the Kistler 6203 pressure transducer

It can be seen that the chamber pressure has reduced to close to the expected level for the ammunition.

4.3.3 Firing 3

Ammunition used by the Birmingham Gun Barrel Proof house ammunition for proofing 7.62mm x 51mm gun barrels was used for this test. Unfortunately there were various problems associated with this testing.

After each firing it was discovered that there was an unusual deposit on the face of the transducer. It was thought that this deposit came from the bullet as it passes the hole due to the extremely high pressures it was under. Tests were repeated using a different transducer (Kistler 217C) which had smaller dimensions to minimise the collection of deposit. However there was little success as deposits were later found. It proved impossible to remove these deposits from the faces of the two transducers without damaging the transducers so tests were therefore abandoned on the position situated closest to the chamber (Position 1). The results for positions 2 – 4 on the suppressor are from transducer 6203 and are shown in Table 10. Tests were unable to be carried out to establish the source of the deposit as it was not possible to remove the deposit from the face of the transducer.

Position along barrel	1	2	3	4
Max Presssure Recorded		1.00	1.56	1.28
for each shot (Bar)		2.71	1.52	1.28
		2.30	1.51	1.44
		1.82	2.81	1.06
		2.64	2.67	1.27
		2.71	1.59	1.32
		1.06	2.29	1.28
		1.01	2.48	1.29
Mean Pressure (Bar)		1.91	2.05	1.28

Table 10 Pressures measured for modified barrel in the Johnson sound suppressor using Proof Ammunition

4.4 Discussion

The results show for the standard powder ammunition that the higher the pressure in the chamber the higher the pressure in the suppressor. Whilst this may be thought to go against the initial suggestion (the higher the chamber pressure the lower the muzzle pressure for the proof ammo) it must be remembered that for firing 1 the powder is the same as firing 2 and therefore the higher initial pressure will result in a greater muzzle pressure.

For the proof ammunition in firing 3 it can be seen that the pressures within the suppressor are exceedingly low. Whilst there are no readings for the chamber pressure due to the damage of the equipment with each shot it can be suggested that the expected chamber pressure is approximately 5000Bar (using a 30% increase in the maximum pressure of standard ammunition). A comparison between all the firings shows that the proof ammunition is not giving a pressure comparable to standard ammunition.

This can be justified by the pressure displacement curves shown below generated by the internal ballistics program QuickLoad (program designed to simulate the pressures reached inside a barrel for various ammunition and rounds). The graphs have been created to show the difference between the two powders commonly used for the standard and proof ammunition. It can be seen that the proof ammunition produces a 30% higher peak pressure to proof the barrel, however by increasing the peak pressure the muzzle pressure is lowered due to the area covered by the pressure displacement curve.

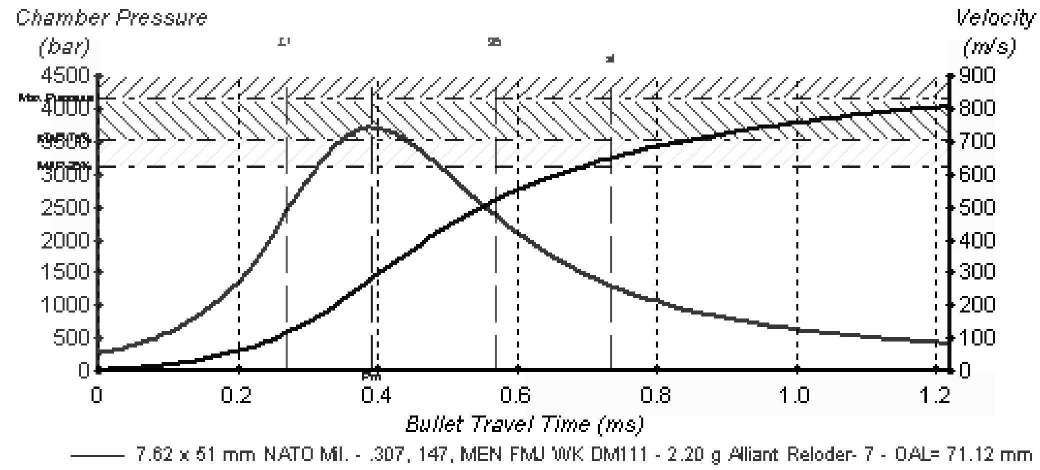


Figure 47 Standard 7.62 round

Standard 7.62 x 51mm cartridge using Reloder 7 powder

Maximum Pressure 3711bar

Muzzle Pressure 374bar

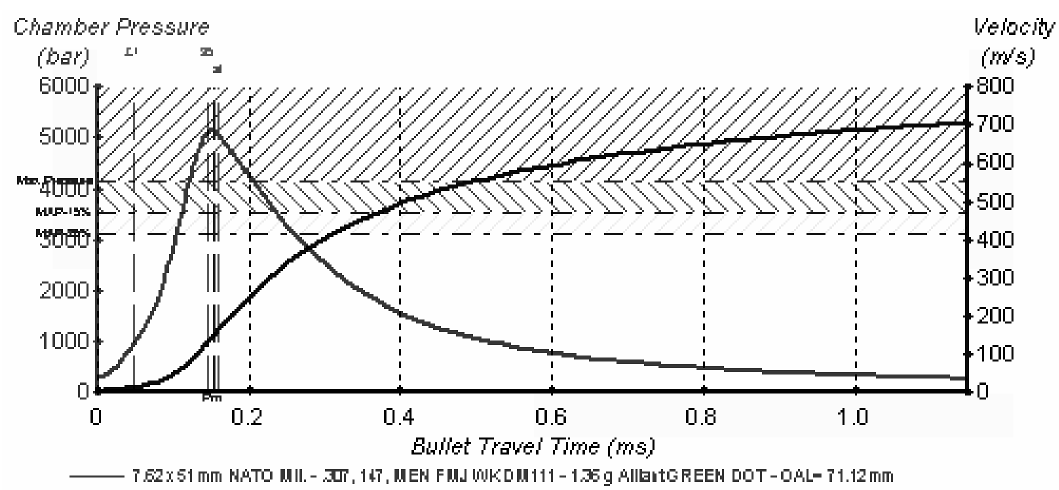


Figure 48 Proof round

Standard 7.62 x 51mm cartridge using greendot powder

Maximum Pressure 5160bar

Muzzle Pressure 238bar

For firing 1 it can be seen that the pressure at position 2 is higher than that at position 3. This could be deemed unusual as the gas leaves the barrel at position 3 where you would expect the highest pressure and then enters the “blowback” part of the suppressor to be measured at position 2. This high result however may be explained by the stagnation pressure of the gas created at position 2 due to the extraordinarily high pressure gas channelled into the “blowback” system.

For firing 2 there is a large drop in pressure between position 3 and 4 which is not experienced in the other tests. This may be due to the effectiveness of the suppressor. For firing 1 the pressures are so high that the suppressor is unable to work effectively, however for firing 2, which uses a standard ammunition and barrel, it is at optimum conditions and will be able to produce effective results.

4.5 Conclusion

Proof ammunition does not give a 30% extra pressure in the suppressor as it does in the chamber. This makes the ammunition un-suitable for proofing suppressors. The results suggest that the proof ammunition gives a lower pressure within the suppressor than standard ammunition. Further work would be needed to establish a suitable method to proof a suppressor.

Chapter 5
Improvised Suppressors

5.1 Introduction

It is known that improvised suppressors are used, usually for illegal purposes, to reduce or disguise the sound of gunfire. The devices used include plastic drinks bottles, vegetable matter and pillows. It was therefore decided to test how effective these items are as a sound suppressor by investigating the sound signature produced as this may shed light on the sound reducing process. There is no quantitative data available for these devices.

Empty plastic bottles are often used as they are readily available. The Idea Gas Law

$$pV = mRT$$

Equation 6 Ideal Gas Law (29)

suggests that for a system where the mass of the gas (m), gas constant (R) and temperature of the gas (T) remain constant the pressure (p) must decrease if there is an increase in the volume (V). This will cause the sound level to be reduced. Summarising, the greater the volume of the bottle the quieter the shot.

Vegetable matter has been used before in terrorist incidents. The principle behind using such items as potatoes and apples is they are solid items and the gas loose energy breaking up the matter and therefore reducing the velocity and noise produced by the gas. In addition, because the matter is solid, the bullet has to force its way through the matter. This can slow the bullet dramatically and for some rounds which travel at a velocity just over the speed of sound causing the velocity to be reduced to below the sound barrier. This prevents the sonic crack created by the round as it passes down range.

5.2 Aim

The aim of the experiment was to test different empty bottles and other household items as suppressors with both a 9mm pistol (subsonic barrel, standard ammunition) and a 7.62mm (supersonic) rifle barrel, by measuring the sound level of a shot being fired. Once tests were completed it was decided to try the most successful items with a 0.22” rifle barrel as the velocity of the rounds are just above the sonic level. It was hoped to see if the muzzle devices could reduce the speed to subsonic therefore removing the sonic crack produced by the round travelling downrange.

5.3 Experimental Procedure

Three barrels used (7.62mm, 9mm and 0.22”) to test the various vegetable matter were mounted in turn in the Number 3 Universal Breech. The universal breech allows many different sized barrels to be secured for firing electronically allowing safe remote firing. For each shot sound measurement equipment was used to capture the sound signature produced upon firing at a perpendicular distance of 1m away from the barrel as in a report by Rahman. **(30)** This measurement of the sound pressure levels is in line with current Military of Defence practice **(10)** which suggests measurements should be “conducted in accordance with the principles of current best practice” Analysis of the results allowed the peak sound pressure level to be determined. Photo Optical Chronographs were also used to measure the velocity of the round as it passed downrange. A comparison between a shot fired without any suppressor allowed the velocity degradation caused by the suppressors to be analysed. A high-speed video camera was also used to capture each event where possible to allow visual analysis of each test. The high speed video captured the trials in black and white.

For each of the 7.62mm and 9mm barrels two initial shots were fired to determine the peak sound level and the velocity of the shot. This could then be used as a comparison between subsonic and supersonic weapons. Items were then tested on the barrels. Bottles were mounted onto the barrel allowing the muzzle to protrude just beyond the neck of the bottle and then taped securely onto the barrel. The vegetables and fruit were mounted directly onto the end of the barrel by pushing them securely on. Table 11 describes the different items used in the tests and also details the reference given to the items used in following tables.

Item	Volume	Material	Reference
Water Bottle	2L	PET	Water L
Fanta Bottle *	500mL	PET	Fanta S
Ocean Spray	1.5L	PET	Ocean L
Oasis	1.5L	PET	Oasis L
Fruit Shoot	200mL	PET	Fruit S
Washing Up Liquid *	1L	HDPE	Wash
Ribena	1L	PET	Ribena
Lucozade Hydroactive	500mL	PET	Hydro S
Asda Lucozade	330mL	PET	Luco S
Pepsi *	2L	PET	Pepsi L
Lucozade Standard *	1L	PET	Luco L
Pepsi	500mL	PET	Pepsi S
Tonic	1L	PET	Tonic
Squash	1L	PET	Squash
Mini Lemonade	200mL	PET	Lem S
White Lightning *	3L	PET	White
Apple *		Cooking	Apple
Melon *		Honeydew	Melon
Potato *		Baking	Potato
Pillow Polyester *		Cotton Cover, Polyester filling	Pillow (P)
Pillow Feather *		Cotton Cover, Feather filling	Pillow (F)
Cushion Polyester *		Cotton Cover, Polyester filling	Cushion (P)
Cushion Feather *		Cotton Cover, Feather filling	Cushion (F)

Table 11 Details of Items Tested

PET – Polyethylene Terephthalate

HDPE – High Density Polyethylene

Once the initial testing was complete the most successful items were then used on the 0.22" barrel. These items are marked * in Table 11.

A full detailed experimental procedure and firing plan can be found in Appendix H.

5.4 Results

It was found that different bottles worked in different ways on the various barrels. Some items reduced the noise level in terms of dB and some items caused the sound signature to be altered. A comparison was drawn between sounds and various common noises such as a balloon popping and books being dropped. Pressure time curves can be found in Appendix I.

5.4.1 7.62mm Results

Barrel only - Velocity 837.1ms^{-1} , Sound level 164.7dB

Silencer Ref	Velocity Drop (m/s)	Reduction in Sound (dB)	Shot Sound Characteristics
Water L	7.95	2.98	
Fanta S	1.70	3.09	
Ocean L	12.05	2.36	
Oasis L	7.15	3.03	
Wash	-2.35	-2.05	
Ribena	10.05	6.40	
Hydro S	16.60	-0.84	
Luco S	3.30	-0.54	
Pepsi L	8.30	7.80	Balloon popping
Luco L	2.65	4.16	Balloon popping
Pepsi S	0.95	2.12	
Tonic	2.30	4.67	Balloon popping
Squash	9.70	6.17	
Lem S	-2.10	0.49	
White	6.05	8.25	Balloon popping
Apple	45.15	9.76	Pile of books dropped to the floor
Potato	161.50	9.89	Pile of books dropped to the floor
Melon	193.85	14.32	Very quiet but little sound difference
Pillow (P)	0.85	3.49	
Cushion (P)	3.85	6.32	
Pillow (F)	-6.00	12.29	

Table 12 7.62mm Results

The sound meter did not record for the Fruit Shoot bottles and the feather cushions so these results have not been able to be included.
All bottles were found to have the base removed by the bullet and exhaust gas.
All vegetable matter was broken into small pieces.

Below is a small selection of still shots from the high speed video camera which captured footage of tests.

Figure 49 Washing up bottle

The washing up bottle has been ripped open by the force of the exhaust gas and the soft plastic has not withstood the shot.

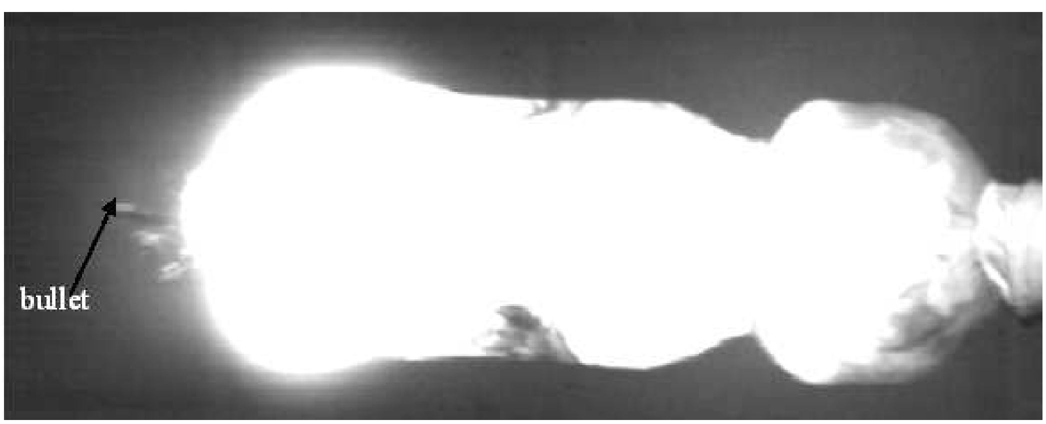


Figure 50 Fanta (S) during shot

The 7.62mm round can be seen exiting the bottle on the left. The muzzle flash has been contained in the bottle.

