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MSc THESIS

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Ballistics of 17th Century Muskets

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DISCLAIMER

ABSTRACT

This Project is an investigation to determine the position that a 17th Century musket ball was fired from a musket, when given the position it was found on the battlefield. Prior to this research the main concerns with making predictions were considered to be associated with the deformed shape of the musket balls affecting their drag coefficient and therefore, their distance to ground impact. The distance they would continue after impact due to bounce and roll was unknown. Previous research has been used and built upon to recreate the conditions of the English Civil War as accurately as possible. It was found that the average distance to ground impacts were in good agreement with predictions using the drag coefficient for a sphere showing that the distorted shape resulting from the firing process of the musket ball made little difference to its drag coefficient in the majority of cases. However, the distance travelled after the first ground impact greatly exceeded expectations, with the musket balls almost doubling the total average distance to their final resting positions - an increase of 81%. From these findings the initial factors thought to have had high relevance to the final resting position of the musket ball (velocity variation and drag co-efficient) become less significant and factors such as ground hardness become more prominent. The knowledge gained during this investigation will re-establish more accurate information to be obtained on the firing positions of opposing forces during conflicts in the English Civil War.

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ABBREVIATIONS

CBR	California Bearing Ratio
C_d	Drag Coefficient
CI	Cone Index
M	Mach number
RFG	Rifle Grained Fine- diameters of about 1 mm and 2 mm, and RFL (rifle grained large)

GLOSSARY

Adiabatically	A thermodynamic process in which no heat is transferred to or from the working fluid
Banding	Visible markings around the circumference of musket balls
Bandoliers	A belt for holding powder in boxes and bullet bag
Countersink	A conical hole cut into a manufactured object, or the cutter used to cut such a hole
Dowel	A cylindrical rod usually made of metal, plastic or metal
Primer powder	Powder used to prime the weapon
Pyrodex	First widely available substitute for Black powder. It is less sensitive than Black powder, but more powerful per unit of mass
Setting Up	Expansion of projectile caused by propellant pressure
Solenoid	A loop of wire often wrapped around a metal core, which produces a magnetic field when an electric current is passed through it
Vickers Test	A method to measure the hardness of a material

Chapter 1: GENERAL INTRODUCTION

1.1 Introduction

17th Century battlefields (English Civil War) have been analysed by archaeologists by studying written records of the time, excavating the sites to gain information on the deployment of troops and the type of weapons used and how they were used. However, there are few written records of the time and there is concern over their reliability. The artefacts recovered from battlefields give useful, but limited, information. The main artefacts recovered consist of large quantities of lead balls but these are recovered from where they landed or were dropped. To be of greater use it is essential to know where they were fired from. This study aims to improve on previous research by conducting research into the ballistics of the muskets used at the time to predict the probable position of their launch point.

Previous research Eyers, (2006) has shown that there are large variations in the diameter of the bore of the muskets and the diameter of the musket balls used. Additionally, the black powder produced considerable fouling of the bore. All of these factors resulted in large and variable clearance between the musket ball and the wall of the barrel. A significant part of the research programme was to investigate the effect of these large and variable clearances on the internal and external ballistics of the weapon. The musket balls of the period were almost pure lead and therefore very soft. Previous trials Eyers, (2006) have shown that this can result in the musket ball "setting up" in the barrel, i.e. the high pressure during firing expanded the musket ball to fit the bore of the weapon. Thus the musket balls will be distorted from their original spherical shape. This will affect their drag coefficient and thus their impact distance. An important part of this research was to measure the velocity loss with range and thus the true drag coefficient of the musket balls.

Musket balls found on the battlefield are not necessarily found at their point of impact with the ground as it is known that when they impact they may bounce and roll. This programme of work investigated this phenomena associated with musket balls for the battlefield analysis.

For accurate experimentation it was necessary to research the powders, weapons and ammunition used in the 17th Century English Civil War period (1642 - 51). This project concentrated on the 19.685mm internal diameter matchlock musket. "*The most common calibre infantry weapon in use*" (Foard, 2009)

1.2 Project Outline

- To retrieve a musket ball after firing without damaging it for later analysis.
- To establish the most suitable modern black powder to replicate 17th Century black powder.
- To recreate the same markings (setting up) seen on a 17th Century musket ball caused by firing.
- To evaluate the effects of wadding on the internal and external ballistics of the matchlock musket.
- To study the effects of different internal barrel diameters on the internal and external ballistics of the matchlock musket.
- To gain a greater understanding of the bounce and roll of the 17th Century musket ball after the initial impact with the ground.

The most suitable black powder must generate the correct pressures in the musket barrel to re-create the same effects (banding) on a fired musket ball as those found on the battlefield of a genuine fired 17^{th} Century musket ball at the correct velocity.

The test firings were conducted at the Small Arms Experimental Range run by Cranfield University sited at the Defence Academy, Shrivenham, and at Ashdown House, a National Trust property close by.

Chapter 2: LITERATURE SURVEY

This chapter examines previous reports and research into the propellants, muskets, musket balls and ballistics to establish accurate information relevant to the period of the English Civil War that can be used for experimental trials

2.1. Black Powder

The propellant used for firearms from the time they were first used to the end of the 19th Century was black powder (or gunpowder) that consisted of a mixture of Saltpetre (Potassium Nitrate), Sulphur and Charcoal.

It would be most useful to compare modern black powders with those used in the Civil War in order to replicate the internal ballistics of the weapon, as they will affect the pressure/time exerted on the musket ball and ultimately the external ballistic properties.

A modern black powder consists of 15% wood charcoal (carbon), 10% sulphur and 75% potassium nitrate (nitre or saltpetre) – earlier mixtures contained much smaller amounts of saltpetre. The three components must be well mixed and finely powdered. As the black powder is ignited, the oxygen from the nitrate allows the sulphur and the carbon to burn rapidly producing a mixture of hot gases including sulphur dioxide and carbon dioxide, this in turn causes a rapid increase in volume. If the black powder is lit in a confined space this rapid increase in gas volume will lead to an increase in pressure and an explosion will occur. As the build up in pressure is relatively undramatic in comparison to a high explosive such as dynamite, black powder is classified as a low explosive (Brown, 2005).

Low explosive, black powder produces a lot of smoke and fumes and fails to explode when damp. However, black powder does produce high levels of energy to push projectiles out of gun barrels at high velocity. Black powder is also very quick and easy to set-off; only requiring a temperature above 300° C.

Little archaeological evidence is available regarding gunpowder manufactured during the Civil War. This is due to post-depositional chemical reactions on any powders that can be found. It is known that powder mills were made from local converted water mills. These mills helped supply powder to besieged towns and take powder production away from London, which was dominated by Parliamentary forces. Saltpetre and charcoal were readily available in most areas and in many towns saltpetre works may well have existed.

The stamp mills used in powder manufacture were mainly unspecialised. Although the existence of many mills is known, due to archaeological findings, it was not until 1649 that a number of important powder mills were documented (Wayne, 2000).
With the limited amount of historical data available and small amounts of research previously conducted, it is difficult to accurately establish how the 17th Century powders would compare to those of today. However, as mentioned previously it is likely that they contained less saltpetre. Testing of black powder in the 17th Century for quality and consistency was carried out by devices known by the French term *'eprovettes'*, vertical ratchet testers and pistol eprovettes. Other early methods also

included measurements of penetration into clay or stacks of wooden board and the range of cannonballs fired from a small mortar. A breakthrough came in 1742 with an invention by Benjamin Robins who produced the ballistic pendulum enabling muzzle velocities to be measured with considerable accuracy (Crocker, 2002).

2.1.2. Early Powder Manufactures

Until the mid-16th Century Britain relied on imported powder. As the Civil War became more imminent private companies began producing powder and the government took active steps to encourage Britons to manufacture their own black powder at home. However, Britain could still not manufacture sufficient black powder and still needed to import. The situation improved towards the end of the sixteenth Century when the East India Company began to import saltpetre from India and set up its own powder mills in England (Brown, 2005, Hogg, 1970).

A good way to evaluate the ballistics of the era and the effectiveness of 17th Century powders compared to modern powders would be to look into ballistic data from the Civil War period and battle statistics. Further post Civil War tests exist which also provide useful data.

"*Benjamin Robins obtained muzzle velocities between 1425 fps (434 m/s) and 1700 fps (518 m/s) in 1742 with a ¾ inch (19.05mm) diameter ball and 45 inch (1.143 m) long barrel. A century later Captain Alfred Mordecai studied gunpowder used for an English musket and recorded an average muzzle velocity of 1561 fps (476 m/s) and that 1477 fps (450 m/s) was adopted as the minimum velocity for proof of powder when using 10 grams of powder, whilst 7.5g of powder achieved a velocity of 1550 fps*

(472 m/s" (Roberts, 2008). After much research, it was concluded that data indicates that the musket ball would have probably averaged, at the muzzle, about 1500 fps.(457 m/s).

This information is supported by Eyers (2006), in her Master's research on the *'Ballistics of matchlock muskets'*. Eyers states that tests carried out in the 1980's in Austria by Krenn (1989), ((cited in Harding 1997), using small arms of the 16th, 17th and the 18th centuries produced muzzle velocities between 450 and 500 metres per second. This was obtained using flintlock muskets of 17 mm calibre with a powder charge of 15 grams. Eyers concluded that 17th Century muskets, had velocities of approximately 400-430 m/s and ranges of approximately 170-180 m when fired horizontally.

Post Civil War data gives a good indication of what muzzle velocities probably were. It is know the powder was "corned" in Civil War times and therefore likely to have been of similar performance to the later make up. Corning or sieving the powder is a method used to retain the powders strength for longer and to regulate the size of the grains to adjust the speed of combustion, optimising it for different weapon types (Harding, 1997).

Crocker (2002), states that gunpowder was originally incorporated and dried, but in this form the powder would not explode consistently and the ingredients tended to separate out again. The practice of corning therefore began in the 16th Century forcing the powder through punched parchment sieves to form the higher grade 'corn powder'. Most early powder was finely but not evenly powdered and was known as serpentine. The powder contained insufficient proportions of saltpetre and what it did contain is not thought to have been very pure. The powder was ground so fine that it was very easy to ram it into a barrel too tightly, thus causing the powder to burn far too slowly to be effective (Brown, 2005).

Nathaniel Nye (1647) a master gunner from Worcester gave a detailed description on black powder production during the Civil War period 1647. Nye describes the ratio of powder to be, "*four parts petre, one part Brimstone and one part Cole*." If producing musket powder 5-1-1, the powder would be five parts saltpetre, one part sulphur and one charcoal.

It is hard to establish the exact purity of the saltpetre or the grain size of powder used in the musket and it is not until much later in history that grain sizes are mentioned. British service gunpowder's were classified as RFG- *rifle grained fine*, (diameters of approximately 1 mm and 2 mm), and RFL - *rifle grained large*, (diameters between approximately 2 mm and 6 mm). These service powders could be categorised by an American scale, which was also used in Britain, the grain sizes were designated 2F for a 2 mm diameter powder (Brown, 2005). Modern military black powders are classified according to British INT DEF STAN 13-166/1 and INT DEF STAN 13-167/1. An example of this specification is G12, dark glazed, uniform granulation and free from foreign matter. Granulation 1 - 2 mm. Other classifications can carry a U.N. number and a designation for example type 3A (Fine) U.N. number 0027 grain size 0.25-0.50 mm. Otherwise it is simply classed as fine or course grain.