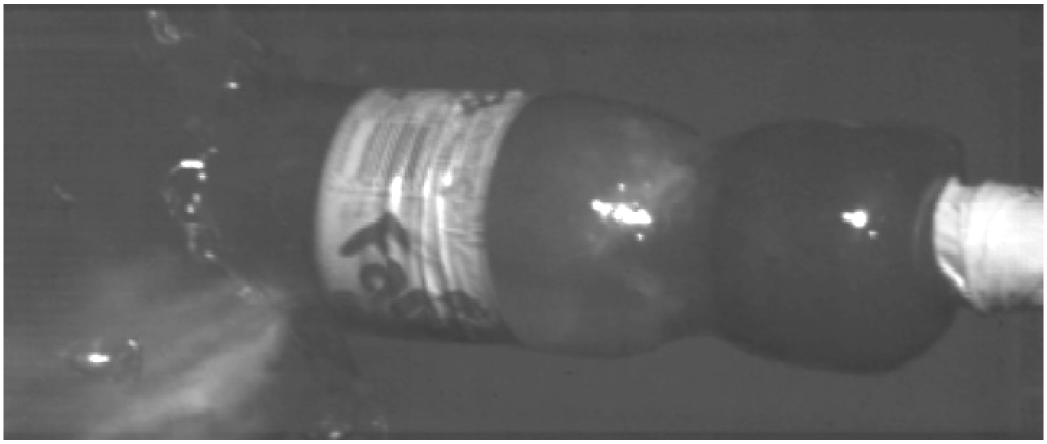


Figure 51 Fanta (S) Damage

The damage caused to the bottle can be seen on the left, the base of the bottle is now in small fragments moving down range. This was typical of all the plastic with the exception of the washing up bottle and Fruit shoot bottle shown in Figure 49 and Figure 54.

Figure 52 Lucozade (L)

The damage to the Lucozade bottle can be seen on the left, once again the base has broken up into plastic fragments moving downrange.

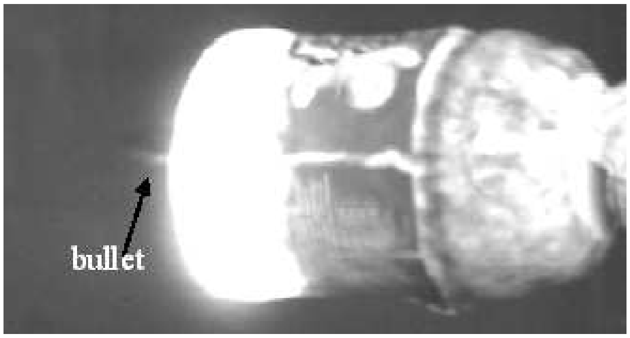


Figure 53 Fruit Shoot during firing

The 7.62mm round can be seen leaving the Fruit Shoot bottle on the left. The bottle has captured the muzzle flash from the firing.

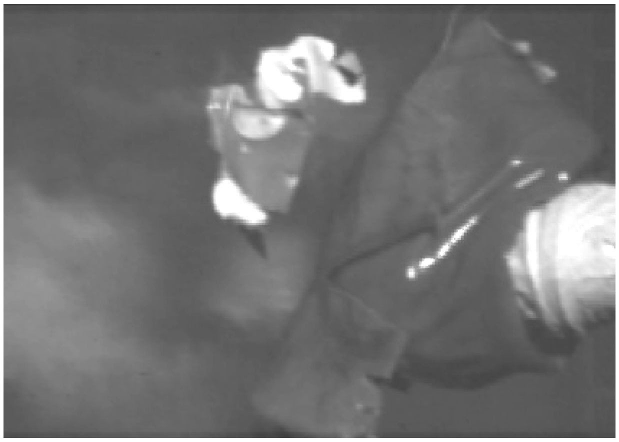


Figure 54 Fruit Shoot damage

The damage to the Fruit Shoot bottle is extensive.

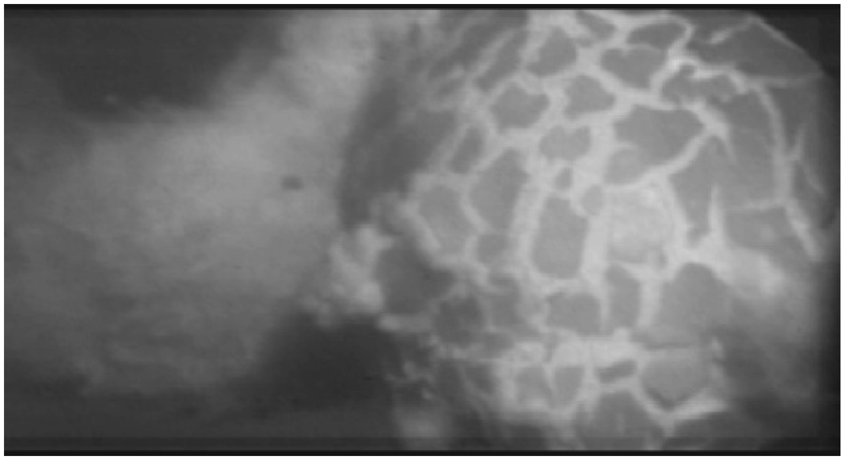


Figure 55 Apple

The apple has been broken into small fragments of approximately $1cm^3$. This damage was typical for the vegetable matter.

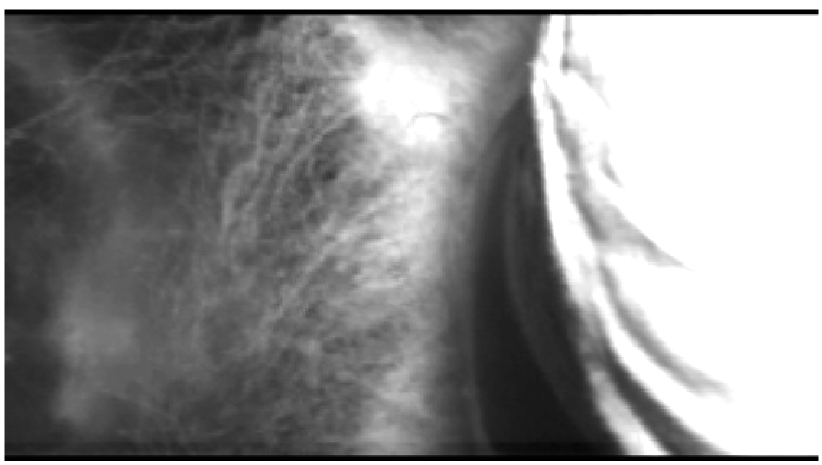


Figure 56 Pillow (P)

The polyester pillow has had the fibres drawn out following the passage of the bullet. The fibres were found to have melted and fused together. The polyester cushion had the same effect. The feather pillow and cushion had a similar effect with the feathers following the bullet out, however the feathers did not melt but were scorched.

5.4.2 9mm Results

Barrel only - Velocity 301.0ms^{-1} , Sound level 157.6dB

Silencer Ref	Velocity drop (m/s)	Reduction in Sound	Shot Sound Characteristics
Luco L	3.95	19.54	Balloon Popping
Tonic	18.70	12.93	
Ocean L	36.70	15.21	
Squash	11.65	16.04	
Oasis L	8.50	18.48	
Fruit S	12.25	9.15	
Lem S	15.26	12.06	
Pepsi L	34.79	14.63	
Fanta S	10.10	15.66	
Water L	7.00	21.21	no sound difference
Pepsi S	3.50	17.89	
Ribena	5.50	18.13	
Luco S	0.90	8.22	
Wash	27.65	24.15	Quiet and like a knock at a door
Apple	38.45	8.18	
White	12.10	19.92	Pile of books droped to the floor
Potato	73.90	19.92	Pile of books droped to the floor
Melon	85.00	28.26	Very Quiet but little sound difference
Pillow (Poly)	62.45	22.67	
Cushion (Poly)	53.45	22.62	
Cushion (Feath)	63.95	24.41	
Pillow (Feath)	46.95	14.44	

Table 13 9mm Results

The sound meter did not record for the ASDA Lucozade Fruit Shoot bottles so these results have not been able to be included.

All bottles were found to have a small bullet hole in the base.

All vegetable matter was broken into even sized pieces.

Below is a small selection of still shots from the high speed video camera which captured footage of tests.

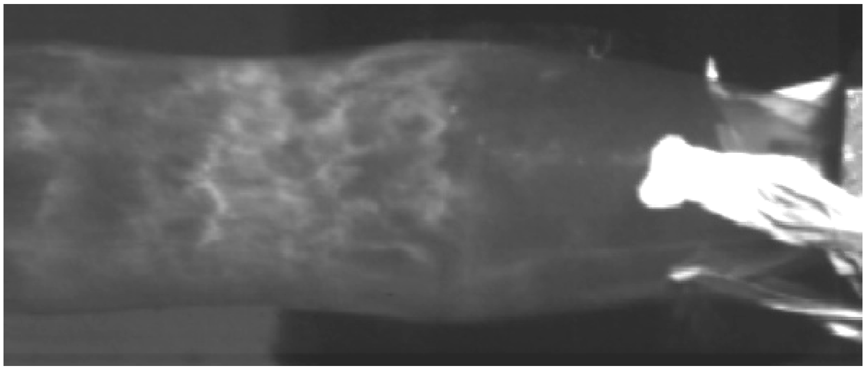


Figure 57 Lucozade (L)

The exhaust gas can be seen in the bottle.

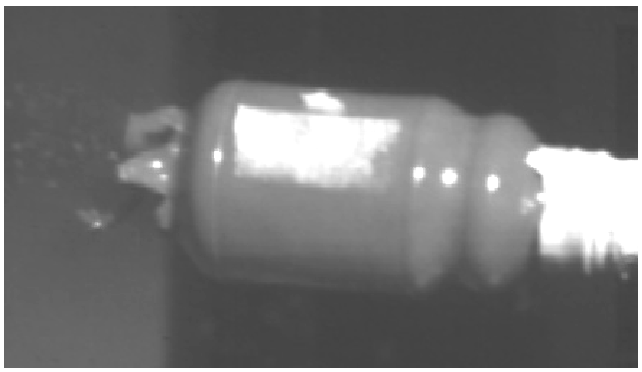


Figure 58 Fruit Shoot

The most damage done to a bottle was to the Fruit Shoot bottle

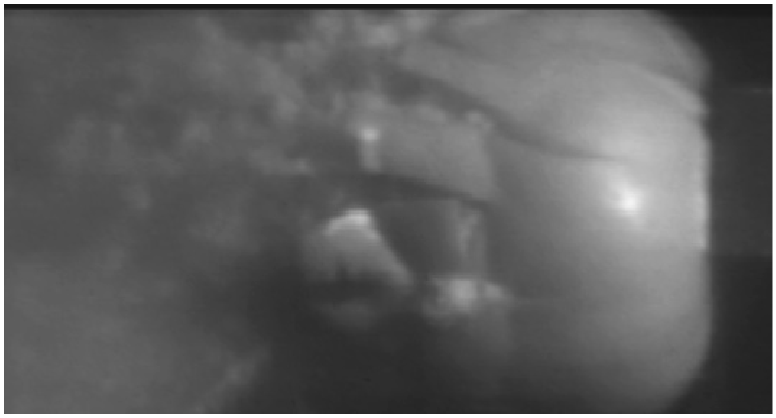


Figure 59 Apple

The damage done to the vegetable matter were pieces of approximately 2 - 3cm^3

5.4.3 0.22" Results

Barrel only - Velocity 411ms^{-1} , Sound level 135.1dB

Silencer Ref	Velocity Drop (m/s)	Reduction in Sound (dB)	Shot Sound Characteristics
Fanta S	55.25	4.36	
Wash	12.95	11.90	
Pepsi L	31.35	5.34	
Luco L	31.45	6.31	
White	29.10	4.62	
Apple	50.80	8.41	balloon being popped
Melon	23.40	15.64	books dropped to the floor
Potato	16.25	7.88	books dropped to the floor
Pillow (P)	10.80	14.87	
Pillow (F)	11.80	13.32	
Cushion (P)	7.85	8.06	
Cushion (F)	11.65	13.91	

Table 14 0.22" Results

All bottles were found to have a small bullet hole in the base.

All vegetable matter was broken into large pieces.

The pillows and cushions were left with a small entrance hole and slightly larger exit hole.

Below is a small selection of still shots from the high speed video camera which captured footage of tests.

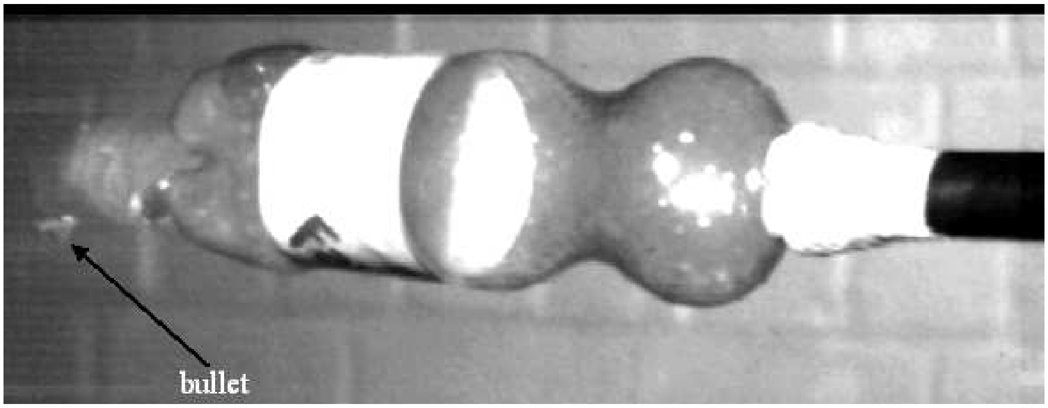


Figure 60 Fanta S

The bullet can be seen leaving from the bottle at the left. The damage to the bottle is the hole created by the bullet. This was typical for the plastic bottles. The video footage also showed the reflection of the gas from the necking of the bottle 1/3 of the way down the bottle. As a result the containment delayed and dispersed the discharge of the gas over a longer period of time.

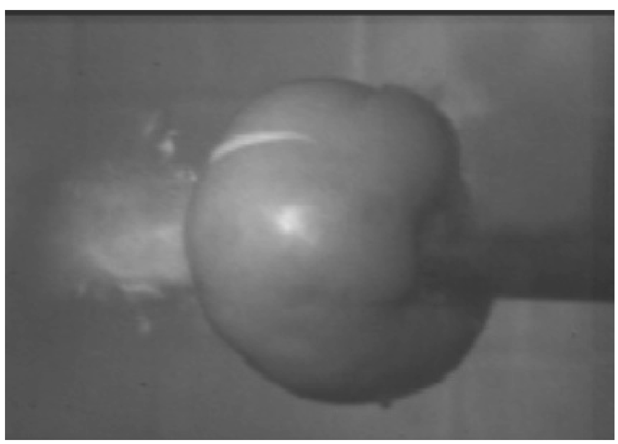


Figure 61 Apple

The apple was broke into 5 large pieces. These large pieces were typical for the vegetable and fruit matter.

5.5 Discussion

5.5.1 7.62mm

It can be seen the most effective item that reduced the sound level was the melon with a reduction of over 14dB. In terms of disguising the sound at the same time as reducing the sound level the potato and apple were very effective.

For the bottles the trend suggested is the greater the volume of the bottle the greater the sound reduction. This is supported by the 3l White Lightening bottle having the greatest reduction followed by the 2l Pepsi bottle and 1l Lucozade and Tonic bottles. This also supports the Ideal Gas Law theory that the greater the volume the gas has to expand into the slower the exit velocity of the gas.

It can also be noted that the empty bottles which had previously contained pressurised liquids seem to offer a greater reduction in sound signature than those which had not contained pressurised liquid. Comparing the 2l Pepsi and Water bottles the Pepsi performs better reducing the sound level and disguising it. With the 1l bottle even though the Squash and Ribena bottles fared slightly better with the reduction of sound the Tonic and Lucozade disguised the sounds produced. For the 500ml bottles the pressurised bottles achieved greater reductions than the non pressurised bottle. This may be due to the thickness or density of the bottle or a different grade of plastic. Further tests would establish this.

Video footage showed the larger bottles were able to contain the muzzle flash within the volume of the bottle. Smaller bottles such as the fruit shoot and ASDA Lucozade bottle were not effective. This suggests that a large volume is needed to contain the muzzle flash.

There was a large variation in the test results obtained between different pillows and cushions. The feather pillow was much more successful than the polyester equivalent. Unfortunately no comparison can be made between the feather and polyester cushions as a fault developed with the sound measurement equipment during the tests of the feather cushions. Due to time constraints in range time further tests were not possible.

5.5.2 9mm

The most effective item was the melon with a reduction of 28dB. The most effective bottle was the 2l water bottle however only one reading was recorded so this could be misleading. Therefore with two confirmed readings of a reduction similar to the water bottle and also an altering of the sound signature, the 1l Lucozade bottle suggests it is the most effective bottle. Compared to the results for the apple and potato for the 7.62mm there is a large difference between the results for the apple and potato of over 10dB.

The feather pillows and cushions were very effective with the 9mm pistol with large reductions in sound levels. There was however a noticeable velocity drop between 45 and 65ms^{-1}. This may be due to the characteristics of the pillows. Feathers may allow large amounts of energy to be dissipated as heat or absorbed through viscous interaction with the material.

5.5.3 0.22”

It can be seen that the most effective item was the melon with a large reduction of 15.6dB and changing of the sound profile for little velocity reduction. The apple and potato performed well at around 8dB, they were more effective than most of the bottles, however they were not as effective as the washing up bottle and the pillows and cushions.

The most effective bottle was the washing up bottle with a sound reduction of 12dB followed by the 2l Pepsi bottle which was recorded at nearly 8dB quieter. The washing up bottle was effective for both the 0.22” and the 9mm however no other item showed such reductions for both the 0.22” and 9mm bottles.

As commented in the results the video footage also showed the reflection of the gas from the necking 1/3 of the way down the bottle. This containment delayed and prolonged the discharge of gas from the bottle. This results in a lower sound signature from the gas. This suggests that baffles are a good addition to sound suppressors.

The sound results for the pillows and cushions show they were effective for the 0.22” rounds. The feather varieties were shown to perform better than the polyester.

5.6 Conclusion

The collated results show that different bottles work well for different ammunition.

High velocity barrels suggest the need for as large a volume as possible for the gas to expand into. Pressurised bottles are the most effective bottle form of improvised suppressors. This is especially true of high velocity rounds.

Low velocity rounds are more suited to a smaller washing up bottle than a larger pressurised bottle.

Pillows are effective with low velocity rounds with feather pillows performing better than polyester filled ones.

Fruit and vegetables, especially potatoes make highly effective suppressors and can dramatically change the sound produced both in terms of a reduction in SPL and its characteristic profile.

The work suggests that the use of baffles within a sound suppressor are beneficial to the performance, extending the time the gas leaves the suppressor.

The video footage also showed suppressors are useful at reducing the flash as it can be contained within the suppressor.

The use of improvised suppressors permitted a visual observation into what was happening within the enclosed volume of the suppressor. This allowed an insight into the complex gas flow which would not have easily been achieved by other methods.

Chapter 6
Discussion

6.1 Experimental

It can be seen from the results that there is an effective configuration which enables a high pressure to be maintained throughout the sound suppressor. It was shown the suppressor maintains maximum pressure throughout its length thus indicating that optimum use is made of its volume. This allows the pressure within the suppressor to equalise with the pressure within the barrel more effectively.

It can be seen that 4mm holes through the barrel are more effective than 2 or 3mm holes for the geometry of the weapon used. The same effect might be seen from the same area ($1.01 \times 10^{-10} m^2$) but using different sized holes. The pressure might however be altered by the discharge coefficient of the holes. This work is beyond the scope of the project but should be investigated for completeness. For example using the area of the combined 8 x 4mm holes and re-distributing this around the barrel as 32 x 2mm holes will not produce the same outcome due to the discharge coefficient and vena contractor effect. The other problem which may result in this is a weakening of the barrel. The reduction in material around the barrel may under the pressure of firing, cause a weakening of the material of the barrel resulting in structural failure. This could lead to catastrophic consequences.

Similarly, using taking the same area and increasing the diameter of the holes to 8mm with only 8 holes may cause fouling with the projectile as it passes down the barrel. This would cause the barrel to fail during repeated use.

It can also be seen that small spaces between baffles are more effective than long separations. It can also be suggested that the longer holes are needed along the length of the suppressor. It was originally thought that there may not be a requirement for smaller spacers further along the barrel, however it can be seen from test 10 that whilst the long spacers have achieved the maximum pressure recorded the pressure drops dramatically along the silencer. The volume within the suppressor therefore has not been used to a maximum.

Whilst these results are applicable to the geometry of the weapon and suppressor used, it has been proven that there is a limit to which a suppressor can perform and that this can be achieved without detriment to the velocity of the projectile.

The results in tests 20 – 23 suggest that holes are needed to allow gas through the baffles in order to achieve a higher pressure within the suppressor chambers. The results of tests 2 – 19 indicate that the size of the holes through the baffles has little effect on the pressure within the suppressor. Therefore it can be suggested for the low pressure suppressor, the size of holes ih the baffles is less effective.

The limited sound results suggested that the use of many baffles is advantageous at reducing the SPL produced upon firing. The results also suggested that bigger holes through the barrel create a bigger pressure within the silencer thus reducing the SPL. In order to confirm this further study would be required.

6.2 Theoretical vs. Experimental

The trends suggested by the theoretical work have been supported by the results obtained experimentally.

A comparison of the results can be found in Table 15. The experimental results have been converted to absolute pressures for accurate comparison.

Set-up	Theoretical Pressure (bar)	Experimental Pressure (bar)	
		2mm baffles	3mm baffles
2mm barrel holes small spacer	14.85	6.20	11.32
2mm barrel holes medium spacer	8.46	6.93	3.31
2mm barrel holes long spacer	6.10	6.08	2.31
3mm barrel holes small spacer	18.98	21.03	13.63
3mm barrel holes medium spacer	11.03	10.52	16.2
3mm barrel holes long spacer	7.62	7.28	16.27
4mm barrel holes small spacer	21.82	27.47	26.42
4mm barrel holes medium spacer	12.58	27.40	8.13
4mm barrel holes long spacer	8.67	78.87	28.23

Table 15 Comparison of Theoretical and Experimental results.

A comparison of the results shows that the theoretical prediction showed a general agreement with trial results. This suggests the Emptying and Filling Silencer program has been successful in predicting the suppressors characteristic performance. The exception to the trend is the 4mm barrel hole results. These do not follow the trend when comparing the results in Table 15 however it can be seen from the results in Chapter 3.5 that the trend shown by the theoretical work is also seen further down the sound suppressor. The results are not exact, due to the theoretical modelling which was not able to replicate the unusual configuration of the cartridge. The discrepancies are also due to the theoretical calculations being based on a steady state assumption when the gas flow is transient which is extremely difficult to model.

The aim of the project was to establish which factors affect the pressures within the suppressor. The theoretical work suggested that the size of holes through the barrel had the greatest effect on the pressure within the sound suppressor. This was supported by the experimental work. Original thoughts suggested that to optimise the pressure along the barrel it may be needed to vary the barrel hole size along the length of the barrel. This has not been necessary as shown in the results, with the 2mm baffle 4mm barrel holes and small spacers, 3mm baffle 4mm barrel holes and small spacers and 3mm baffle 4mm barrel holes and long spacers (tests 8, 17 and 19.) The test results had shown that a stabilised pressure had established along these suppressors.

The limited sound results suggested that an increase in barrel hole size has lead to a quieter sound produced as predicted by the theoretical work. However there are limited results available and further work would have to be undertaken to confirm this.

6.3 Observations from further work

Whilst there had been a delay in the availability of the pressure transducers, further work was carried out within the field of suppressors.

With the possibility of different pressures within the suppressor dependant on any barrel alterations the practice of proofing suppressors was investigated. The work has shown that the current practice of proofing barrel was not sufficient for the proofing of a suppressor. The use of a higher charge round did increase the pressure within the barrel but due to the pressure distribution it created a lower pressure than for a standard cartridge in the external suppressor being investigated. The current practice of proofing a barrel was shown not to be a suitable practice for proofing a suppressor.

With the results from the experimental work for the various configurations it can be seen the importance of proofing a suppressor for the design and the ammunition to be used. An alteration by a manufacturer or consumer such as increasing the diameter of the holes in the barrel would lead to a greater pressure in the suppressor. This may be undesirable as increasing pressure may lead to structural failure.

Work with improvised suppressors showed that when the volume of the suppressor was increased a quieter sound was recorded. This is supported by the ideal gas law and suggests that during design that this should be considered. However the addition of a large sound suppressor should not detract from the primary role of the weapon. The dimensions of the suppressor should therefore be determined by the intended role of the weapon.

Energy dissipation has also been shown to be a useful method of silencing a weapon. The use of fruit and vegetable matter was highly successful. The energy from the gas was used to break the items reducing the sound signature of the shot.

From the analysis of the high speed video footage has shown the importance of baffles. The video of item such as the Fanta bottle showed the reflection of the gas from the constrictions of the bottle. These delayed the passage of the gas leaving the bottle. Whilst this was only by a short period of time this was sufficient to create a lower sound signature. This suggests that baffles are a useful contribution to reduce the sound signature of the weapon.

Chapter 7
Conclusion

The geometry of a suppressor and the transient nature and heat flow of the gas produced upon firing make this a highly complex problem to investigate using theoretical modelling techniques. However by simplifying the problem a theoretical approach can give useful results in the form of trends.

Theoretical work has shown that it is possible to explore the variables which affects the pressure within a suppressor however it is not possible to accurately predict the pressure levels within the suppressor. This is useful for investigation into general trends and to identify those variables that have the greatest effect and therefore are worthy of more detailed investigation. To obtain accurate base line data it was necessary to use experimental procedures. The theoretical work suggested the area of the holes through the barrel would have the greatest effect on the pressure within the suppressor.

Experimental testing has shown that the use of baffles within a suppressor is important and for the low pressure system being considered. It has been shown that the spacing and number of baffles are important. More baffles with smaller spacing between them are better than fewer baffles spaced further apart. This uses the volume within the suppressor to its maximum. Large barrel holes were shown to be more effective at raising the pressure of the gas in the suppressor than smaller barrel holes. The optimum configuration was shown to be 2mm baffle holes, 4mm barrel holes and small spacers with the 3mm baffle holes, 2mm barrel holes and long spacers showing the lowest pressures within the suppressor. The size of the hole which allows gas to travel through the baffles did not have a significant effect on the pressure within the suppressor.

The experimental work supported the theoretical deduction that the greater the diameter of holes through the barrel the greater the pressure within the suppressor. The limited sound results obtained confirm that a larger barrel hole size results in a lower sound signature.

Current proofing practice requires a 30% increase in the level of pressure in the suppressor. The results from the testing indicated that this increase is not being attained. It is suggested that current practice tests to a pressure below normal operating level.

Experimental work also showed that modifications to the barrel regarding the number and size of holes may seriously increase the pressure in the suppressor leading to invalidation of the proofing of the suppressor and lead to possible catastrophic failure.

Improvised suppressors are an effective means of suppressing a weapon. The project has shown that when the volume of the suppressor was increased a quieter sound was recorded. The transparent nature of some plastic bottles proved to be very useful in identifying gas flows within the containing medium. The work has also shown the importance of baffles within a suppressor which delay the expulsion of gas thus reducing the sound signature. The high speed video footage has helped to provide visual records showing the effect of a suppressor at reducing the muzzle flash.

Chapter 8
Recommendations for Further Work

Further work could be carried out to establish the sound pressure levels for all the tests undertaken. This is essential to give a wider understanding of the problem investigated within the project. Further work is also needed to determine whether the conclusions reached for the low pressure system are also justified for higher pressure systems.

There is a need to establish a method of proofing suppressors efficiently and accurately as current practice is not sufficient.

Further work could determine whether modifications to improvised silencers would improve their performance. For example shrouding bottles with dark material might improve their performance at reducing the muzzle flash.