The percentage of saltpetre was steadily increased to 75%, which became the common figure around 1700 and has remained so ever since. The methods of purifying the components, particularly the saltpetre, were greatly improved and the replacement of stamp mills took place by incorporating (or rolling) mills around 1740. The important process of corning or granulating from the middle of the 16th Century enabled the blending to be carried out much more effectively.

Some powder used during the Civil War times may have been manufactured by simply powdering the three components separately and then grinding them together in a mortar with a hand operated pestle. Larger scale powder production would be carried out by the use of stamp mills. At the mills the powder mixture was pounded in wooden mortars by wooden-headed stamps which were moved up and down, by using horse or water power. It is unclear if stamp mills produced an inferior quality of powder to incorporating mills or whether they were just more dangerous or time consuming. There were frequent fires or explosions at stamp mills and as a result they were banned and replaced by incorporating mills in 1772 (Brown, 2005).

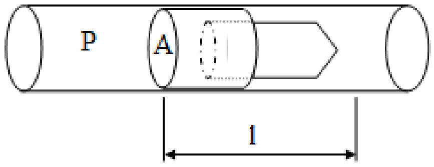
An incorporating mill consisted of two edge runners (two heavy, wide wheels) that are parallel to each other and are situated above a flat circular bed with a raised edge containing the powder mixture which had been moistened with distilled water. The edge runners, which were 2.5 m in diameter and 0.5 m wide, were controlled through a system of gears and run over the bed of moistened powder. Initially the wheels were made of stone, as in the old flour mills and then of cast iron but steel was eventually used, with wheels weighing up to 7 tonnes. The pressure of the runners slowly crushed the mixture and ground it together. This process was carried out for up to eight hours resulting in a hard mass, called mill-cake which could be made to different densities by altering the intensity and duration of the milling. In the corning process, the mill-cake was passed through a series of rollers which broke it down into smaller and smaller grains, the different sizes being separated by sieves. The sieved grains were then polished by rotating them for up to six hours in a drum and were generally glazed by adding a little graphite. 1 kg of corned powder was as effective as 1.5 kg of serpentine powder (Brown, 2005).

This research will study the internal and external ballistic properties of the 17th Century musket to gain an accurate assessment of its performance with varied parameters.

2.2. Internal Ballistics

Internal ballistics can be defined as the scientific study of the operating processes within the gun from the moment that the burning of propellant is initiated, (Farrar et al, 1999). It may also be defined as *"A term signifying the effects of the combustion of the explosive so far as they relate to the gun and to the projectile as long as it is within the gun"* (Greener, 1910). Greener continues "*The object of exploding a charge of gunpowder within a gun-barrel is to move a load from a condition of rest and impart to it a certain velocity. Time for the translation of the energy is all- important. As it is impossible to overcome the inertia of mass save by the application of a force for a period of time proportional to the weight, the ballistic value of an explosive depends upon the time required for the combustion, which with black powder, may be to some extent regulated by the shape, size and density of the grains. By a proper adjustment of the powder-charge to the weight of the bullet and capacity of the barrel, such a pressure is maintained upon the base of the projectile as to increase its* *velocity as long as it remains in the barrel. A theoretically perfect result would be obtained if the last atom of powder were converted into a gas at the moment the bullet leaves the muzzle. Too rapid combustion produces an increase of heat and pressure, but the pressure being local-that is, confined to the chamber it does not act upon the base of the projectile for the same distance; consequently the ballistic value is less, whilst the excess pressure may prove dangerous, and is always detrimental".* This means it is important to match the correct propellant to the weapon being fired, for example, a heavy projectile needs to be gradually accelerated along a long barrel using a slow burning propellant. A fast burning propellant would build up pressure too quickly before the inertia of the projectile is overcome resulting in possible damage and an "all burnt" situation before the projectile has left the barrel. Light projectiles can be given a fast burning propellant and use much shorter barrels. It is important to study various powders to determine the most appropriate for the 17th Century musket.

Figure 2.1 shows a simplified diagram illustrating that ignited propellant deflagrates to hot gas generating high pressure, which drives the projectile converting the chemical energy of the propellant to work done on the projectile and finally to the projectile kinetic energy.



Kinetic Energy of projectile = Work Done by propellant gas

Kinetic Energy of projectile = $\frac{M.v^2}{2}$

Work done by propellant gas =P.A.l

Where:
M = projectile mass
v = projectile velocity
P = pressure acting on base of projectile
A = area of base of projectile
l = barrel length

Figure 2.1: Projectile propulsion (Allsop, 2009)

2.3 Choice of Powder

The rate at which the powder burns is dependent on its composition, density, grain shape, grain size and surface treatment. The total surface area of the powder is also a factor to consider (see Figure 2.2) as the powder can only burn inwards on its surface, therefore, for equal weights, a low density, fine grained, unglazed porous powder would burn more rapidly than a dense, large grained, glazed powder (Brown, 2005).

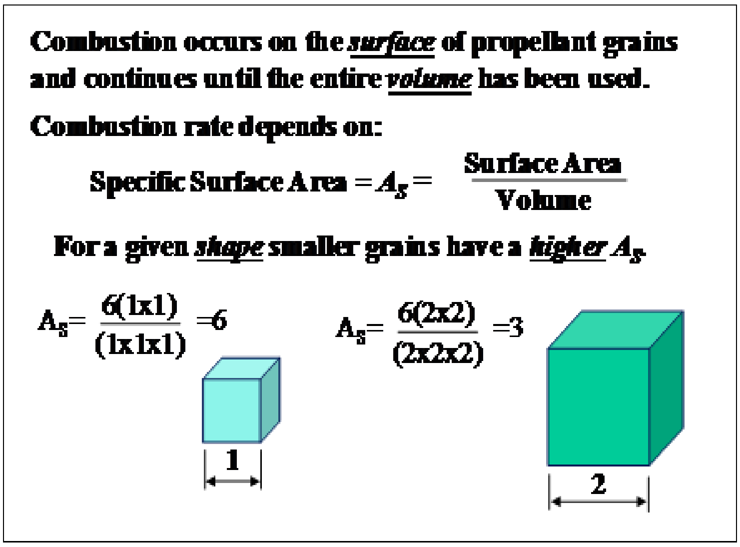


Figure 2.2: Specific surface areas of grain in powder.(Allsop 2009)

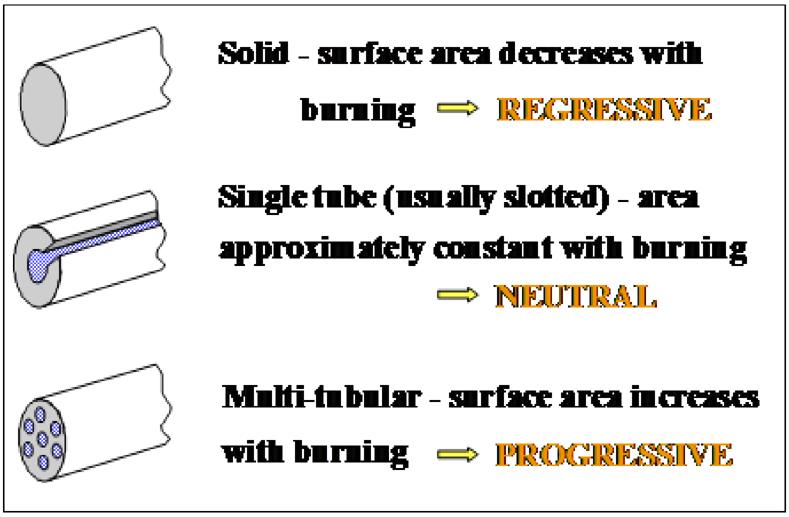


Figure 2.3: Effect of Propellant Form. (Allsop 2009)

The shape of the propellant has a large effect on the way it burns as can be seen in Figure 2.3. Black powder although not a perfect sphere, is sphere shaped and therefore, will burn regressively, as it is reduced in size by burning, its surface area also reduces thus it produces less gas. However, black powder can be porous allowing burning to its inner surfaces meaning in extreme cases it could become progressive. Research carried out by Tudge, (2002) in his MSc thesis on “Black Powder Substitutes” compared different black powders with various “pyrodex” powder substitutes in shot guns and concluded that the peak pressure remains unaltered with varying grain size, with the largest variance being approximately 100bar. However, analysis of the pressures did suggest that finer grained powder give a more consistent pressure than coarser grained powders. Tudge also examined the effects of different black powders with double the charge weight. He found that the maximum pressure increase with black powder was 40% and the minimum 20%; far less than would be the case with nitro powders. This suggests that black powder is far less likely to give overpressure than nitro powders. There is a large variation in mean peak pressure produced from different manufactures using the same charge weight as can be seen from Table 2.1. A Charge weight of 13 grams of black powder was used and 35.4 grams of number six shot fired from a 12 bore barrel.

Table 2.1: Black powder comparison. (Tudge, 2002)

Powder Sample	**Mean Peak Pressure (Bar)**	**Standard Deviation**
Swiss No.2	1272.67	1.87
Swiss No. 1	1141.41	95.4
TPPH	866.03	47.25
Henry Cranks Medium	721.12	48.8
Henry Cranks Fine	640.51	18.8

It is known that black powder was used in the 17th Century musket as nitro powders were yet to be developed. However, it is important to find a black powder that will replicate the internal ballistics of the muskets used during the Civil War. As mentioned previously modern powder is "75% saltpetre, 15% charcoal and 10% Sulphur". It comes in a variety of grain sizes, which as discussed, will affect the burning rate and peak pressure. In selecting an appropriate powder the internal ballistic cycle needs to be studied.

2.4 The Internal Ballistic Cycle

The internal ballistics cycle of the musket can be described as follows (as seen in Figure 2.4): Once the primer powder is lit, hot gases are forced into the chamber causing a rapid increase in pressure. As the heat is absorbed by the propellant, the pressure drops and the propellant surface is able to ignite, in turn releasing more hot gases. This again increases the pressure within the chamber until the projectile starts to move, this is known as the 'shot start pressure'. The volume then increases, to a point where the volumetric rate of gas production equals the increase in volume caused by projectile movement. This occurs at the peak pressure. The projectile then outstrips the gas production and the pressure decays. Once all the propellant is consumed ("all burnt"), the gas expands adiabatically (Eyers, 2006).

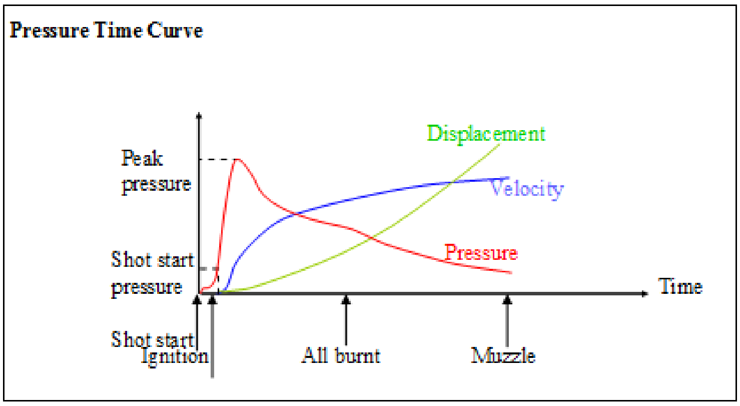


Figure 2.4: Internal Ballistic Cycle (Allsop, 2009).

*Curve obtained by measurement or calculation.

It was important to measure the Pressure/Time curves generated by modern black powders in order to deduce the best match for the 17th Century musket. Too high a peak pressure from faster burning powders would cause damage to the weapon; too slow burning powders would not build up enough pressure in time to launch the projectile at a high enough velocity before leaving the barrel.