Appendix A

AutoCAD Drawings

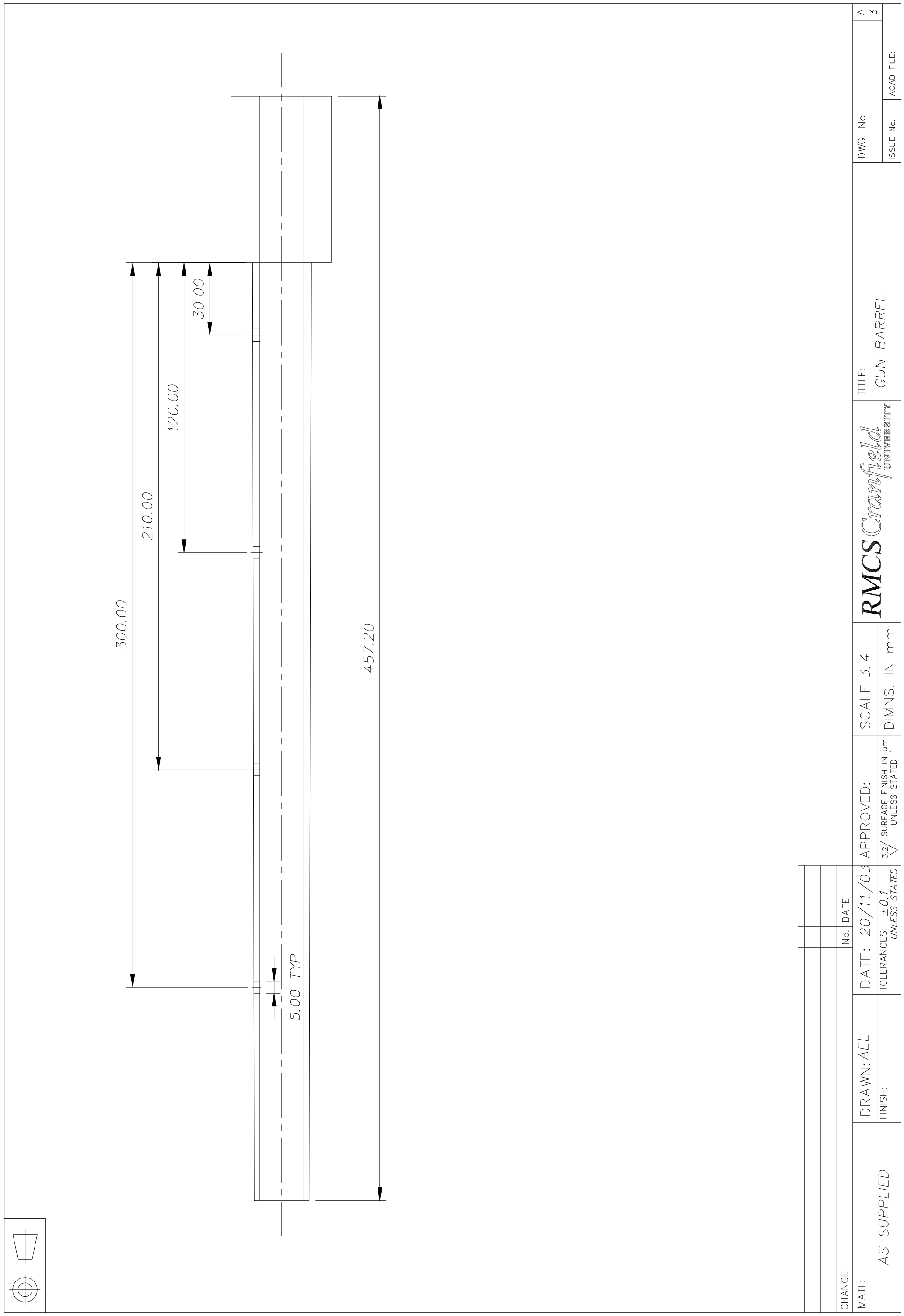
Testing of 18” barrel

Barrel

Collar

Plug

General Assembly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210.00
300.00
457.20
5.00 TYP
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FINISH:
DATE: 20/11/03
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APPROVED:
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RMCS Cranfield UNIVERSITY
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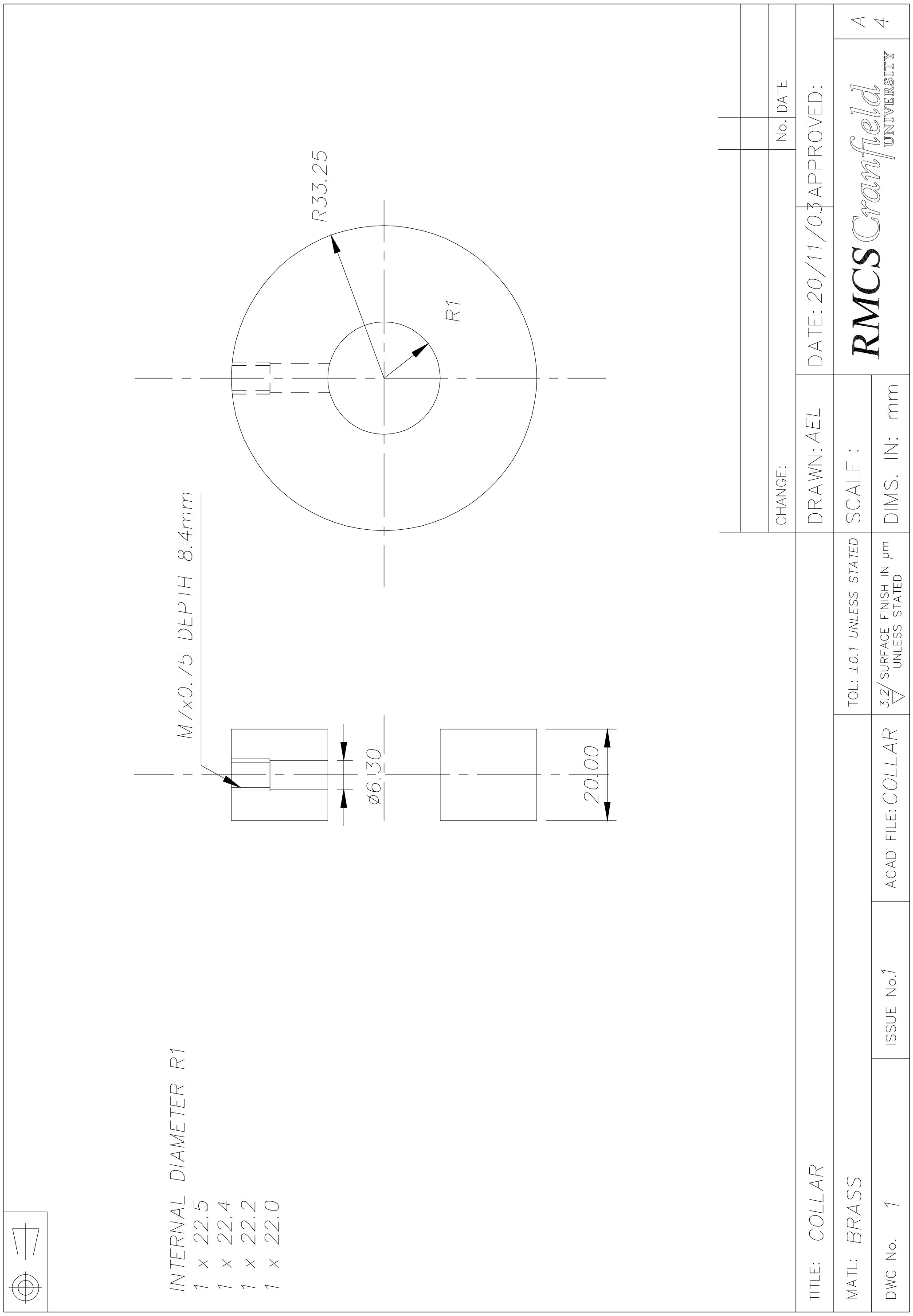
DWG. No.
ISSUE No.
ACAD FILE:
A3


INTERNAL DIAMETER R1
1 x 22.5
1 x 22.4
1 x 22.2
1 x 22.0
M7x0.75 DEPTH 8.4mm
R33.25
R1
ø6.30
20.00
CHANGE:
No.
DATE
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MATL: BRASS
DWG No. 1
ISSUE No.1
ACAD FILE: COLLAR
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DIMS. IN: mm
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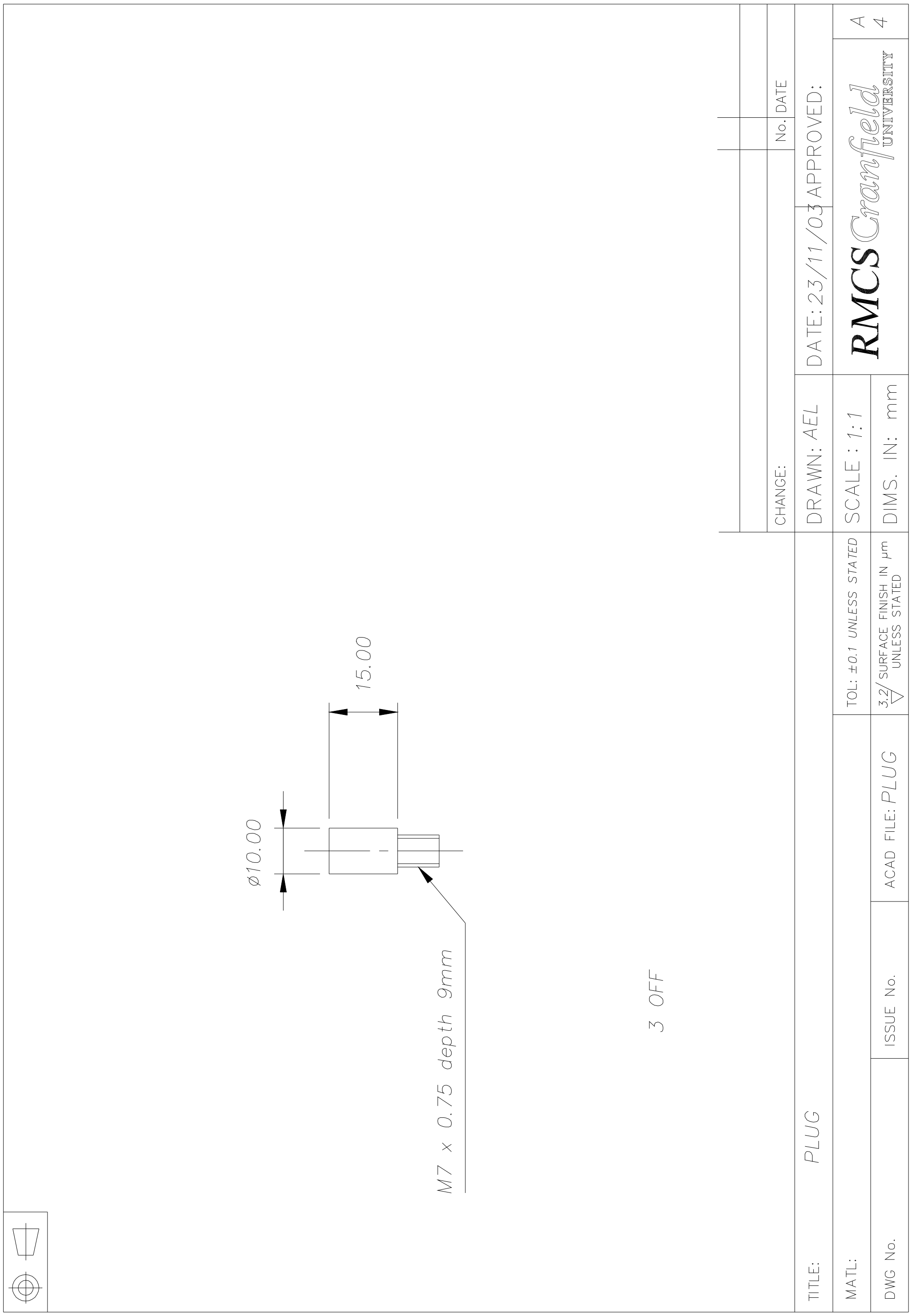
APPROVED:
RMCS Cranfield UNIVERSITY
A 4



15.00
Ø10.00
M7 x 0.75 depth 9mm
3 OFF
No. DATE
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DATE: 23/11/03
APPROVED:
SCALE : 1:1
DIMS. IN: mm
RMCS Cranfield UNIVERSITY
A4
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ISSUE No.
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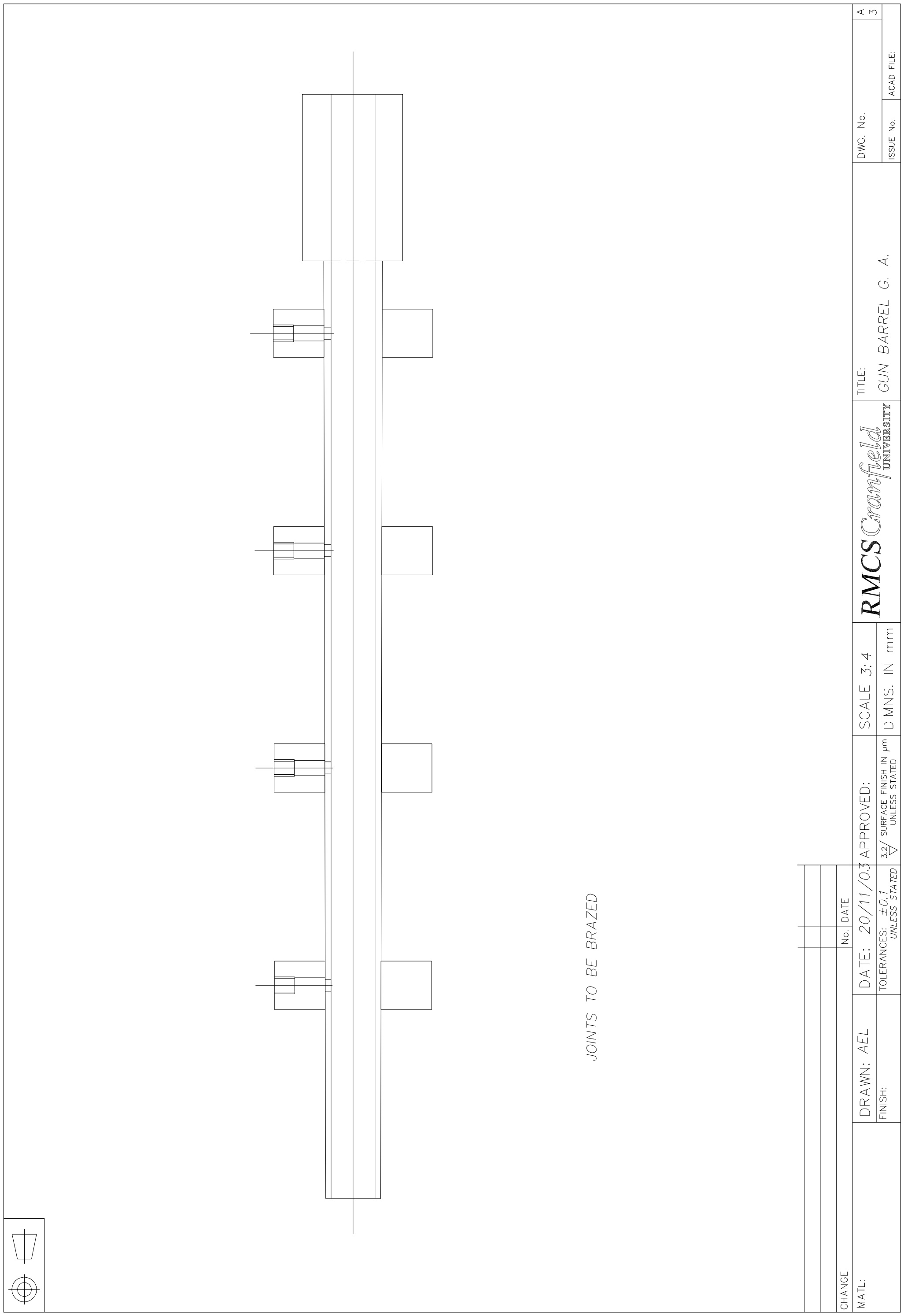
3.2 SURFACE FINISH IN µm UNLESS STATED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DATE: 20/11/03
APPROVED:
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DIMNS. IN mm
TOLERANCES: ±0.1 UNLESS STATED
3.2 SURFACE FINISH IN µm UNLESS STATED
FINISH:
MATL:
CHANGE
No. DATE
RMCS Cranfield UNIVERSITY
TITLE:
GUN BARREL G. A.
DWG. No.
ISSUE No.
ACAD FILE:
A3

Testing of Suppressor

Barrel

Baffle

Spacer

End Cap Breech

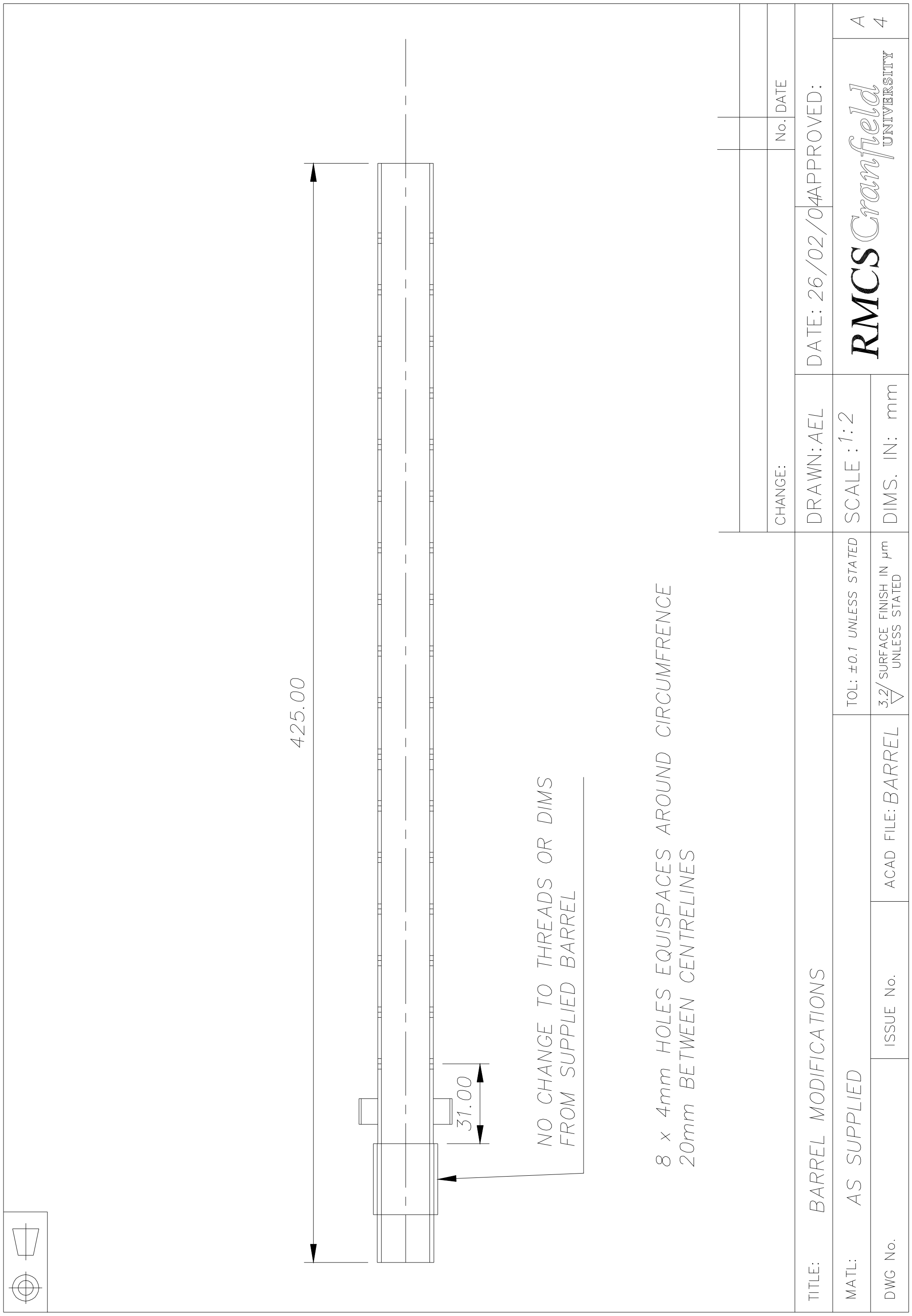
End Cap Muzzle

Silencer Housing

Pressure Transducer Adaptor

General Assembly

Parts list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31.00
NO CHANGE TO THREADS OR DIMS
FROM SUPPLIED BARREL
8 x 4mm HOLES EQUISPACES AROUND CIRCUMFRENCE
20mm BETWEEN CENTRELINES
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3.2 SURFACE FINISH IN μm UNLESS STATED
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ISSUE No.
ACAD FILE: BARREL
CHANGE:
No.
DATE
DRAWN: AEL
DATE: 26/02/04
APPROVED:
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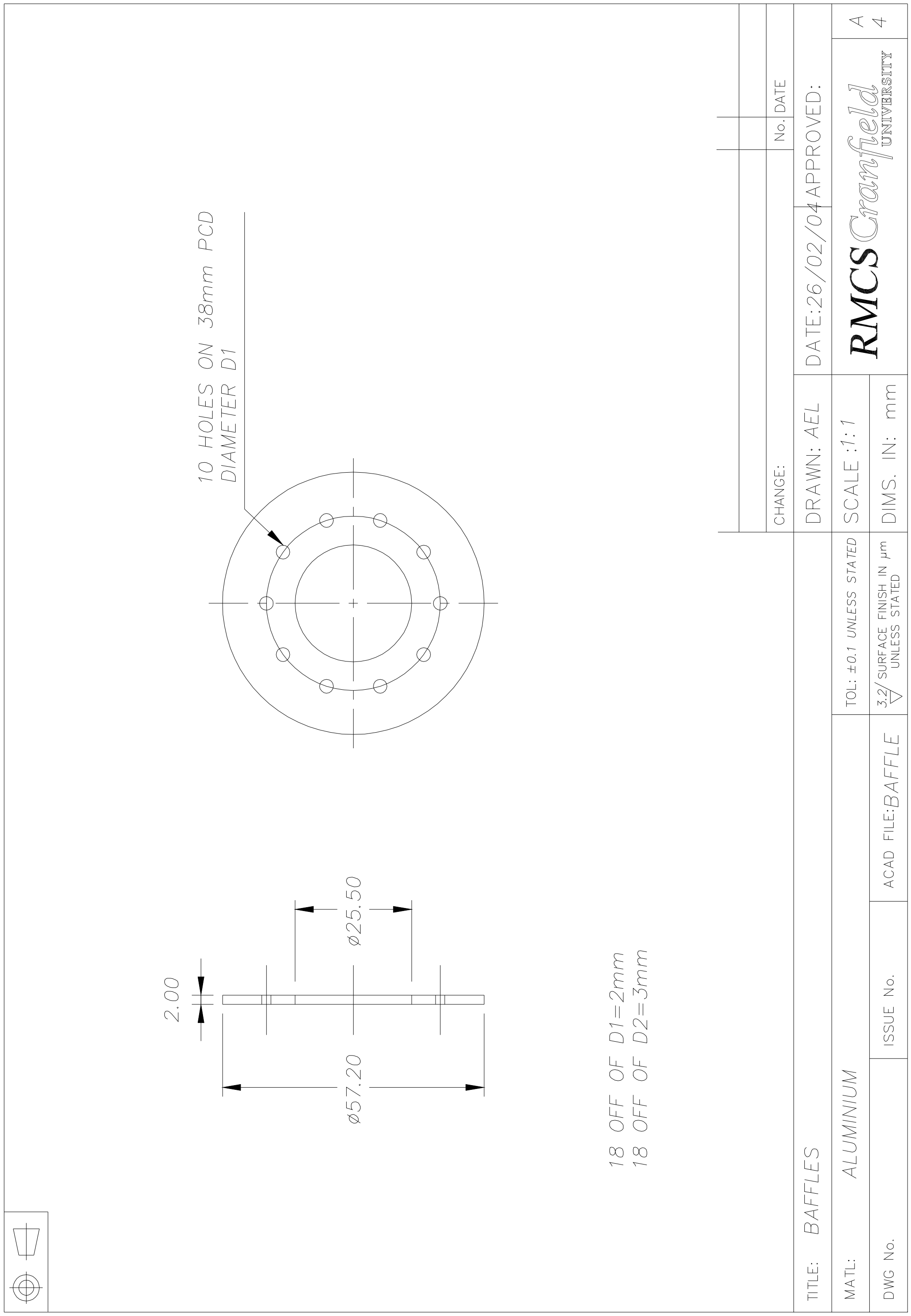
DIMS. IN: mm
RMCS Cranfield UNIVERSITY
A4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ø25.50
ø57.20
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18 OFF OF D2=3mm
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CHANGE:
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DATE:26/02/04
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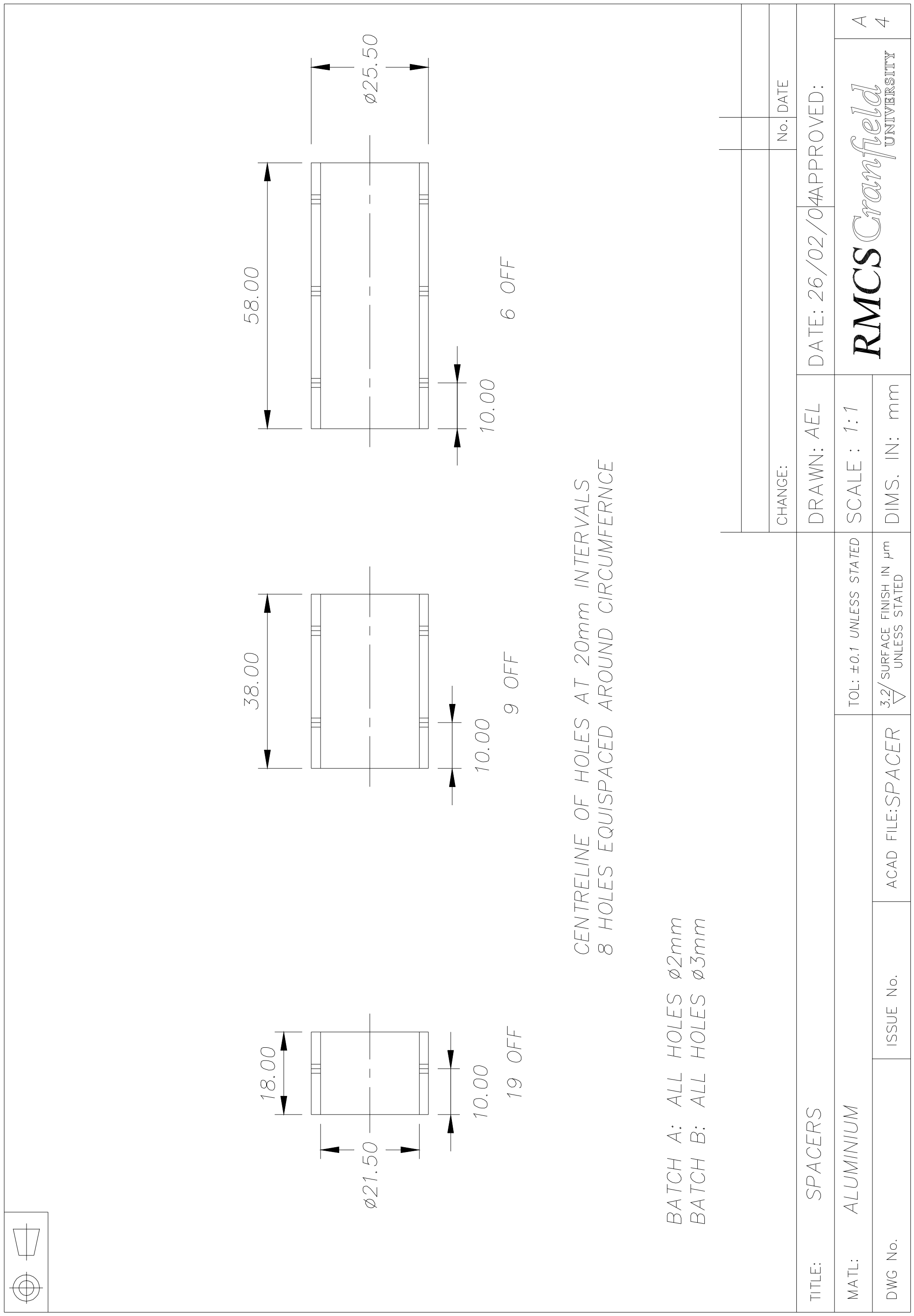
DWG No.
RMCS Cranfield UNIVERSITY
A4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10.00
6 OFF
38.00
10.00
9 OFF
18.00
ø21.50
10.00
19 OFF
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8 HOLES EQUISPACED AROUND CIRCUMFERNCE
BATCH A: ALL HOLES ø2mm
BATCH B: ALL HOLES ø3mm
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No.
DATE
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ISSUE No.
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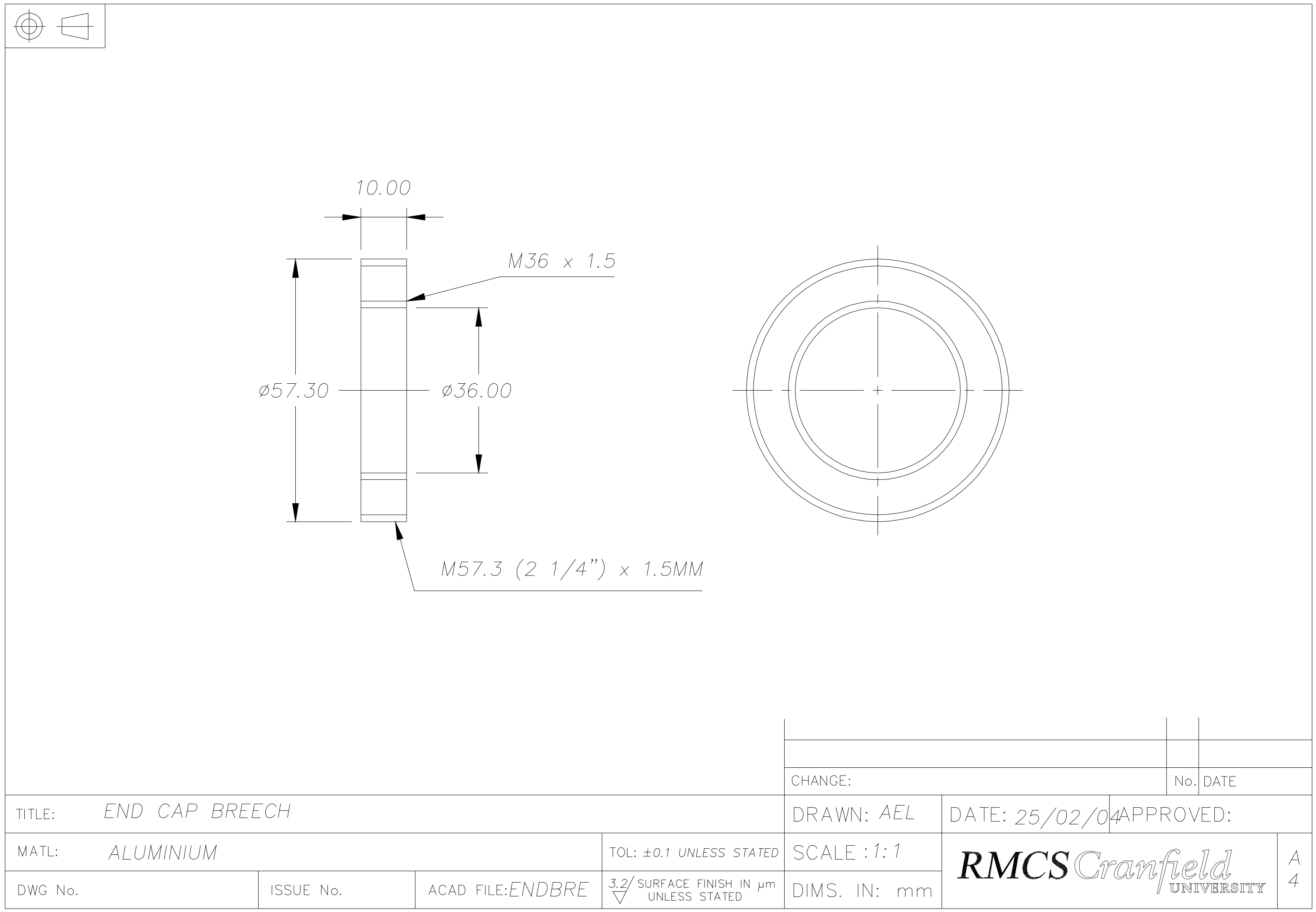
APPROVED:
RMCS Cranfield UNIVERSITY
A 4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M36 x 1.5
ø57.30
ø36.00
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DRAWN: AEL
DATE: 25/02/04
APPROVED:
MATL: ALUMINIUM
TOL: ±0.1 UNLESS STATED
SCALE : 1:1
RMCS Cranfield UNIVERSITY
A4
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ISSUE No.
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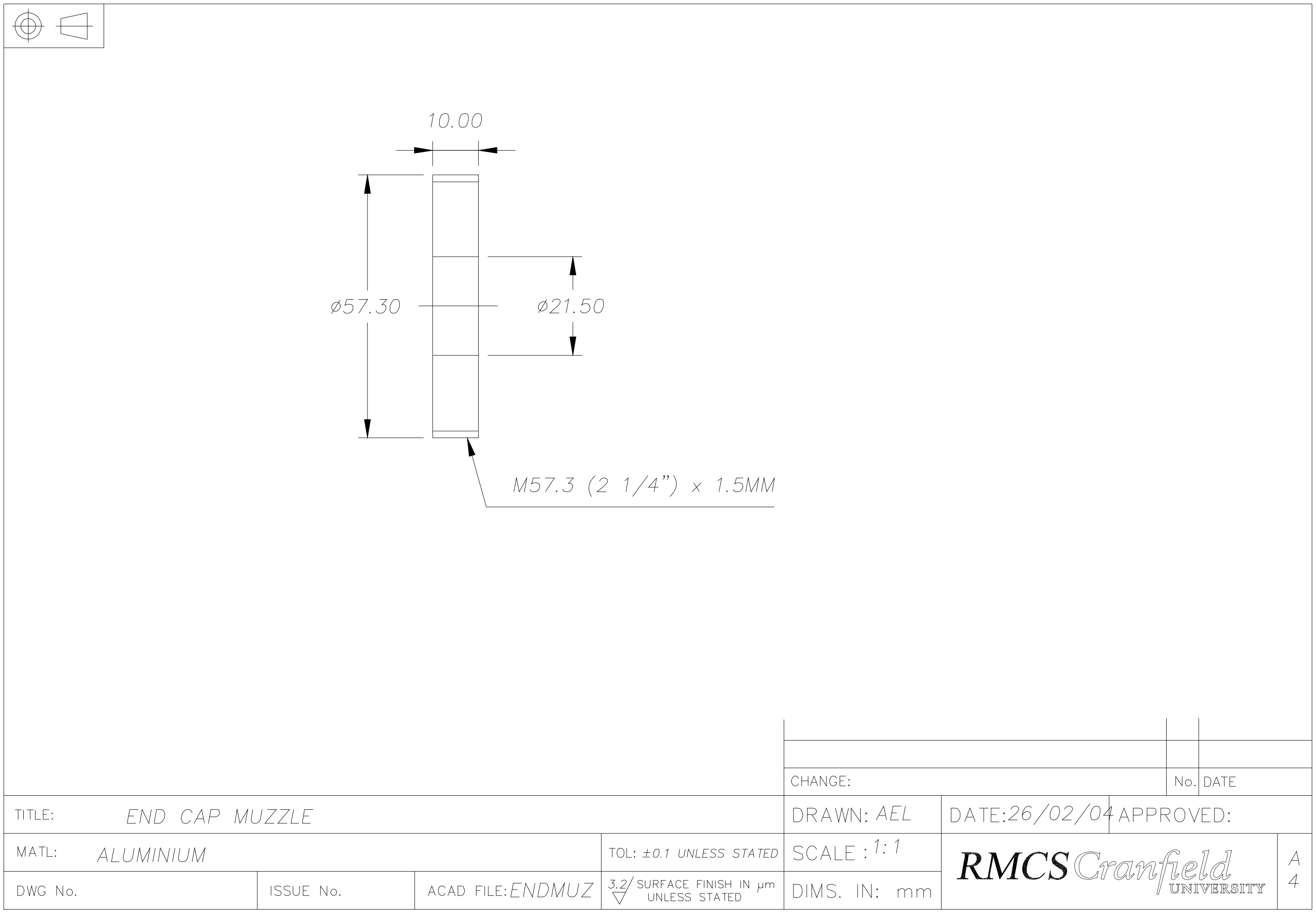
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DATE:26/02/04
APPROVED:
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TOL: ±0.1 UNLESS STATED
SCALE : 1:1
RMCS Cranfield UNIVERSITY
A 4
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ISSUE No.
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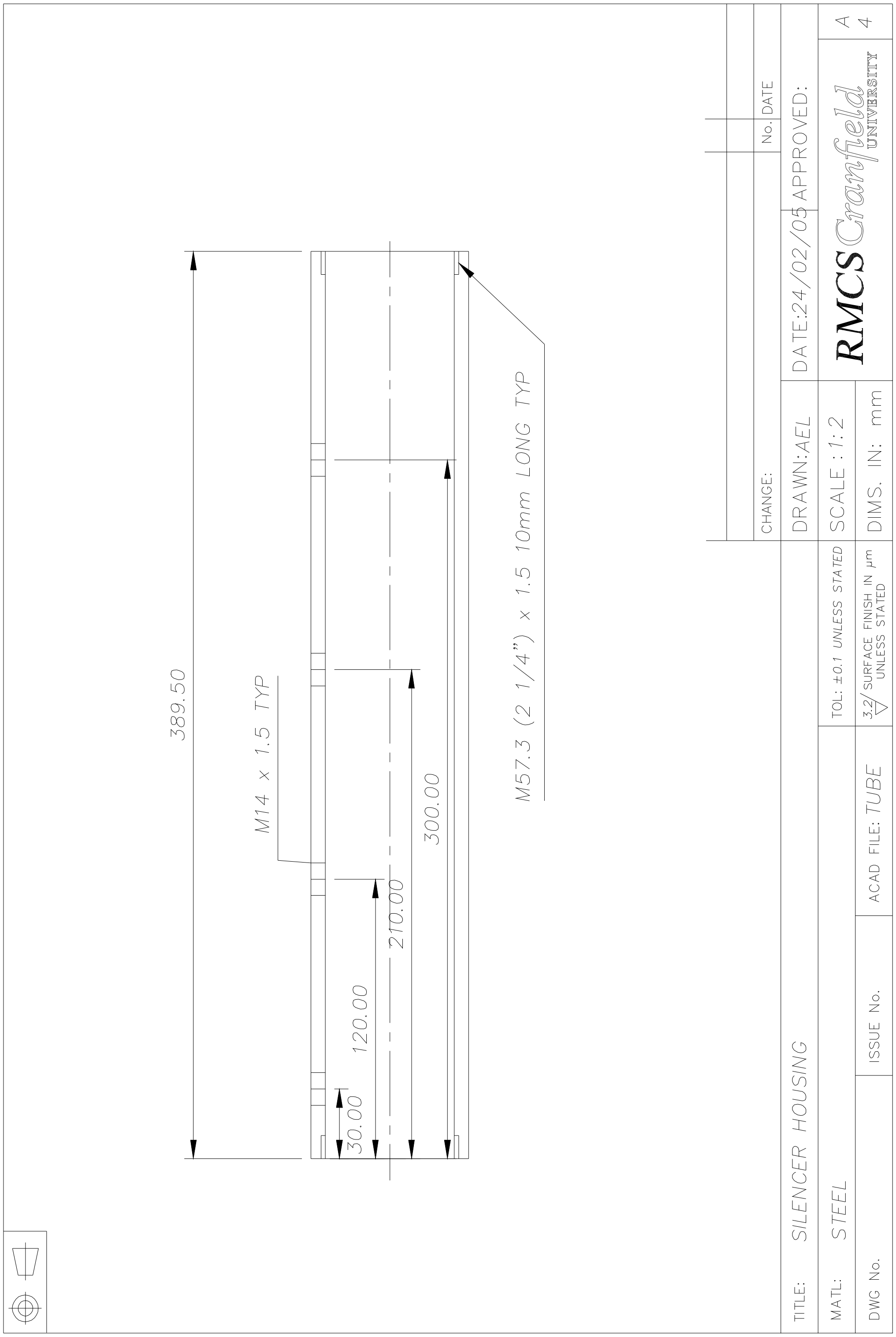
DIMS. IN: mm