2.5 Burning Rate

The burning rate of the powder is governed by the rate of heat conduction into the propellant grain. The rate can be calculated as follows:

$$\textit{Burning Rate} = \beta.P^{\alpha} mm/s, \qquad (2.1)$$

Where, P = Pressure

β = Burning Rate Coefficient, mm/s/MPa

α = Burning Rate Index.

Propellant	β	α
Smokeless	1.5-2.5	0.9-1.1
Gunpowder	15-30	0.2-0.7

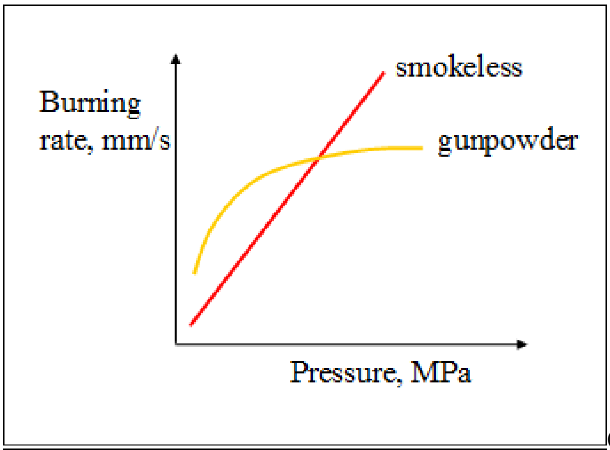


Figure 2.5: Graph to show burning rate against pressure. (Allsop, 2005)

From Figure 2.5 it can be seen that smokeless (Nitro powders) have a burning rate index of approximately one, which produces a directly proportional relationship between the pressure and burning rate. Gunpowder (black powder) has a much lower burning rate index, the burning rate increases with pressure but this increase reduces as the pressure increases, until it levels out completely, resulting in a constant burning rate with pressure. It is therefore impossible to exceed a set maximum pressure and it is less likely to cause damage to the barrel. Black powder has a burning rate co-efficient of up to twenty times that of nitro powders. This means it has a very high burning rate at low pressures, it is capable of generating a high volume of gas with less need for high pressures so it will not be effected by the tightness of seal in the barrel as much as nitro powders and therefore the use of "wads" and amount of "windage" will have less effect on the velocity of the musket ball than modern nitro powders would.

Greener (1910) compares Black Powders to modern Nitro-Compounds. Greener states that the main advantages of nitro powders over black powders is that they do not produce smoke after the discharge and that it produces a small amount of residue in the barrel. The differences between the powders arise due to the percentage of available gases contained in the nitro-compound. Black powders give 65% solid residue and 35% available gas, whereas the best nitro-compounds give 30% solid residue and 70% available gas. Black powder of course has to drive out the solid residue out of the barrel in addition to the charge of shot and wads in front of it, the major portion of the solids being in a state of fine division or smoke. Whereas, one half the charge of nitro-powder, by weight, is equivalent in force to a full charge of black powder. This leaves therefore, only about 15 per cent solid residue to be expelled from the barrel against nearly 65 parts solid from black powder. The Textbook of Ballistics and Gunnery (1987), contradicts Greener's view for nitro powders stating, "*When the propellant is ignited and burns, as in the gun, it is converted into gaseous products according to the general equation:*"

$$\boldsymbol{C_aH_bN_cO_d}(s) \rightarrow {}_e\boldsymbol{CO}(g) + f\boldsymbol{CO_2}(g) + g\boldsymbol{H_2}(g) + h\boldsymbol{H_2O}(g) + i\boldsymbol{N_2}(g) \qquad (2.2)$$

This would imply that all the propellant is actually converted into a gas.

2.6 Propellant Charge

The quantity and the burning rate of a powder are critical to the ballistics of the weapon.

Rogers (1968) refers to proof charges from Henry Roland Gun Makers in 1631. *"The proof was to be with good and sufficient Gunpowder the weight of the Bullet of Lead"* (the proof is double the normal size of the charge). It was also stated that a crown over the letter v would be stamped on the barrel in its rough state and then a second test carried out in finished state where a crown over the letters GP for (Gun makers Proof) would be issued.

Using this information we can deduce the weight of powder used would be half the weight of a 12 bore musket ball = half 37.3 grams (nominal) = 18.65 grams. Eyers (2006) quotes from Turner (1683) *"A musket requires the half weight of her ball in fine powder and two thirds of common powder"* and *"...the weight of powder for small arms as half the weight of the ball..."* In slight contradiction to this Pollard

(1983) states, *"In 1639 the English Ordinance Officers suggested that the musket-barrel be reduced to three and a half feet and the charge, to lessen recoil to only half the weight of the bullet instead of two-thirds*."

Another indication to the quantity of powder charge is the Bandoliers used at the time. Bandoliers usually contained a single charge and were carried by the majority of soldiers. However, examples of surviving bandolier flasks are capable of holding a charge larger than half the weight of the ball (Eyers, 2006) this would vary depending on the density and grain size of the powder.

If there are any significant changes in the black powder performance of today to that of the 17th Century it appears to have occurred in 1787 (Rogers, 1968). Rogers describes how in the latter parts of the 18th Century French Gunpowder was thought of as far superior to the English Gunpowder. This was so apparent during the American Civil War that after its conclusion an inquiry was instituted by Major Congreve and Captain Bloomfield of the board of ordinance. The investigation found many frauds and defects in the supply of the ammunition and the arms. One result of this investigation was that the Royal Gunpowder Factory was established at Waltham Abbey, Essex. The powder which the Royal Factory turned out soon became the best in the world. It consisted of 75% of saltpetre, 15% of charcoal and 10% of sulphur and the ingredients were better mixed.

The new powder being so much more powerful than the old powder resulted in the discovery of many doctored and faulty barrels, when they were submitted to proof.

The ultimate result was that at the time of the Napoleonic Wars British service firearms and ammunition were the best of the contending armies.

It has to be understood that simply stating more powerful is somewhat open to interpretation. It could simply mean that the burning rate is quicker resulting in higher peak pressures. This would certainly explain the reason for the breaking of weapons and also explain why weapons could be made with shorter barrels with less powder charge e.g. the Bakers rifle in 1800 used one third the weight of the ball for the charge (Rogers, 1968).

2.7 The ballistic performance of the musket

Greener (1910) wrote *"120 yards is the average distance at which the ball strikes the ground when fired horizontally at five feet above the level."* He explains that low levels of accuracy and range was considered satisfactory. This is supposedly due to the nature of battle at the time when soldiers simply fired into the line of opposing troops. He also produced a table of muzzle loading weapons of the British Army. The table states that for 12 bore, 0.729 inch diameter (18.5mm) matchlock Muskets of the 17th Century with a 48 inch barrel, a powder charge of 165 grains (10.714 grams) would be needed but he fails to give a range. However, Greener does give a range of an Old Army Musket dated 1750 at 200 yards using 124 grains (8.052 grams) of powder. This musket was 11 bore and had a 42 inch barrel. He also quotes the Brown Bess dated 1800 of having a 200 yard range.

Colonel Hanger (1841), as quoted in Smith and Smith (1963) states *"A soldier's musket if not exceedingly ill-bored (as many are), will strike the figure of a man at 80 yards, perhaps even 100: but a soldier must be very unfortunate indeed who shall be* *wounded by a common musket at 150 yards."* The same book refers to trials conducted by the Royal Engineers in 1841 on the "Brown Bess." The trials showed that the carrying distance of muskets would vary depending on elevation from anywhere between 100 - 700 yards. However, it was also noted that there was also a difference of carrying distance between muskets fired from the same level of elevation of as much as 300 yards. The level of accuracy was explained as follows: *"At 150 yards they could by very careful shooting hit a target twice as high and twice as broad as a man, three times out of four shots."* Further than 150 yards (even with the muskets vised into rests) could not hit the same target twice. The mark was then increased in size to be twice as wide as previously and of 10 shots at 250 yards not one struck.

Holmes (2003) confirms these findings when discussing the battle of Naseby in 1645. He found that a musket that fired a bullet weighing 12 to the pound was lethal up to 400 yards (365m) but was only effective up to 150 yards (137m). Bonsall (from Pollard, et al, 2008) states the range of a Civil War musket of between 183 - 380 metres. However, he does not mention what elevation the weapon is fired at.

Hughes (1997) supports Holmes by stating that the effective range of the musket was between 100 - 200 yards. When referring to the muskets of the 18th and 19th Centuries, Hughes identified the accuracy issue. He determined that with its heavy bullets, large windage and its low muzzle velocity, the musket had a poor ballistic performance and that the bullet followed a trajectory that became excessively curved and erratic at all but very short ranges.

2.8 External Ballistics

"Once the projectile has left the gun and the influence of emerging gases, the part of flight known as external ballistics begins". (Farrar, Leeming, 1999).

From their introduction, musket balls found on the battlefield often have distinctive banding marks around their circumference which may affect their external ballistic properties. This research has compared experimental firings with calculated distance tables of a perfect sphere to establish any changes to the drag co-efficient of the musket ball due to its change in shape. An understanding of external ballistics is necessary in calculating the theoretical distances that a musket ball would travel.

Several factors affect the motion of a projectile as it travels through the air. These factors can be associated with either the projectile itself, .i.e. the mass/shape of the sphere; or the atmosphere the sphere is travelling through, i.e. the density, pressure, temperature and viscosity (Farrar, Leeming, 1999)

Newton's law of inertia states that a body persists its state of rest or of uniform motion unless acted upon by an external unbalanced force. This would therefore suggest that unless an external force such as gravity acted upon the projectile, then the projectile would continue its initial direction and maintain its muzzle velocity. However, in the instance of a projectile leaving a weapon, there is an external force of gravity which has the effect of pulling the projectile back towards the centre of the earth with an acceleration of g m/s^2. The value of 'g' varies with the distance from the earth but for short range weapons, such as small arms, it can be assumed that the gravitational field is uniform, and take a constant value of 9.81 m/s^2.

Gravity is not the only external factor to affect the projectile. As the sphere travels through the atmosphere, the air surrounding it becomes displaced by kinetic energy of the projectile. This loss of energy from the projectile is known as drag and causes the continual loss of projectile velocity. The amount of drag on a projectile is affected by its shape, this determines its drag coefficient (C_d).The C_d can be divided up into the following components.

2.8.1 Forbody Drag.

The compression of air, which occurs immediately in front of the projectile, is transmitted to the surrounding air as a pressure wave. This causes a disturbance which travels through the air at the same speed as sound waves. At ambient pressure and temperature the speed of sound in air is taken as 340 m/s. When the projectile is travelling at a speed below the speed of sound, which is below 340 m/s, the disturbances move faster than the projectile and so spread out away from it. Forbody drag is of the greatest significance in the supersonic region. When the projectile is travelling faster than sound no part of the disturbance can escape directly in front of the projectile. The result is that the compression waves "bunch up", and a shock wave is created at the nose of the projectile. In general a conical shock wave is produced which has an angle θ where $\sin \theta = 1/M$. M is the Mach number and is defined as the velocity of the projectile divided by the local speed of sound in air, $M= V/a$. Forbody drag increases steadily as velocity increases, and a steep rise is noticed as the velocity of sound is approached. The increase is maintained for a time, at this rate in the supersonic zone but gradually reduces.

2.8.2 Base Drag.

There is considerable turbulence behind a projectile. This turbulence is called the wake and causes a further resistance known as 'base drag'. Base drag occurs due to a region of low pressure immediately behind the projectile which occurs when the air flow cannot return quickly enough to fill the space behind the projectile. The consequence is a vacuum or suction effect which shows itself in the form of a resistance to motion. Base drag increases with velocity until the velocity of sound is reached but then remains fairly constant. This is because as the velocity of the projectile approaches the speed of sound, the air pressure behind the base tends to zero.