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210.00
120.00
30.00
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MATL: STEEL
DWG No.
ISSUE No.
ACAD FILE: TUBE
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3.2 SURFACE FINISH IN μm UNLESS STATED
CHANGE:
No. DATE
DRAWN: AEL
DATE: 24/02/05
APPROVED:
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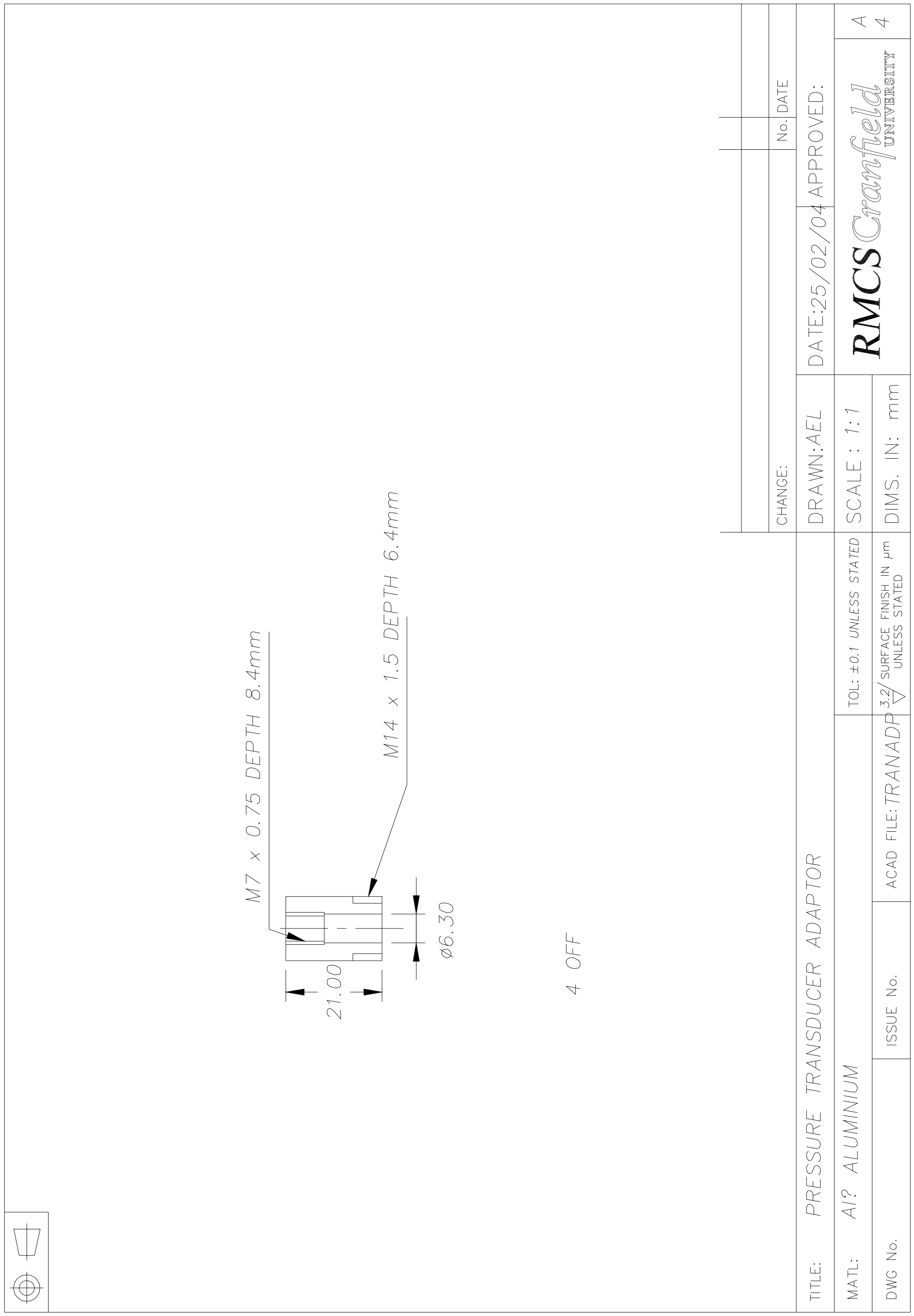
DIMS. IN: mm
RMCS Cranfield UNIVERSITY
A4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M14 x 1.5 DEPTH 6.4mm
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Ø6.30
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MATL: Al? ALUMINIUM
DWG No.
ISSUE No.
ACAD FILE: TRANADP
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3.2 SURFACE FINISH IN µm UNLESS STATED
CHANGE:
No.
DATE
DRAWN: AEL
DATE: 25/02/04
APPROVED:
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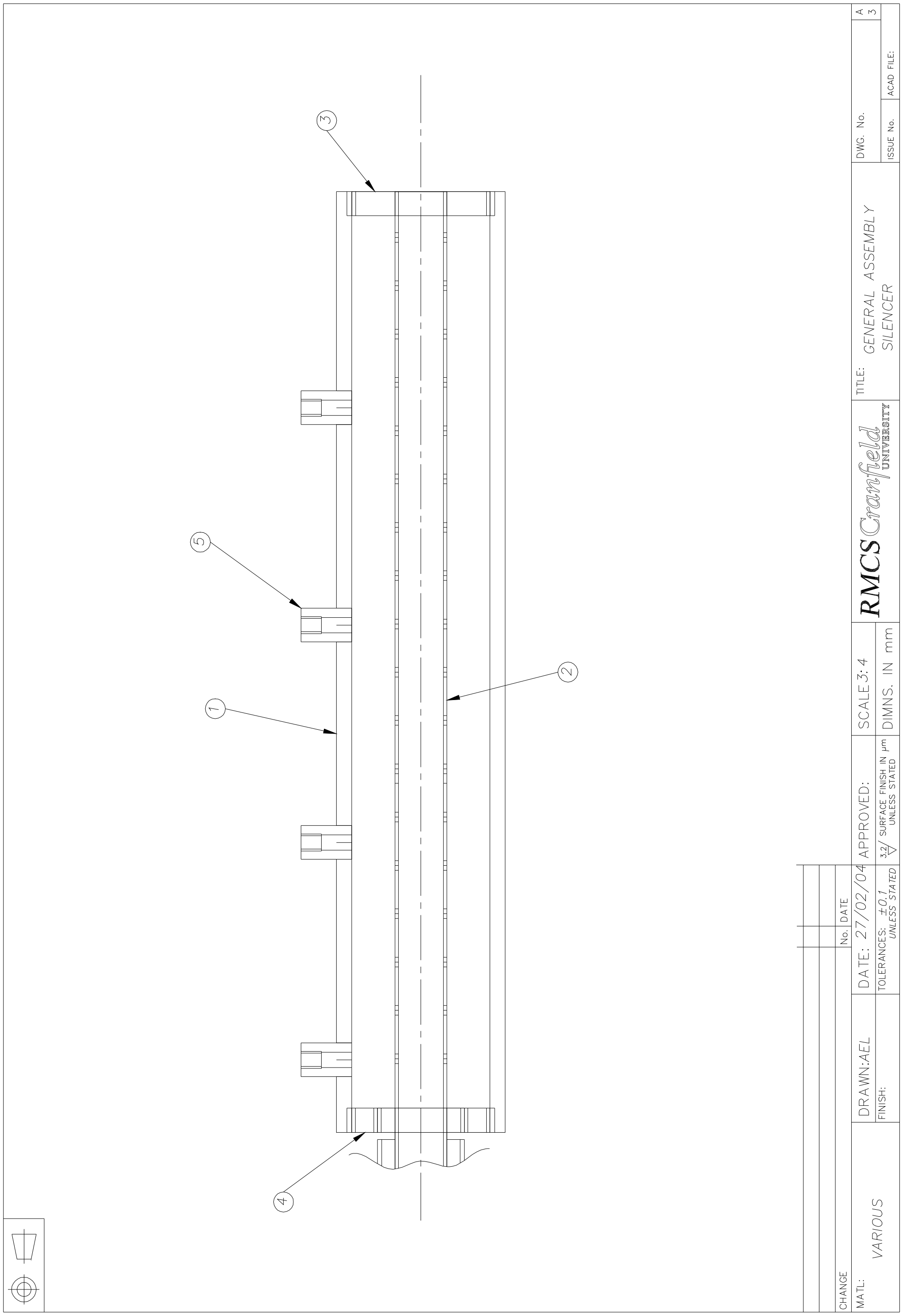
DIMS. IN: mm
RMCS Cranfield UNIVERSITY
A4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2
3
4
5
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ISSUE No.
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RMCS Cranfield UNIVERSITY
SCALE 3:4
DIMNS. IN mm
APPROVED:
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DATE: 27/02/04
TOLERANCES: ±0.1 UNLESS STATED
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FINISH:
MATL: VARIOUS
CHANGE
No.
DATE