2.8.3 Skin Friction.

Additional resistance to motion is caused by air adhering to the surface of the projectile. The mechanism is that the air at the surface of the projectile is moving at the same speed as projectile; the next layer of air is moving a little more slowly and so on outwards. Frictional drag is generally relatively small for most projectiles and is normally of the least consequence.

2.8.4 Transonic Zone.

Around the velocity of sound there is a zone in which the projectile's behaviour is unpredictable due to the rapid change in air resistance between subsonic and supersonic. There is an increase in the drag coefficient due to the formation of shock waves.

Newton's Laws of Motion are also used to predict the direction of the path of a projectile, i.e. its trajectory.

2.9 Projectile Trajectory

As explained previously in section 2.8, projectiles are pulled towards the centre of the earth by gravity denoted as ***g*** (9.81 m/s^2). This generates a force on the projectile of

$$Fg = mg, \text{ where } m \text{ is the mass of the projectile in kg.} \tag{2.3}$$

If a projectile were fired in a vacuum there would not be any drag forces acting upon it, therefore

d(x) = vt , where ***d(x)*** is the distance moved in the x direction, (2.4)

v is the velocity (m/s) and ***t*** is the time (sec).

The distance moved in the y direction (downwards) would be equal to

d(y) = ½ at^2 , where ***d(y)*** is the distance moved in the y direction, (2.5)

a is the acceleration due to gravity (9.81 m/s).

Using an example for a muzzle velocity of 400 m/s. x and y values can be calculated using 0.1 second time steps as shown in the table and chart below Figures. 2.6 and Table 2.2. Range against projectile drop.

Table 2.2: X and Y co-ordinates from a velocity of 400 m/s. (Eyers, 2006)

Time Elapsed (S)	X Distance (M)	Y Drop (m)
0.1	40	-0.04905
0.2	80	-0.1962
0.3	120	-0.44145
0.4	160	-0.7848
0.5	200	-1.22625
0.6	240	-1.7658
0.7	280	-2.40345
0.8	320	-3.1392
0.9	360	-3.97305
1.0	400	-4.905

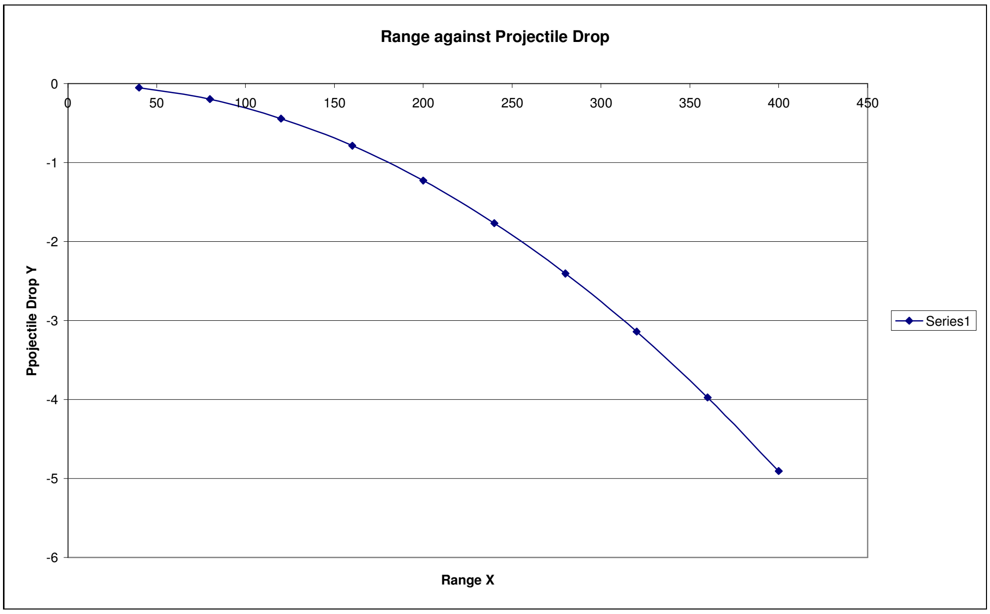


Figure 2.6: A graph to show range against projectile drop. (Eyers, 2006)

When a projectile is fired on earth, in the presence of an atmosphere, it will slow down due to the effects of drag. The velocity loss with range can be calculated from the following:

$$\textbf{Velocity Loss with Range} = \frac{\Delta V}{\Delta S} = \frac{C_d \rho . V . A}{2m} \qquad (2.6)$$

Where C_d = drag coefficient (dimensionless)

ρ = density of the air, (1.25kg/m^3 @ 21^{o}C)

V = projectile velocity, m/s

A = cross-sectional area of the projectile, m^2

m = mass of the projectile, kg

S = projectile displacement, m

A can be calculated by using the diameter on the 12 bore musket ball to be a nominal 18.51 mm, and the formula for a cross sectional area $A = \pi . r^2$ (2.7)

$$\therefore\ A = \pi\, 0.009255^2 = 2.691\times10^{-4}\,m^2 \tag{2.8}$$

We know that mass of the musket ball to be = $3.79\text{x}10^{-2}$ kg

Using 1 m increments for ΔS.

$$\frac{\Delta V}{\Delta S} = \frac{C_d \times V \times 2.691\times10^{-4} \times 1.25}{2 \times 3.79 \times 10^{-2}} = C_d \times V \times 4.43 \times 10^{-3} \tag{2.9}$$

The drag coefficient varies with the velocity of the projectile. It is found experimentally and is dependent on the shape of the projectile. Typically the drag coefficient is expressed not in terms of its velocity but in terms of its Mach number which is the ratio of the velocity of the projectile to that of the speed of sound through the air through which it is travelling. For air at sea level at 21°C the speed of sound is 340m/s, thus a projectile travelling at this velocity is said to be travelling at Mach 1.

A curve of the drag coefficient against Mach No. is characterised by three different sections with a gradual transition between the sections. At low subsonic velocities the drag coefficient is low and constant with Mach number. This is followed by a steep increase in drag coefficient as the projectile passes through the transition from subsonic to supersonic velocities. A peak value is reached followed by a gradual reduction in drag coefficient.

There is good experimental data on the drag coefficient for spheres from Braun (1973), this can be simplified without undue reduction in accuracy to the diagram shown in Figure 2.7.

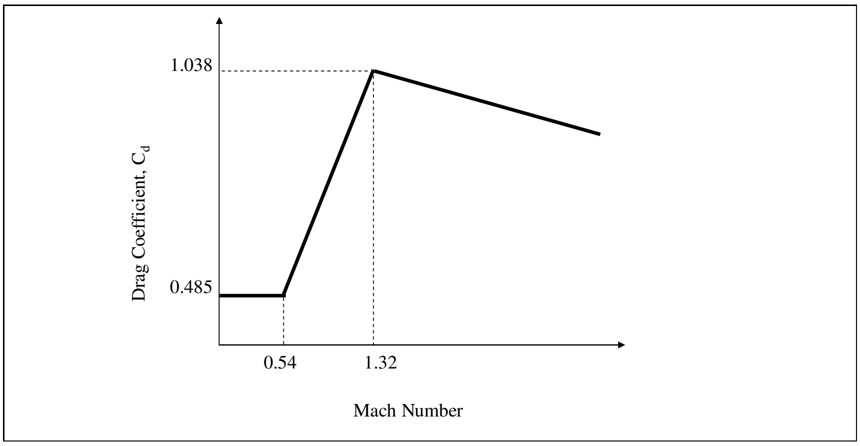


Figure 2.7: A Graph to show the relationship between Drag Coefficient and Mach number for a sphere.

From the chart it can seen that a Mach number of 0.54 is equivalent to 184m/s (340 × 0.54) therefore, from 0 to 184 m/s the drag coefficient is constant at 0.485. For velocities from 185 m/s to 450 m/s (Mach 1.32) there is a straight line as drag coefficient is proportional to velocity thus the formula y = mx + c can be used, where 'm' is the gradient 'x' is the Mach number and c is the y intercept point where the line crosses the 'y' axis if it were continued on. The slope of the line (m) is 2.08×10^{-3}

$$\therefore Y = 2.08 \times 10^{-3} \times \text{Mach number} + 0.107 \qquad (2.10)$$

From this the following expression can be used:

$$C_d = 0.107 + 2.08 \times 10^{-3} \times V \qquad (2.11)$$

After Mach 1.32 (450 m/s) it can be seen that the drag coefficient begins to decline.

The range (distance travelled) can be divided into small steps and for each step the velocity loss over that step can be calculated, this can then be used to calculate the new average velocity over that step and so on giving a new curve. Using this method a simple point mass trajectory model was developed to predict the impact distance of a musket ball for a given muzzle velocity, launch height above the ground and launch angle. This trajectory model was originally developed by Cranfield University to estimate the maximum range of spherical pellets fired from shotguns. The model has been validated by actual measurements of range achieved from weapon firings. Agreement with the predicted values was better than 1.0%.

Figure 2.8 shows the predicted trajectory for a 18.51mm diameter (12 bore) lead ball launched at 400m/s parallel to the ground and at a launch height of 0.5 m. It can be seen that the maximum predicted range of the weapon is 109 m, which compares with 128 m if there was no aerodynamic drag.

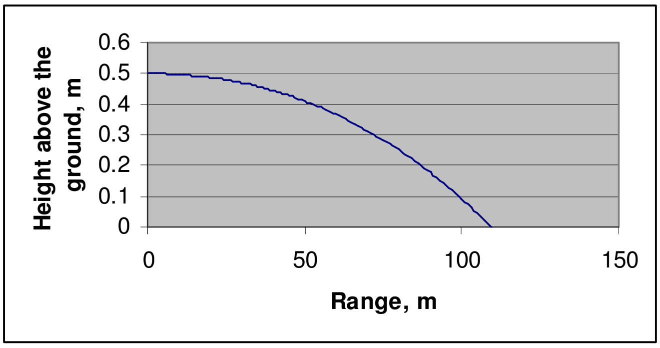


Figure 2.8: A Graph showing the predicted trajectory from a 12 bore lead ball at 0.5 m elevation at 400 m/s.

Braun's experimental data has also been used by Compton (1996) in "An Experimental and Theoretical Investigation of Shot Cloud Ballistics." He states *"It can be seen that at subsonic velocities below Mac 0.5 , the drag coefficient is constant. At transonic velocities between Mach 0.5 and Mach 1.4 the drag coefficient is approximately proportional to the velocity. At higher supersonic velocities (greater than 1.4) the drag coefficient becomes approximately constant again. There is a slight difference in values owing to the interpretation of "best fit" lines of the graph."* He also compared Braun's experiments with data from Charters and Thomas (1945) to validate the results and concluded. *"Comparing the two sets of results it can be seen* *that they show good agreement even though the experiments were carried out 30 years apart".*

2.10 Armour Penetration

Armour used during the Civil War were usually claimed to be caliver or pistol proof with few withstanding musket fire. The armour often showed a dent in the breastplate that was a type of proofing to identify that the armour plate had resisted a firearm (Bull, 1991).

Recent research carried out at the Small Arms Experimental Range Shrivenham by Williams on reproduction armour panels with a 12 bore lead musket ball perforated the armour at 335 m/s but stopped at 278 m/s at 325 m/s there was a partial perforation. These results indicate the velocity of the 17th Century musket to be at least 325 m/s because as stated earlier it was capable of perforating armour.

2.11 The Civil War Musket

It is important to be able to replicate the 17th Century musket. The barrel length and the calibre used in the Civil War are necessary requirements to reproduce authentic results in experimentation.

Previous work conducted by Eyers (2006) has established that the main weapon used was a 19.685mm internal diameter matchlock musket with a 48 inch (1.219 m) long barrel. The information was gained by both literature searches and by inspecting 52 weapons from the "Littlecote collection" at the Royal Armouries, Leeds. These weapons are all believed to be from the Civil War period. The Barrel internal diameters were measured and varied in diameter from a maximum of 22.35 mm to a minimum of 18.87 mm with the mean diameter being 19.87 mm.

The true calibre of 10 bore equates to 19.685 mm (that is the diameter from a sphere of lead weighing one 10^{th} of a pound). There were also many other calibre weapons in use at this time many obtained from private sources (Eyers, (2006) quoting from Young and Holmes, 2000).

There are many references to the calibre of the 17^{th} Century musket for example, *"The bore of the barrel was standardised at 10, and this was designed to provide an easy fit for a 12-bore bullet"* (Rogers, 1968). With regards to the barrel length, again there are many references to be found, for example Bull (1991) quotes *"c.1640 commonest of all infantry arms in the seventeenth Century was the matchlock musket. The regulation 48 inches long"*. As well as variations in individual musket calibre it is likely that most barrels would not have been perfectly straight. According to Greener (1910) *"Previous to 1795 there was no reliable method of ascertaining when a barrel was or was not perfectly straight. The barrels of the finest ancient guns were usually far from straight"*.

The 17^{th} Century musket would not have been capable of withstanding the pressures that a modern weapon could, as modern steels and manufacturing processes would not have been available. Greener (1910), states *"The method of making barrels prior to the introduction of Damascus iron (1820) from the east was to forge them from plates or strips of iron-this iron manufactured from old horse shoe nails"*. This could be one of the limiting factors affecting the maximum velocity of the 17^{th} Century musket.

2.12 The Civil War Musket Ball

A detailed study of the 17th Century musket ball was carried out by Harkins (2006) in his MSc work on forensic techniques in battlefield archaeology. He used a recovered a bullet from the Battle of Marston Moor in July 1664 which he analysed for the purpose of comparison with modern replicas. The 17th Century bullet had an average hardness of 6.32 Vickers and was determined to be 99.7% lead. Further musket bullets from the battle of Edgehill on the 23rd October 1642 were analysed. These were 12 bore with a theoretical diameter of 18.51 mm, 0.730 inch and were equivalent to 12 lead balls to the pound 37.9 grams, 1.313 oz each.

Foard (2009) also conducted postgraduate research into musket balls discovered at Edgehill and states that 12 bore was by far the most common calibre represented. The musket ball would be cast from a split mould of two halves with the mould line representing the junction of the two halves. In reference to the sprue, Foard states that "*single bullet moulds will have typically left a single sprue, occasionally seen in surviving bullets. However, the sprue was normally removed to complete the manufacturing process*". A replica 12 bore musket ball made to the same specifications was used in the musket trials.

2.13 Banding

Banding can be described as a distinctive firing mark where the bullet is flattened in a band around the circumference of the bullet. There is a continuum in the degree of banding from slight flattening around part of the circumference, to intense wide banding around the whole circumference Foard, (2009). Foard mentions that there is a close association between banded bullets and the presence of pitting on the lower hemisphere of the bullet. He also states that in some bullets, the degree of melting is such that radiating striations are also present on the lower hemisphere of banded bullets, which faced towards the powder charge, the upper hemisphere typically remains as an unaltered bullet. It was necessary to soft capture and analyse fired musket balls from the reproduction musket to inspect for banding, as this gave an indication that firing conditions were accurately being recreated. Foard (2009) suggests that banding could be the result of an increase in pressure in the barrel caused by a tight fitting ball. Figures 2.9 and 2.10 show examples of banded bullets.

Figure 2.9: Musket Ball showing banding (Foard, 2009)

From Figure 2.9 it can seen that the musket ball is slightly elongated, with a wide irregular band width thus reducing the calibre of the bullet. A distinct pitting can also be seen.

Figure 2.10: A Musket Ball showing severe banding. (Foard, 2009)

From Figure 2.10 it can seen that the musket ball shows severe banding with extreme markings. Again, as in Figure 2.9, pitting can be seen and an impacted hemisphere can also be seen to the right of the musket ball.

2.14 Windage

Windage can be described as the difference between the ball and the barrel of a musket. A 17th Century musket that was 10 bore (19.68 mm) internal diameter and fired a 12 bore (18.51 mm) ball would be said to have a large amount a “windage”. Foard (2009), mentions in his research that the average amount of windage was 1.5 mm. This large amount was probably to ensure the musket ball would easily slide to the bottom of the musket barrel even when the barrel had become fouled from the black powder residue after several firings. It is thought that such a large amount of windage was required to ensure the firing of up to a dozen bullets without having to clean the barrel. The disadvantage of such a large amount of windage is that it would reduce the muzzle velocity due to gases escaping past the musket ball and quite possibly a reduced accuracy. Both of these were worthy trade offs since the musket was used mainly against a large target, i.e. a block of opposing soldiers at short ranges. This research project investigated the different effects of windage.

2.14.1 Fouling

Deposits left inside the barrel of the musket after firing will alter the amount of windage, especially if there is a cumulative effect. As discussed by Greener (1910), over 50% of constituents produced by black powders are non-gaseous. This material either takes the state of a liquid during the combustion cycle, or as a powder found either escaping as smoke at the end of the barrel, or as particles left inside the barrel. In large cannons this residue can build up to 0.75 inch thick at the breech end of the barrel. If very foul, the resistance to the projectile may be so great that a dangerous local pressure is set up in the barrel but usually the result is a loss of velocity only in the projectile. However, as mentioned in Hughes (1997), the requirement for the barrel to be cleaned would have rendered the musketeer defenceless for several minutes.

2.15 Wads

The use of a wad can have a marked effect on the ballistics of weapons. A wad primarily acts as a seal between the powder charge and the projectile while keeping the powder tightly in place. The wad can also be used to keep the projectile in the barrel, particularly with large amounts of Windage (see Section 2.14).

It has been suggested by Roger Boyle the first Earl of Orrery from Grose 1801 (quoted in Eyers, 2006) among others that wadding was used during the Civil War. He states that *“(musketeers) seldom put any paper, tow or grass to ram the bullet in”* as was to be expected, due to the shortness of time between firings. This suspicion is also confirmed by Grose (1801) stating *“... such softe haire as they stuff saddles with... this soldier must use when time permits”* – implying that a wad would be used if there were time to do so.

However, research conducted by Foard (2009), found that the musketeer would usually load his musket without wadding. This would make loading and firing quicker but also increase the chances of the ball rolling out of the barrel. To avoid this problem Munro recommended the use of cartridges, enabling rapid reloading and with the paper providing the wadding. However, manuals and supply records demonstrate that throughout the war this remained the exception, the vast majority of troops being equipped with a bandolier of powder boxes, each holding a single charge of gunpowder. Foard also states *“Despite the potential to load without ramming, musket drill typically required the ramming home of the bullet with a scouring stick or ramrod”*. Foard’’s findings are supported by Rogers (1968) who found that various unusual and unauthorised methods of loading were used by soldiers to speed up the time between firings since the time of Charles I. Powder was poured into the end of the barrel, the musket ball dropped on top without wadding. The charge was then rammed home by banging the butt of the musket on the ground. This led to the range and penetration ability of the musket ball to suffer.

Chapter 3: PROJECTILE SOFT CAPTURE METHODS

3.0 Introduction

As discussed in the Literature Survey the shape of the musket ball is modified by 'setting up' in the barrel. To study this effect, experiments were carried out to produce a soft capture system capable of capturing the musket ball without causing it any subsequent damage so that the change in shape to the musket ball caused by the firing process could be studied. Recreating the 'setting up' of the musket ball when fired was an important part of the project as it is an indication whether similar conditions were present in the original 17th Century musket. It was also important to generate the deformity in shape to establish whether it had a notable effect on its ballistic properties.

3.1 Manufacture of Musket Balls

To cast the reproduction musket balls for the experiment, lead was heated in a melting pot with a Bunsen burner. The top layer of residue was then removed and the molten lead poured into a split mould as seen in Figure 3.1.

Figure 3.1: Split mould with lead musket ball

The lead was then allowed to cool and the mould was opened to extract the musket ball. A 'sprue' remained on the ball from where the lead was poured as seen in Figure 3.2. Most of it was removed using hand cutters. A small flash was also visible where the two halves of the mould joined and these marks would be found on a genuine 17th Century musket ball (see section 2.12). A lead musket ball from the Marston Moor conflict has been analysed (Harkins, 2006) and was found to be very soft and made of almost pure lead. Soft lead of this type was used throughout all of this research. The lead used was checked for composition with a Scanning Electron Microscope and tested for hardness with a Vickers test machine to ensure its match with an original 17th Century musket ball.

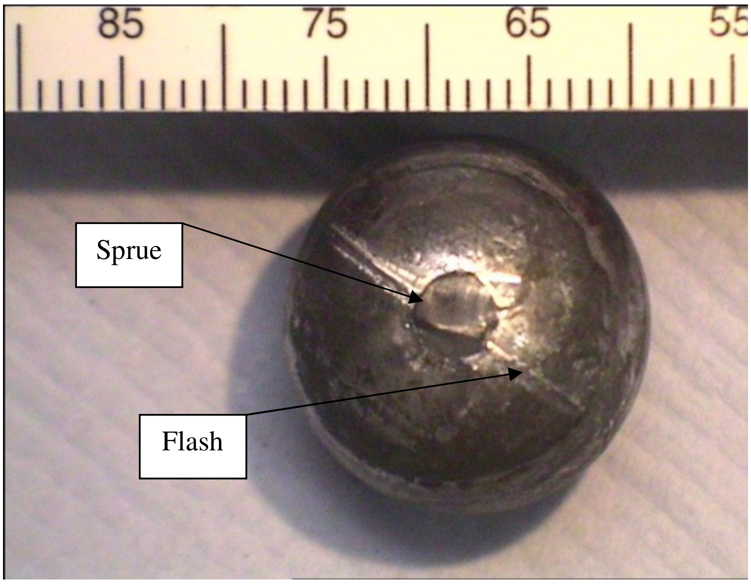


Figure 3.2: Cast reproduction 18.51 mm diameter (12 bore) musket ball showing 'sprue' and flash mark

3.2 Experimental Set up

A muzzle loading 19.49 mm internal diameter (10 bore) barrel with a length of 39 inches (990mm,) was used. This was shorter than the 17th Century musket but still suitable for testing soft capture methods prior to a 48 inch long barrel becoming available. The barrel had a screw thread on one end to attach it to a specially manufactured breech block with a touch hole in the side, counter-sunk to allow priming gunpowder to be positioned on top of the touch hole, see Figure 3.3 and Figure 3.4. A tapping for a pressure transducer was also fitted into the end of the breech.