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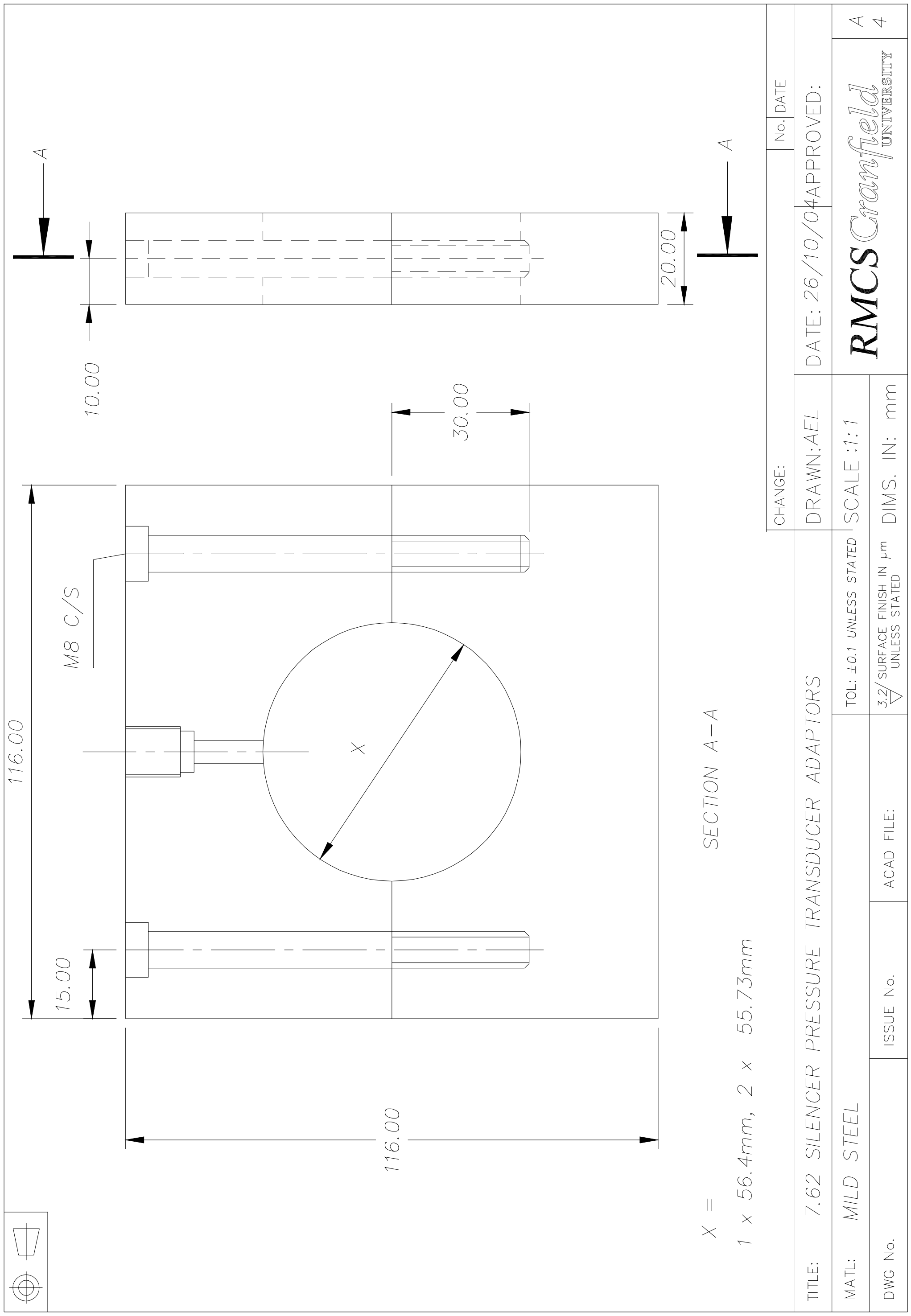
3	3	END CAP MUZZLE	1		ENDMUZ	ALUMINIUM		3
4	4	END CAP BREECH	1		ENDBRE	ALUMINIUM		4
5	5	TRANSDUCER ADAPTOR	4		TRANADP	ALUMINIUM		5
6								6
7								7
8								8
9								9
10								10
11								11
12								12
13								13
14								14
15								15
16								16
17								17
18								18
19								19
20								20
21								21
22								22

SHEET No. 1 OF 1	DRAWN: AEL	DATE: 27/02/04	APPROVED:	
DWG No.	ISSUE No.	ACAD FILE: PARTLIST	SPECIFICATION SHEET FOR: GA SILENCER	RMCS Cranfield UNIVERSITY

Testing for Proof Suppressor

Pressure Transducer Adaptor



A
A
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20.00
30.00
116.00
15.00
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X
SECTION A–A
116.00
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No. DATE
TITLE: 7.62 SILENCER PRESSURE TRANSDUCER ADAPTORS
DRAWN: AEL
DATE: 26/10/04
APPROVED:
MATL: MILD STEEL
TOL: ±0.1 UNLESS STATED
SCALE :1:1
RMCS Cranfield UNIVERSITY
DWG No.
ISSUE No.
ACAD FILE:
3.2 SURFACE FINISH IN μm UNLESS STATED
DIMS. IN: mm
A 4

Appendix B

Energy, Continuity and Mass Transfer Equations for a Gun/Silencer

By Dr Bryan Lawton

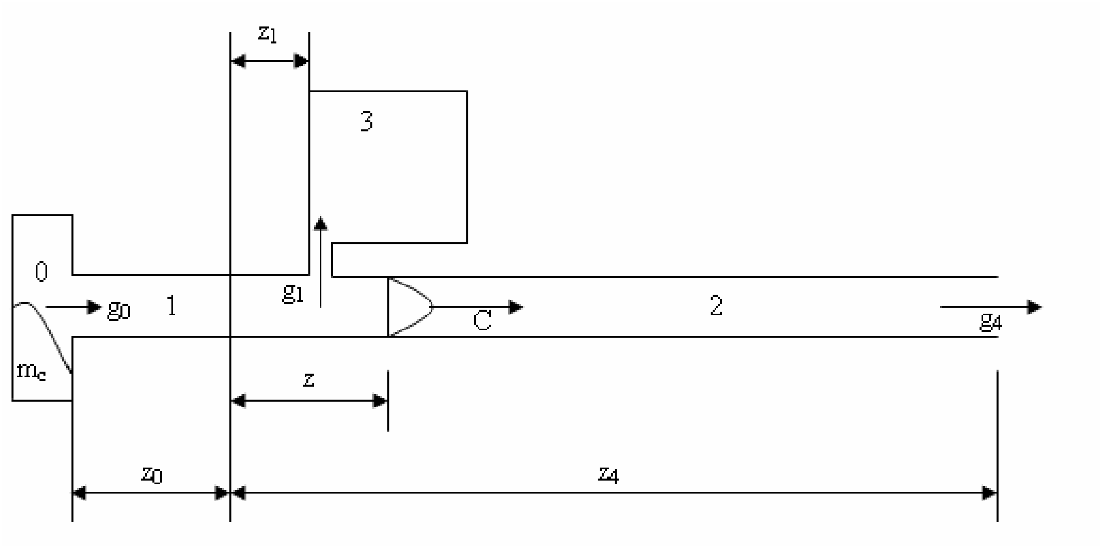

Figure 62 Schematic diagram of a gun and silencer.

The four chambers (0 to 3 in bold face) are connected, as indicated, by three orifices through which gas flows from high pressure to low pressure. Each chamber is at uniform pressure and temperature and the mass transfer into a chamber is assumed to mix instantly. Combustion occurs in chamber 0 and the gaseous products flow into chamber 1 through orifice 0. The projectile starts to move when the pressure p_1 reaches the shot start pressure. As the projectile moves down the barrel from its initial position ($z = 0$) mass transfer through orifice 1 is switched between chamber 2 (ahead of the projectile) and chamber 1 (behind the projectile). The orifice is assumed to open and close instantly as the rear of the projectile passes over. Chamber 2 is assumed to remain at atmospheric pressure and temperature. After shot exit the gas in chamber 1 flows into the atmosphere. Propellant combustion occurs only in chamber 0.

Energy Equation

$$\frac{dU_0}{dt} = \frac{d(m_0 c_v T_0)}{dt} = E\dot{m}_b$$
$$-g_0 c_p (T_0 \text{ if } \mathrm{g}_0 > 0 \text{ else } T_1)$$

$$\frac{dU_1}{dt} = \frac{d(m_1 c_v T_1)}{dt} = -\frac{\pi}{4} D_1^2 (p_1 - p_2) C - \frac{dQ}{dt} \quad \mathrm{Z{<}Z_4}$$
$$g_0 c_p (T_0 \text{ if } \mathrm{g}_0 > 0 \text{ else } T_1)$$
$$-g_1 c_p (T_1 \text{ if } g_1 > 0 \text{ else } T_3) \quad \mathrm{Z{>}Z_1}$$
$$-g_4 c_p (T_1 \text{ if } g_4 > 0 \text{ else } T_a) \quad \mathrm{Z{>}Z_4}$$

Note: The whole term (gc_vT) depends on the position of the shot, Z, as specified.

$$\frac{dU_3}{dt} = \frac{d(m_3 c_v T_3)}{dt} =$$
$$+g_1 c_p (T_2 \text{ if } g_1 > 0 \text{ else } T_3) \quad Z < Z_1$$
$$+g_1 c_p (T_1 \text{ if } g_1 > 0 \text{ else } T_3) \quad Z > Z_1$$

Gas Laws

$$p_i(V_i - am_i) = Rm_iT_i \qquad i = 0,1,3$$

$$F = RT_f = (\gamma - 1)E \qquad R = \frac{R_0}{M}$$

$$c_v = c_p - R \qquad \gamma = \frac{c_p}{c_v}$$

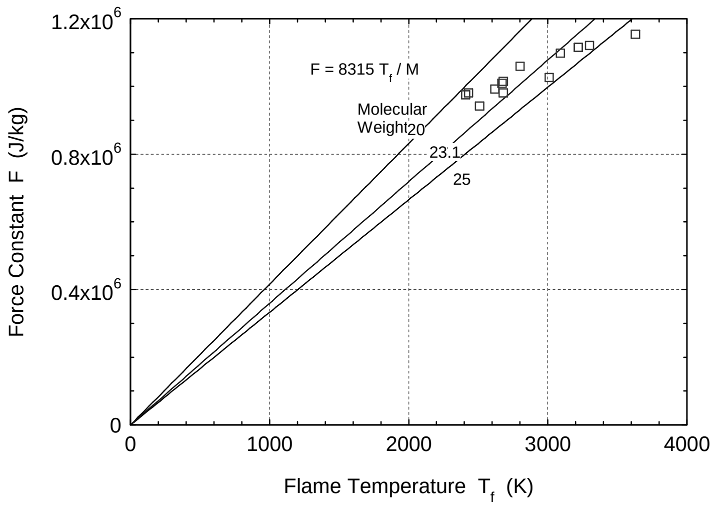

Figure 63 Force constant for typical British propellants.

Continuity Equations

$$\frac{dm_0}{dt} = \dot{m}_b - g_0$$

$$\frac{dm_1}{dt} = g_0$$
$$-g_1 \qquad Z > Z_1$$
$$-g_4 \qquad Z > Z_4$$

$$\frac{dm_3}{dt} = g_1$$

$$\frac{m_{ct}}{m_c} = (1 - f)(1 + \theta f)$$

$$\dot{m}_b = m_c(\theta - 1 - 2\theta f)\frac{df}{dt}$$

$$\frac{df}{dt} = -\frac{\beta}{D}p_1$$

Shape of Grain	Size D	Form Function θ	Remarks
Long Cord	Diameter	1	
Long Tube	Wall Thickness	0	
Long Slotted Tube	Wall Thickness	D^2/A	A= cross-sectional area of tube
Multi-tube	1.15 x Web Thickness	-0.172	
Ribbon	Thickness	1/m	mD=width of ribbon
Square Flake	Thickness	2/m	mD=side of square

Table 16 Typical Values of Form Function

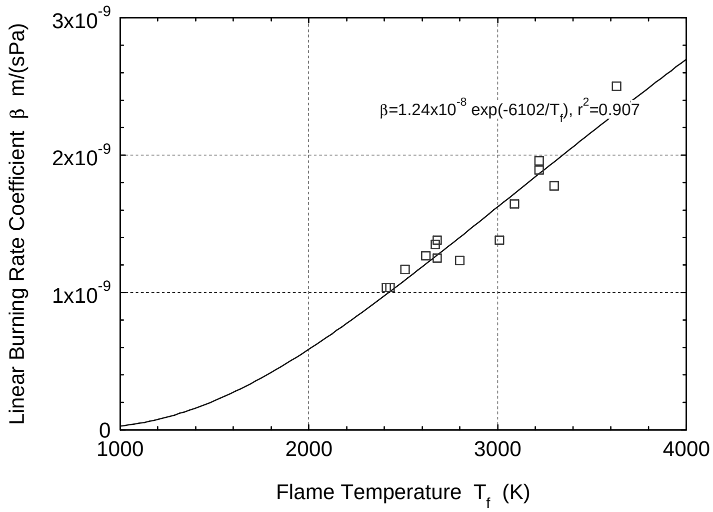

Figure 64 Linear Burning rate for British propellants.

As an approximation the linear burning rate may be estimated from the propellant flame temperature by:

$$\beta = 1.55\text{x}10^{-8} \exp\left(\frac{-6723}{T_f}\right) \quad \text{m/s/Pa}$$

<u>Volumes</u>

$$V_0 = \frac{m_c}{\rho_L} - \frac{m_c - m_{ct}}{\rho_{prop}}$$

$$V_1 = \frac{\pi}{4} D_1^2 (Z_0 + Z \text{ if } Z < Z_4 \text{ else } Z_4)$$

$$V_3 \text{ is constant}$$

Mass Flow Rates

The mass flow rates through the ports in the positive direction, as shown in Figure 62, are given by the following equations. The upstream and downstream pressure and temperature (p_u, T_u, p_d, T_d) need to be specified for each port.

$$r_c = \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)} \qquad K_c = \sqrt{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

$$r = \frac{p_d}{p_u} \qquad K(r) = r^{1/\gamma}\sqrt{\frac{2\gamma}{\gamma-1}(1-r^{(\gamma-1)/\gamma})}$$

$$\frac{g\sqrt{RT_u}}{Ap_u} = K_c \qquad 0 < r < r_c$$

$$\frac{g\sqrt{RT_u}}{Ap_u} = K(r) \qquad r_c < r < 1$$

$$\frac{g\sqrt{RT_d}}{Ap_d} = -K(1/r) \qquad 1 < r < 1/r_c$$

$$\frac{g\sqrt{RT_d}}{Ap_d} = -K(1/r_c) \qquad 1/r_c < r < \infty$$

The last two equations are for reverse flow ($p_u/p_d>1$).

The upstream and downstream pressures and temperatures for each of the three orifices are as follows.

Orifice	p_u	T_u	p_d	T_d
0 g_0	p_0	T_0	P_1	T_1
1 g_1	p_2 if $Z<Z_1$ else p_1	T_2 if $Z<Z_1$ else T_1	p_3	T_3
4 g_4	p_2 if $Z<Z_4$ else p_1	T_2 if $Z<Z_4$ else T_a	p_a	T_a

Table 17 Pressure and Temperature for orifices

Equation of Motion

$$\left(1.03m_r + \frac{m_1}{3}\right)\frac{dC}{dt} = \frac{\pi}{4}D_2^2(p_1 - p_2)$$

$$\frac{dZ}{dt} = C$$

$$p_1 > p_c \text{ for shot start} \qquad p_2 = p_a$$

This assumes that friction etc amounts to 3% of the kinetic energy of the projectile (hence 1.03) and that the gas velocity in the barrel is linearly distributed from zero at the breach to the shot velocity at the projectile (hence $m_1/3$).