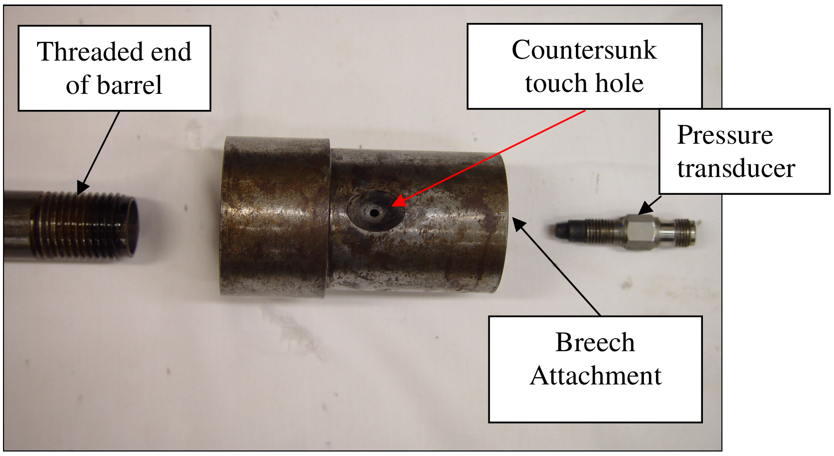


Figure 3.3: The experimental breech block and threaded end of barrel

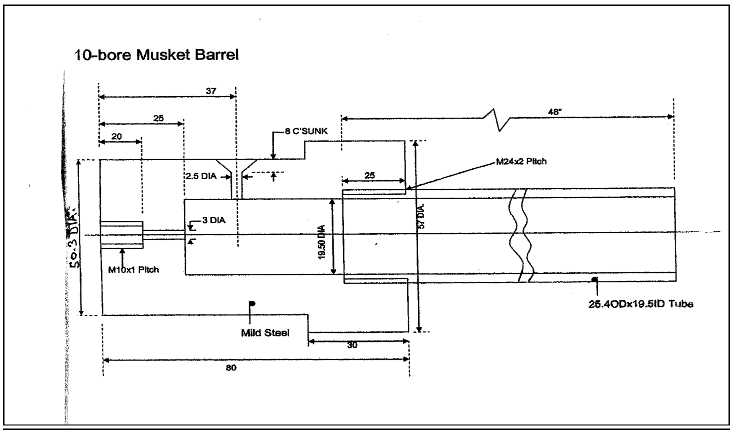


Figure 3.4: A Drawing of Breech block and musket barrel from Eyers, (2006). Note barrel length shown is for 48 inch barrel length

The test barrel was screwed into the breech block, which in turn was inserted into a Number 3 proof housing, shown in Figure 3.5 and secured with a back nut. The proof housing was bolted to a stand which allowed movement of the gun horizontally and vertically. A laser pointer was attached to the rear of the proof housing for accurate aiming. A Weibel Doppler radar type W700 was also used to record the velocities of the musket balls.

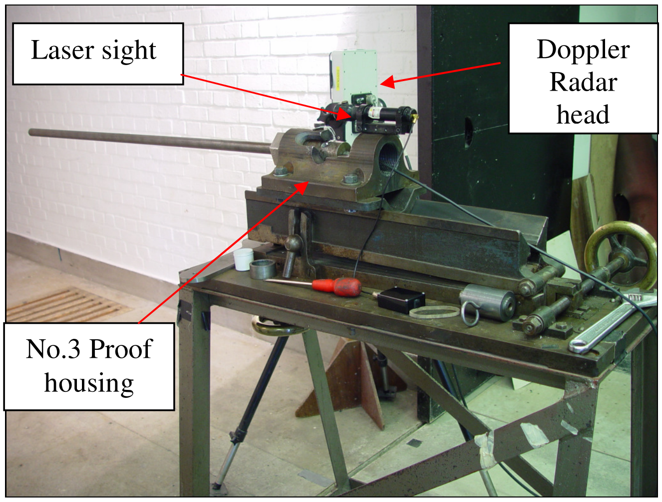


Figure 3.5: Number 3 proof housing mounted on stand with barrel attached

3.3 Firing procedure

3.3.1 Loading

For each firing, the barrel and the number 3 proof housing were unbolted from the stand to enable loading in a vertical position. A small wooden dowel was inserted into the touch hole to ensure that the powder did not leak out when it was being poured into the barrel. The black powder was weighed out and poured into the mouth of the barrel via a funnel as seen in Figure 3.6.

Figure 3.6: Pouring the black powder

For wadding, nine sheets of rolled tissue made a good tight fit in the barrel; these were lightly rammed in with a ram rod. The musket ball was then inserted into the barrel and very gently rammed in to ensure it had gone all the way to the bottom. Two sheets of tissue were inserted into the barrel and gently rammed in on top of the musket ball. The barrel and the proof housing were then lifted onto the stand and secured with two bolts. The dowel was removed and a small amount of priming powder (Swiss no.1) poured into the touch hole and allowed to spread around the counter-sink.

An electrical igniter consisting of two wires joined by a match head was taped over the priming powder as seen in Figure 3.7.

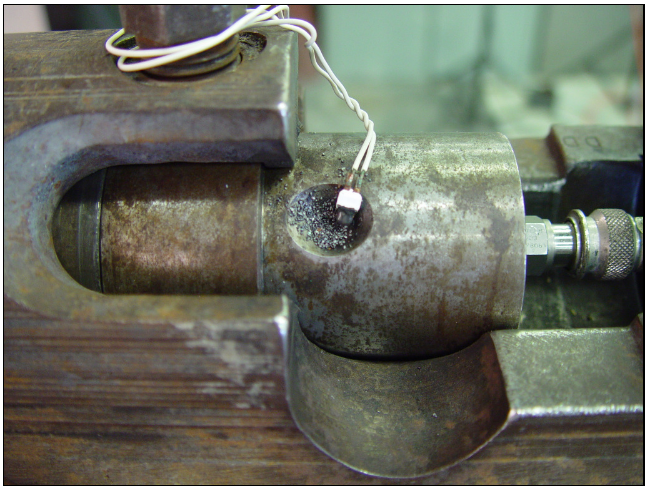


Figure 3.7: Electrical match positioned over black powder touch hole prior to taping

The igniter wires were then run to a remote firing position in the observation room for safety. The match was initiated with a 20v electrical supply completing the circuit to the match head. Figure 3.8 shows the musket barrel as it is fired.

Figure 3.8: Firing experimental musket barrel

Various charge weights were used to gain a variety of velocities from the musket balls. Black Powder type G12 was selected from available powders for the initial soft capture testing. The velocities recorded from the various charge weights are shown in Table 3.1.

Table 3.1: Velocities from varied charge weights

G12 Black Powder (g)	**Velocity (m/s)**
8	227
10	290
17	417
20	455

3.3.2 Soft Capture Method – Shredded Rubber

Shredded rubber is commonly used as a bullet stopping medium on ballistic ranges. It was therefore selected as the first method for capturing the musket ball.

A steel box size measuring 300mm square was filled with rubber, as seen in Figure 3.9 and 3.10. The box was then mounted on a stand 10 metres from the muzzle of the experimental musket. A piece of card was taped over the front to prevent the rubber falling out. A charge of 15 grams G12 powder was loaded into the barrel with wadding. A muzzle velocity of 367 m/s was recorded and the depth of shredded rubber proved to be insufficient to slow the musket ball down before hitting the rear of the box as significant damage to the musket ball was noted.

Figure 3.9: Steel box filled with shredded rubber. (Front cover partially removed to show shredded rubber)

Figure 3.10: Shredded Rubber acting as a soft capture method

A polythene bag was filled with more shredded rubber to increase the depth by a further 400mm and positioned in front of the steel box. The experiment was repeated with the same quantity of black powder.

3.3.2.1 Results

A muzzle velocity of 379 m/s was noted. Examination of the musket ball revealed that it had been stopped by the rubber shavings, but damage was sustained to the soft lead as shown in Figure 3.11.

Figure 3.11: Damaged musket ball stopped in rubber shavings

Rubber shavings were ruled out as a form of soft capture at this velocity because the musket ball was too badly damaged. Upon examination the condition of the musket ball, although damaged, indicated that “setting up” was not evident.

3.3.3 Soft Capture Method - Foam and Rags

Previous tests carried out by Harkins (2006), used multiple layers of foam rubber such as from boat buoyancy aids. 600mm of this rubber was found to stop a musket ball at a reduced velocity of 200 m/s. A small amount of foam was available however, 600mm of foam was placed 10 metres from the muzzle of the musket and a 530 × 400 mm box containing rags positioned behind it. The black powder charge was raised to 20 grams to increase barrel pressure and try to create ‘setting up’ of the musket ball.

3.3.3.1 Results

With the velocity increased to 423 m/s, the musket ball perforated the soft capture system. It was retrieved from the sand butts 20 metres from the muzzle. The musket ball was damaged but there was some indication of 'setting up' as seen in Figure 3.12. This system was a possible solution but would require a very large amount of foam and rags.

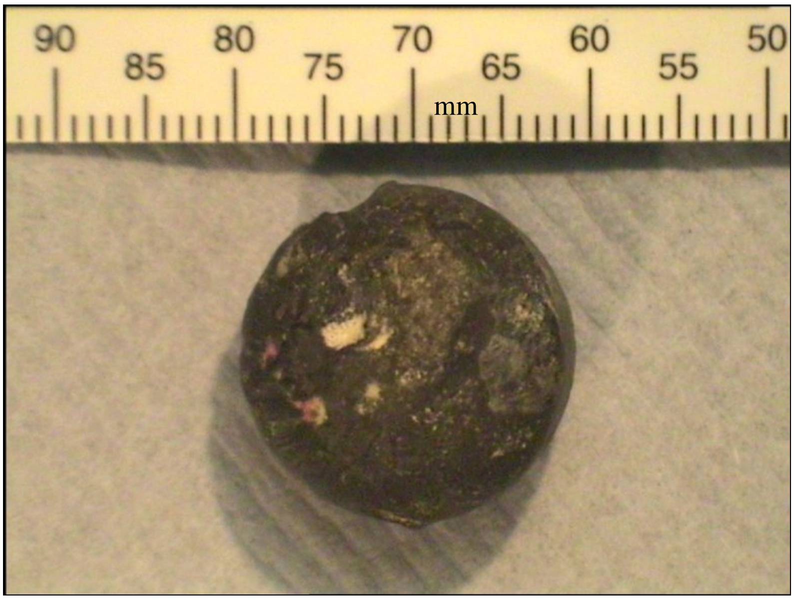


Figure 3.12: Damaged musket ball recovered after soft capture in foam and rags

3.3.4 Soft Capture Method - Water Tank

A steel tank measuring 2000 mm long, 200 mm wide and 400mm in depth was filled with water as another soft capture system. The black powder charge was reduced to 8 grams as a safety precaution and to protect the tank. The barrel was raised above the tank and angled at the far corner into the water as can be seen in Figures 3.13 and 3.14.

Figure 3.13: Barrel angled into water tank

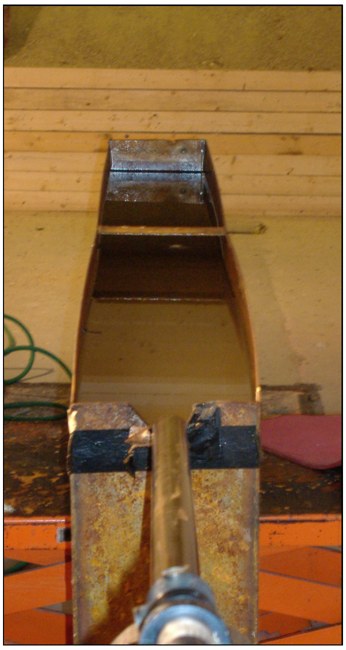


Figure 3.14: Water tank

3.3.4.1 Result.

The velocity was estimated at 227 m/s and obtained from previous data as no velocity reading could be taken as the barrel was firing directly into a water tank.

After firing, the musket ball was retrieved and inspected. A large proportion of the musket ball remained intact; however it hit the base of the tank leaving a large indentation on the musket ball as shown in Figure 3.15.

Fig. 3.15- Musket ball retrieved from water tank

Water could be used as a capture system, however a much larger tank would have to be manufactured. It would take considerable time to fill the tank and the retrieval of the musket ball would be difficult, therefore it was decided to try other methods.

3.3.5 Soft Capture Method - Kevlar

The rear portion of a body armour jacket containing 18 layers of Kevlar was supported on a target stand 10 metres from the muzzle of the experimental musket.

The Kevlar was loosely supported so that it would be released from the stand on impact to catch the lead musket ball and then continue down the range to slowly dissipate the energy. This firing was conducted using a 300 mm long 12 bore shot gun barrel attached to the number 3 proof housing in the same manner as the musket barrel. A Winchester one ounce solid slug was used rather than the musket ball as shown in Figure 3.16.

Figure 3.16: Winchester solid slug shot gun cartridge

This method greatly reduced firing times and wastage of musket balls because the shot gun barrel could be breech loaded. A block containing a firing pin was screwed in behind the cartridge and fired remotely by means of a solenoid. Figure 2.17 and 2.18 show the solid slug loaded in the number 3 proof housing prior to firing.

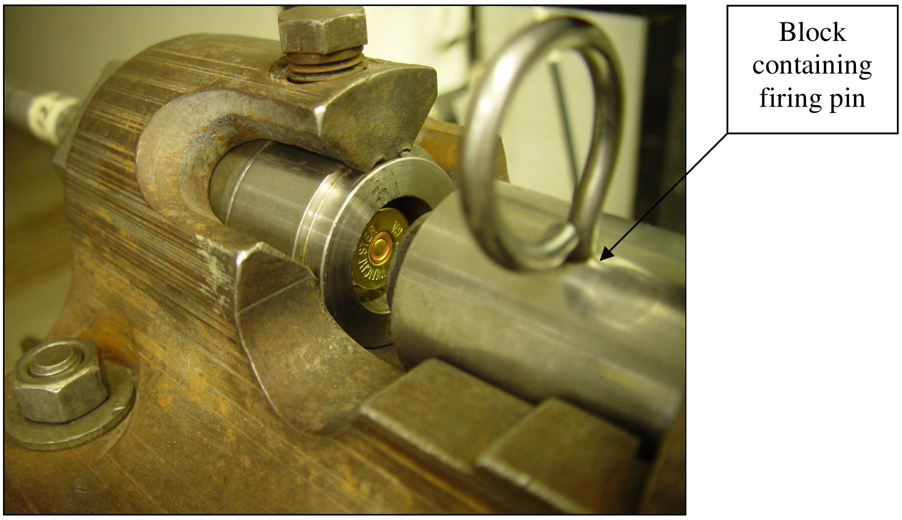


Figure 3.17: Solid slug positioned in shot gun barrel held in number 3 proof housing

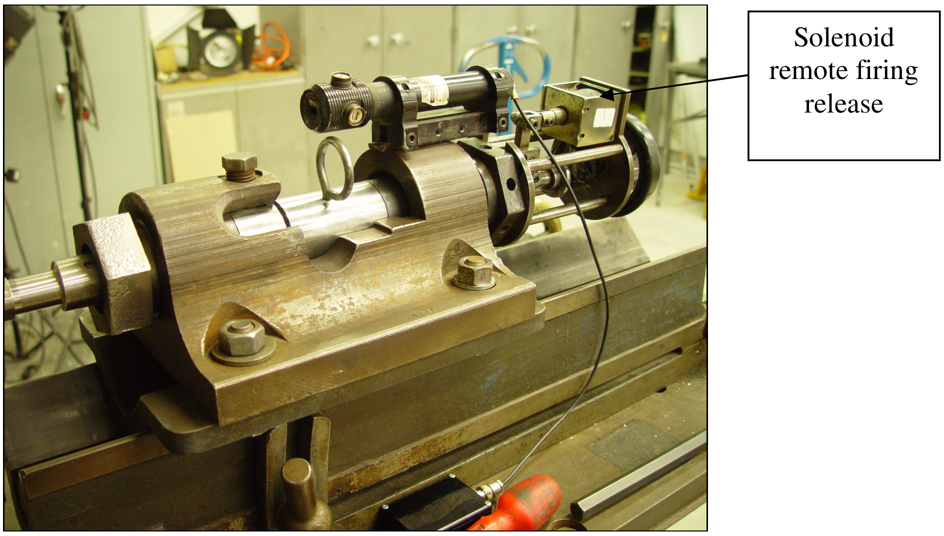


Figure 3.18: Solid slug in shot gun barrel held in number 3 proof housing

The solid slug is known to be harder than a pure lead musket ball as it is a lead antimony alloy. It was assumed if it was damaged by the capture system then a musket ball would also be damaged at an increased level.

3.3.5.1 Results

A velocity for the solid slug was recorded at 400 m/s. The Kevlar travelled four metres backwards from the target stand and the solid slug completely perforated it and was lost in the sand butt at the far end of the range.

The Kevlar was then cut into smaller squares of 250mm × 250mm to try and minimise its weight while increasing its thickness to 24 layers in a bid to prevent perforation. A shorter shot gun barrel of 250mm was also used to reduce velocity.

The velocity was then recorded at 388m/s with the shorter barrel. The Kevlar travelled completely to the 20 metre end of the range and captured the solid slug. It was badly damaged. Figure 3.19 shows the solid slug in the Kevlar and Figure 3.20 shows the front face of the solid slug. The marks from the Kevlar are clearly visible on the surface. The Doppler Radar also registered a velocity of 38 m/s which could have been the velocity of the Kevlar and captured solid slug moving after initial impact.

Figure 3.19: Captured solid slug in Kevlar

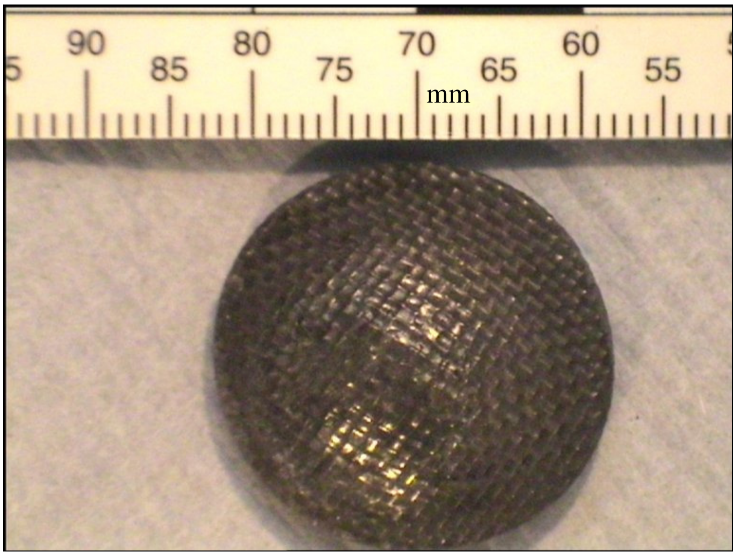


Figure 3.20: Front face of solid slug retrieved from Kevlar

The results showed that Kevlar soft capture system would not be satisfactory as it caused a large amount of damage to the lead alloy slug.

3.3.6 Soft Capture Method - Plastozote (R) Lure foam

84 pieces of Plastozote foam 330×200×30 mm thick followed by 600 mm of boat buoyancy foam and linotex laminate combination were positioned 10 m from the muzzle of the shot gun barrel (Figure 3.21) and a Winchester solid slug was fired into it.

Figure 3.21: Plastozote and foam/linotex combination

3.3.6.1 Results

The velocity was recorded for this firing on the Doppler radar at 429 m/s. The solid slug was retrieved 150mm into the boat buoyancy foam/linotex combination. The solid slug was undamaged by the capture system and very visible banding due to setting up was evident as seen in Figure 3.22 and Figure 3.23.

Figure 3.22: Solid slug retrieved from Plastozote and foam/Linotex

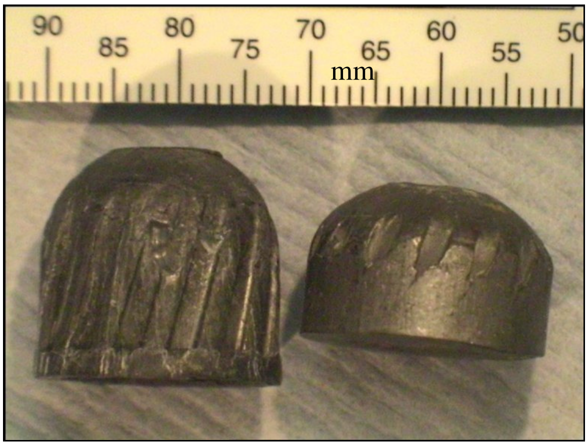


Figure 3.23 Solid slug before and after firing

The solid slug was replaced in the shot gun cartridge with a lead musket ball and the musket ball was fired into the same soft capture system.

The velocity of the musket ball was recorded at 417 m/s and the musket ball was found on the floor of the range, undamaged by the soft capture system. It had fallen out of the buoyancy foam/linotex when it all fell onto the floor on impact. It was estimated to have travelled 450 mm into the buoyancy/linotex laminate.

Setting up was clearly evident (Figure 3.24) and it was far greater than would be expected for a musket ball fired with black powder due to the increased pressures and pressure rise time generated by modern propellants. The rear of the musket ball had been pressed flat from the pressure behind the wad and the sides formed parallel to the barrel. However it demonstrated that this soft capture system worked.

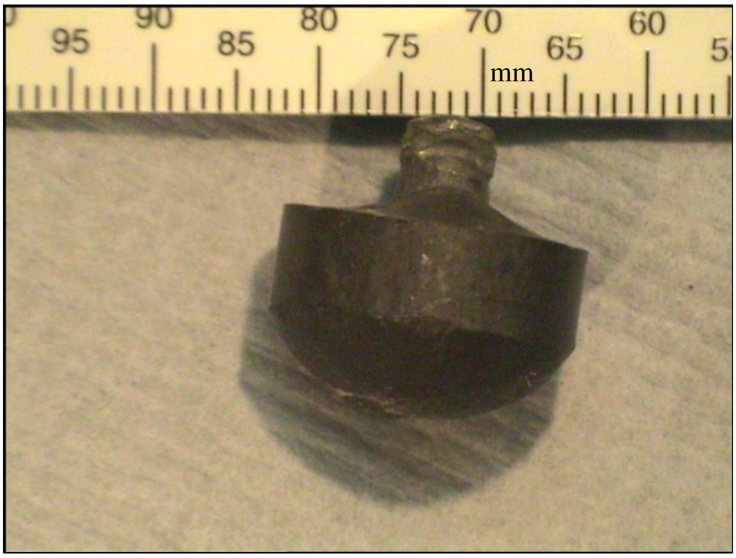


Fig.3.24 Musket ball fired from shot gun cartridge retrieved from soft capture

By introducing more sheets of Plastozote the buoyancy foam was eliminated from the soft capture system. Sheets of paper were introduced at regular distances between the plastazote panels to aid in the recovery of the musket ball which can be seen in Figure 3.25.

Figure 3.25: A typical retrieved musket ball that has successfully been captured by the soft capture system at 417 m/s using black powder

3.3.6.2 Depth of Penetration into Plastozote

The distance the musket ball travelled into the Plastazote was recorded to gather information about its rate of deceleration. The results are shown in Table 3.2.

Table 3.2: Velocity, distance travelled by musket ball into Plastozote and deceleration of the musket ball.