Heat Loss

Heat transfer between the gas and the chamber walls is modelled by the instantaneous convective heat transfer equation:

$$\frac{dQ_h}{dt} = hA_h(T_g - T_w)$$

Q_h is the total heat transfer from the gas to the surfaces of chambers 0 and 1, h is the heat transfer coefficient, A_h is the surface area, T_g is the gas temperature, and T_w is the wall temperature. All these variables change with time and are determined from:

$$h = 0.4\frac{k}{D_1}\mathrm{Re}^{.7} \qquad \mathrm{Re} = \frac{(m_0 + m_1)CD_1}{(V_0 + V_1)\mu}$$

$$A_h = \frac{4(V_0 + V_1)}{D_1} \qquad T_g = \frac{T_1 + T_2}{2}$$

$$Q_h = \int_0^t dQ_h$$

$$T_w = 300 + \frac{2 * Q_h}{\rho_s c_{vs} A_h \sqrt{4K_s t}}$$

Re is the Reynolds number, *k* the thermal conductivity of the gas, μ the gas viscosity, T_w is the mean wall temperature of the chambers, ρ_s is the density of the steel barrel, c_{vs} is the specific heat of the steel barrel, and K_s is the thermal diffusivity of the steel barrel.

This is the total heat transfer and it is shared between chambers 0 and 1 in proportion to their areas. Heat transfer in the silencer is ignored.

Notation

A - co-volume of propellant gas, m^3/kg

A - effective orifice area, m^2

A_h - surface area for heat transfer, m^2

c_v - specific heat of gas at constant volume, J/kgK

c_{vs} - specific heat of barrel steel, J/kgK

c_p - specific heat of gas at constant pressure, J/kgK,

C - shot velocity, m/s

D - web thickness, m

D_i - i = 0, 1, 2, 3 diameter of chamber i (see figure), m

E - energy content of solid propellant, J/kg

f - linear fraction of propellant web thickness (f=1 at t=0), m

F - force constant, J/kgK

g - mass flow rate through orifice, kg/s

g_i - i = 0,1, 4, mass flow rate through orifice i (see figure), kg/s

h - heat transfer coefficient, W/m^2K

$K(r)$ - flow parameter for un-choked flow

K_c - critical parameter for choked flow

K_s - thermal diffusivity of barrel steel, m^2/s

$\dot{m}_b$ - mass burning rate of solid propellant, kg/s

m_c - charge mass, kg

m_{ct} - mass of burnt charge at time t, kg

m_i - i = 0, 1, 2, 3, mass of gas in chamber i, kg

m_r - shot mass, kg

M - molecular weight of propellant gas

r - pressure ratio

r_c - critical pressure ration for choked flow

R - gas constant, J/kgK

Re - Reynolds number

R_0 - universal gas constant, 8315 J/kg-mol K

t - time, s

T - ambient temperature, K

T_f - propellant flame temperature, K

T_g - mean gas temperature, K

T_i - i = 0, 1, 2, 3 temperature of gas in chamber i, K

T_u - upstream temperature, K

T_d - downstream temperature, K

T_w - mean wall temperature, K

p_a - atmospheric pressure, Pa

p_i - i = 0, 1, 2, 3, pressure of gas in chamber i, Pa

p_d - downstream pressure, Pa

p_u - upstream pressure, Pa

dQ_h/dt - rate of heat transfer from barrel, W

U_i - i = 0, 1, 2, 3, internal energy of chamber i, J

V_i - i = 0, 1, 2, 3, volume of gas in chamber, m^3

V_{pro} - volume of projectile

Z -shot travel from initial position, m

Z_i - i = 0, 1, 4 distances defined in figure, m

β - linear burning rate coefficient, m/s Pa

γ - ratio of specific heats

θ - form function

μ - viscosity of gas, Ns/m^2

ρ_L - loading density, kg/m^3

ρ_{prop} - density of solid propellant, kg/m^3

ρ_s - density of barrel steel, kg/m^3

Dr B Lawton,

13th July, 2005.

23rd September, 2005

Appendix C

Experimental Procedure Firing

Equipment

Kistler Pressure Transducer 211B (later replaced with 217C SN 2022228 and SN 2022233) and associated cables

Coupler 5108A

Power cables

Power Source set to 24V

Nicolet 410 Digital Storage Oscilloscope

Stock, barrel adapted for pressure transducers

Universal Mount with firing lanyard.

Cartridges made with 0.25g Green Dot

Dummy Darts

Equipment Setup

Ensure all equipment has an up-to-date calibration certificate.

Insert the weapon securely into the universal mount.

Attach a pressure transducer via the transducer cable to the coupler. Take the feed from the coupler to the oscilloscope. Attach the coupler to the power source. Ensure all equipment is switched on and functioning.

Fit the pressure transducer into the 1st position.

Repeat if using more than 1 transducer and ensure all other ports not being used are sealed off with blank adaptors.

Ensure the photo optical chronographs are set to the correct settings for the projectile and ready to record the velocity of the projectile.

Firing procedure

Set the Oscilloscope to trigger and record with the next firing

Load the weapon with the dart and cartridge. Cock the weapon. Evacuate room and remotely fire the weapon.

Unload the weapon.

Ensure data is saved from firing and repeat process until 3 results are saved for the position.

Move the pressure transducers into any positions that require readings and repeat the process

Equipment accuracy

The pressure transducers were accurate to ±0.9% of the pressure recorded. This gave a small percentage error with the results so was not included when processing the results.

The other source of experimental error was the cartridge. The primers used were produced by external manufacturers for which there was no quality control data available. However, as they are industry and commercial standard it is believed that they are of high quality with little deviation in performance. The load of the cartridges was accurate to ±0.001g. The manufacturing process for the cartridges was standard for all cartridges and carried out with the utmost care and attention however accuracy may be affected by the non-standard process for manufacture. Accuracy data regarding the performance of the cartridges could not be determined. It is believed that this is the greatest source of possible error.

Photo Optical Chronographs are accurate to ±1ms^{-1}.

Appendix D

Experimental Procedure Firing

Equipment

Kistler Pressure Transducer 217C SN 2022228 and SN 2022233 and associated cables

Coupler 5108A

Power cables

Power Source set to 24V

Nicolet 410 Digital Storage Oscilloscope

Stock, barrel and attached suppressor with relevant setup

Universal Mount with firing lanyard.

Cartridges made with 0.25g Green Dot

Dummy Darts

Equipment Setup

Ensure all equipment has an up-to-date calibration certificate.

Insert the weapon securely into the universal mount.

Attach a pressure transducer via the transducer cable to the coupler. Take the feed from the coupler to the oscilloscope. Attach the coupler to the power source. Ensure all equipment is switched on and functioning.

Fit the pressure transducer into the 1st position.

Repeat if using more than 1 transducer and ensure all other ports not being used are sealed off with blank adaptors.

Ensure the photo optical chronographs are set to the correct settings for the projectile and ready to record the velocity of the projectile.

Firing procedure

Set the Oscilloscope to trigger and record with the next firing

Load the weapon with the dart and cartridge. Cock the weapon. Evacuate room and remotely fire the weapon.

Unload the weapon.

Ensure data is saved from firing and repeat process until 3 results are saved for the position.

Move the pressure transducers into any positions that require readings and repeat the process.

Equipment accuracy

The pressure transducers were accurate to ±0.9% of the pressure recorded. This gave a small percentage error with the results so was not included when processing the results.

The other source of error was the cartridge. The primers used were produced by external manufacturers. For which there was no quality control data available. However, as they are industry and commercial standard it is believed that they are of high quality with little deviation in performance. The load of the cartridges was accurate to ±0.001g. The manufacturing process for the cartridges was standard for all cartridges and carried out with the utmost care and attention however accuracy may be affected by the non-standard process for manufacture. Accuracy data regarding the performance of the cartridges could not be determined. It is believed that this is the greatest source of possible error.

Photo Optical Chronographs are accurate to ±1ms^{-1}.

Appendix E

Experimental Results

See attached disk

Appendix F
Experimental Procedure Firing, Proofing a Suppressor

Equipment

Pressure Transducer 6203 and associated cables SN 278061 and 379787
Blank adaptors
Charge amplifier Kiag Swiss type 5001
Nicolet 410 Digital Storage Oscilloscope
Number 3 proof housing
Jackson Reflex suppressor T8 with M14x1 thread, fitted for pressure transducers.
7.62mm barrel length 560mm to fit silencer (length measured from chamber to muzzle)
7.62 x 51mm ball ammunition
Photo Optical chronograph

Equipment Setup

Ensure all equipment has an up-to-date calibration certificate.
Mount the barrel with silencer attached into the proof housing ensuring it is secure.
Attach the pressure transducers via the transducer cables to the charge amplifiers. Ensure the charge amplifier has the correct settings for the corresponding pressure transducer. Take the feed from the amplifier to the oscilloscope. Ensure all equipment is switched on and functioning.
Fit the pressure transducers into the first two positions for pressure to be measured and ensure all other ports not being used are sealed off with blank adaptors.

Ensure the photo optical chronographs are set to the correct settings for the projectile and ready to record the velocity of the projectile.

Firing procedure

Set the Oscilloscope to trigger and record with the next firing

Load the barrel with the ammunition attaching the electronic firing system.

Evacuate room and remotely fire the weapon.

Once fired clear weapon, ensure data is saved from firing and record the projectile velocity

Repeat process until 10 results are saved.

Move the pressure transducers into any positions that require readings and repeat process.

Equipment accuracy

The pressure transducers were accurate to ±0.9% of the pressure recorded. This gave a small percentage error with the results so was not included when processing the results.

The other source of error was the cartridge. The primers used were produced by external manufacturers. For which there was no quality control data available, however as they are industry and commercial standard it is believed that they are of high quality with little deviation in performance. The load of the cartridges was accurate to ±0.001g. The manufacturing process for the cartridges was standard for all cartridges and carried out with the utmost care and attention however accuracy may be affected by the non-standard process for manufacture. Accuracy data regarding the performance of the cartridges could not be determined. It is believed that this is the greatest source of possible error.

Photo Optical Chronographs are accurate to ±1ms^{-1}.

Appendix G

Chapter 4 Experimental Results

See attached disk

Appendix H
Experimental Procedure
Improvised Suppressors

Equipment

Sound Measurement Equipment

Brüel and Kjaer (B&K) condenser microphone ¼" cartridge Type 4135 and associated coupling cables
Power supply Type 2804 and associated coupling cables
Pico AD-212 analogue/digital converter and associated coupling cables
Portable PC with Picolog software
Calibrator CEL-284/2

Barrels

7.62mm barrel length* 530mm
9mm barrel length* 285mm (Due to the short barrel there is a lower muzzle velocity than for standard issue pistols. This enabled subsonic and supersonic projectiles to be observed.)
0.22" barrel length* 750mm
* Length is measured from beginning of the chamber to muzzle
Number 3 Proof Housing

Ammunition

7.62 x 51mm Ball
9 x 19mm Ball
0.22" long Eley Match

Photo Optical Chronographs

High Speed Camera

Dell Inspiron 9100 running Pentium 4, XP and associated cables

Phantom Camera Control software

Phantom 7 Camera and associated cables

Sigma 24-70 EXDG f32 – 2.8 lens

Photon Beam 1000 light

MSI 712 microphone as remote trigger.

Improvised Suppressor

Item	Volume	Material	Reference
Water Bottle	2L	PET	Water L
Fanta Bottle *	500mL	PET	Fanta S
Ocean Spray	1.5L	PET	Ocean L
Oasis	1.5L	PET	Oasis L
Fruit Shoot	200mL	PET	Fruit S
Washing Up Liquid *	1L	HDPE	Wash
Ribena	1L	PET	Ribena
Lucozade Hydroactive	500mL	PET	Hydro S
Asda Lucozade	330mL	PET	Luco S
Pepsi *	2L	PET	Pepsi L
Lucozade Standard *	1L	PET	Luco L
Pepsi	500mL	PET	Pepsi S
Tonic	1L	PET	Tonic
Squash	1L	PET	Squash
Mini Lemonade	200mL	PET	Lem S
White Lightning *	3L	PET	White
Apple *		Cooking	Apple
Melon *		Honeydew	Melon
Potato *		Baking	Potato
Pillow Polyester *		Cotton Cover, Polyester filling	Pillow (P)
Pillow Feather *		Cotton Cover, Feather filling	Pillow (F)
Cushion Polyester *		Cotton Cover, Polyester filling	Cushion (P)
Cushion Feather *		Cotton Cover, Feather filling	Cushion (F)

Table 18 Improvised Suppressor items tested

Bottles were empty with lids removed. Items indicated by * were also tested on the 0.22” barrel.

Method

Sound Equipment

The B&K microphone was mounted on a tripod and connected to the power supply. The output in volts was directed through the Pico converter and fed to the laptop for storage. The Picolog software was used to record the signal. The microphone was positioned 1m perpendicular to the muzzle of the barrel facing downrange.

The Picolog program was set up to receive AC current over ±1V range for 32000nanoseconds (ns). The program was set to record the output from the microphone from 5% before a trigger threshold of 0.05V.

The equipment was calibrated using the calibrator which outputs a signal at 114dB. The sound level recorded was then used as the reference value when obtaining Sound Pressure Levels for each shot.

High Speed Camera

The camera with lens attached was connected to the computer. The software was run with a frame rate of 15000 frames/second. A pre-trigger of 500 frames/second was used with the microphone triggering the capture of the picture. Auto Exposure was on. A focal length of 5.6 was used.

Firing Procedure

The barrel was mounted into the number 3 proof housing.

The selected improvised suppressor was then mounted on the barrel. When testing bottles, tape was used to secure the open end of bottle to the muzzle of the barrel. For vegetables they were pushed onto the muzzle of the barrel.

Pillows and cushions were taped to the muzzle. Two firings were carried out with each improvised suppressor on the 7.62mm and 9mm barrel.

The barrel was loaded and each shot was fired remotely with the velocity of the bullet recorded by the photo optical chronographs and the microphone output recorded by the Picolog program.

Once the chamber was un-loaded the next improvised suppressor was attached to the barrel and the firing process repeated giving two results for an item on the barrel. Each item detailed in Table 18 was tested.

The microphone was then checked against the calibrated signal to ensure the accuracy of the results.

The barrel was then changed and the process repeated.

Items that were deemed to have performed better on either the 7.62mm barrel or the 9mm barrel were repeated on the 0.22" barrel using the same method. These items are shown in Table 18 with a *.

During the testing the ambient temperature, humidity and pressure was maintained at a constant level by air conditioning.

Processing of Results

Once tests were completed the output (in Volts) recorded by the Picolog software could be converted to a sound pressure level. The raw results were exported to Microsoft Excel for plotting.

The peak voltage which corresponded with the firing was found. This was not necessarily the peak recorded voltage due to the wave reflection from the walls in the indoor range. Using the equation

$$t = \frac{d}{v}$$

Equation 7 Distance speed time equation

Where t is the time take for the sound wave to reach the microphone, d is the distance to the microphone and v is the velocity of the sound wave. Using the distance as 1m and the velocity of sound as 340ms^{-1} this gives a time of 3ms for when the sound wave should reach the microphone. Therefore the results were limited to just beyond this period to ensure reflections from the walls did not affect the results.

The peak sound pressure level was then found and converted from volts to deciBels using the equation

$$SPL = 114 + 20LOG_{10}\left(\frac{V}{V_0}\right)$$

Equation 8 Sound Pressure Level

Where V is the voltage measured in volts from the muzzle blast and V0 is the calibration measurement in volts. Units for Sound Pressure Level (SPL) are in dB

Equipment accuracy

To preserve experimental accuracy the sound equipment was calibrated before and after use. Due to the loan of the equipment it was not possible to determine the exact percentage accuracy of the microphone used as no data sheet was available. Comparisons between a handheld meter used for governmental work and the digital readings for a signal showed a very good correlation and accuracy within 1%.

Photo Optical Chronographs are accurate to ±1ms$^{-1.}$.

Appendix I

Improvised Suppressor Results

See attached disk

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