Velocity on impact (m/s)	**Distance travelled into Plastazote (m)**	**Deceleration (m/s)/m**
472	6	78.6
465	5.8	80.2
410	5.1	80.4
403	4.97	81.1
351	3.53	99.4
410	5.4	75.9

The results of Velocity and depth of penetration into the Plastozote were then plotted into the chart below-Figure 3.25. It showed a linear correlation

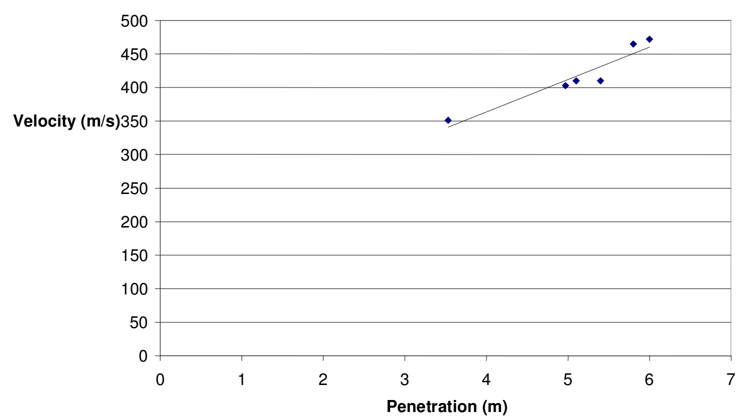


Figure 3.25: A graph showing the depth of penetration into Plastozote

The average musket ball deceleration was 82.6 m/s per metre, enough to avoid damage owing to its extreme softness.

Chapter 4: MUSKET TEST FIRINGS

4.1 Introduction

Having determined the most suitable soft capture method it was possible to conduct further trials to determine the effect of black powder composition, velocity, wadding and barrel diameter on the banding pattern of the musket ball. Details of the experimental setup, loading and soft capture methods can be seen in section 3.

4.2 Instrumentation

The following equipment was used in the trials:

Weibel W700 Doplar Radar

Kistler pressure measurement transducer type 6203

Charge amplifier type 5007

National Instruments data capture for computer

Plastozote (R) Lure foam, (See section 3. Soft Capture)

The test firings were carried out using a 48" long 10 bore musket barrel with an internal diameter 19.685 mm. The barrel was previously manufactured for experimentation by Eyes, (2006) and would therefore be beneficial in drawing comparisons between results. The barrel was chosen because its specifications matched those of the most commonly used muskets from the civil war period. 12 bore musket balls were manufactured for the tests with a diameter of 18.51mm nominal as they were the most commonly used calibre in the civil war.

The above instrumentation was used to record velocity and pressures for the following tests. A pressure transducer was screwed into the back of a specially manufactured breech block (Figure 4.1) and connected to a charge amplifier (Figure 4.2). The signal was then transferred to a pc via a data capture card.

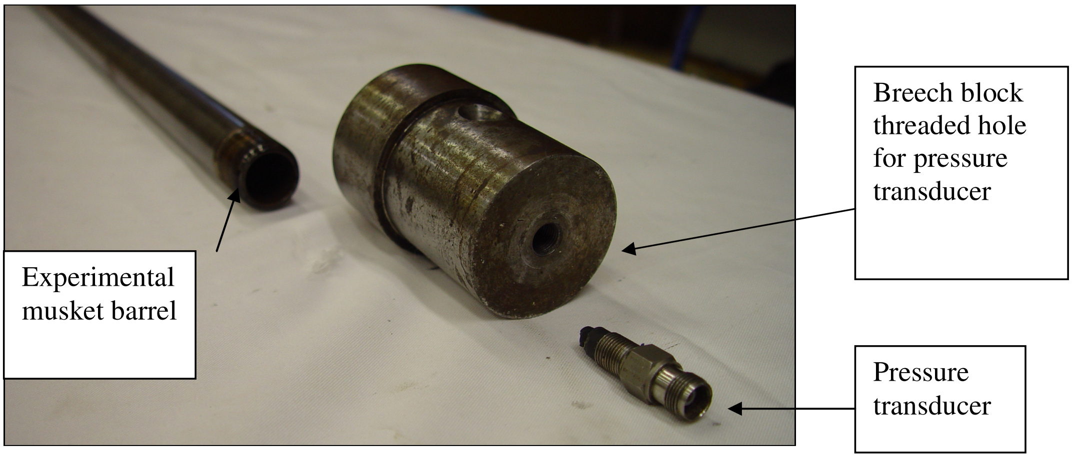


Figure 4.1- Showing the Kistler pressure transducer, breech block and barrel

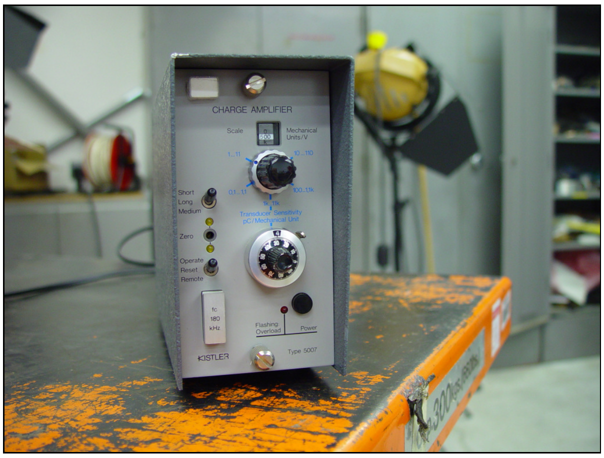


Figure 4.2 Charge amplifier

4.3 Black powder Selection

Tests were carried out to establish a comparison between three selected black powders to determine the best match of the 17th Century musket. As it is possible that wadding may have been used during the Civil War, tests were made both with and without a wad. The criteria for establishing the most appropriate powder was determined by the quantity required to obtain correct velocities without overpressure, but be able to generate enough pressure to produce the 'banding effects' seen on musket balls retrieved from the battle field. Based on the firings of soft capture tests an initial charge weight of 12.5 grams was used. A full set of results are listed in Appendix A.

Three available black powders with distinct differences were selected to establish the most suitable type. They were: Swiss No.1 a fast burning black powder, 3A a fine grained powder and G12 a course grained powder. Figure 4.3 shows the different available powders tested and Table 4.1 also shows the grain size of the powder type.

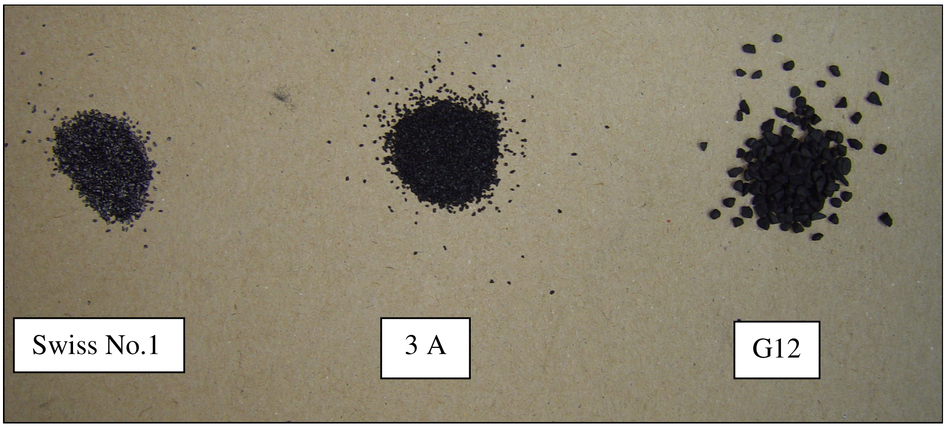


Figure 4.3: The three selected black powders

Table 4.1: Powder grain size

Powder	Grain Size (mm)
Swiss No. 1	0.226-0.508
3 A	0.25-0.5
G 12	1 - 2

Having determined that a charge weight of 12.5 grams would be suitable, it was necessary to determine the difference between the black powders at a given charge and then to determine whether there was any difference in the results when the wadding was removed. This was carried out using pressure time/plots.

4.4 Pressure Time Plots

The Charts below show the pressure/time plots recorded from the data capture computer obtained from the first set of results. The X axis reads the time in milliseconds and the Y axis the voltage produced from the charge amplifier. A Conversion factor Volts × 100 = the pressure in bar is used which is determined by the settings on the charge amplifier.

The peak pressure seen at the top of the curve is most useful for comparing the powder types. The rise time and fall times are signified by the slope of the curve and are also useful for determining the most suitable powder. The trigger value remained constant for all the firings.

4.5 Experimental Musket Trials with wadding

4.5.1 Powder type: 3A, Charge 12.5 grams, wadded

It can be seen from Figure 4.4 that the peak pressure was recorded at 2.278 Volts which can be converted to 228 Bar and that the peak pressure was recorded at 2.65 milliseconds from the trigger point.

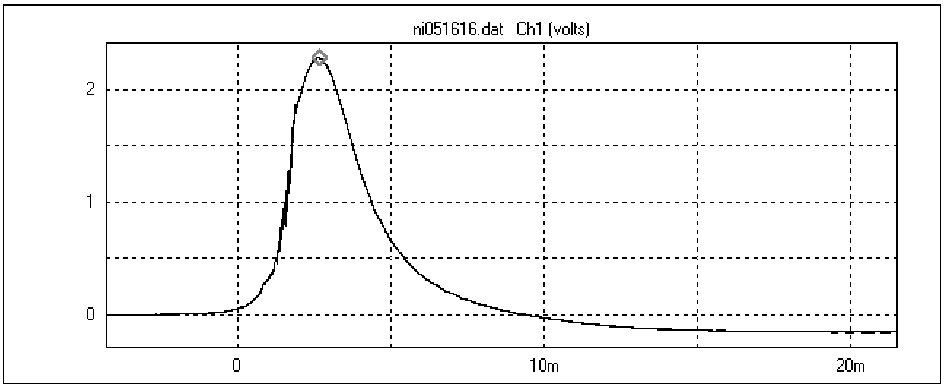


Figure 4.4: Pressure/Time plot for 3A powder type, with a 12.5grams charge and wadding

4.5.2 Powder type: G12, Charge 12.5 grams, wadded

It can be seen from Figure 4.5 that the peak pressure was recorded at 1.763 volts (176.3 Bar) and at 2.324 milliseconds from the trigger point.

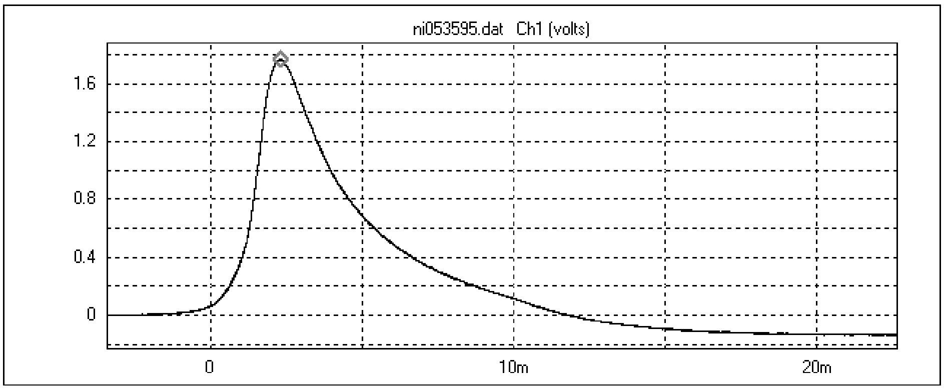


Figure 4.5: Pressure/Time plot for G12 powder type, with 12.5grams charge and wadding

4.5.3 Powder type: Swiss No.1, Charge 12.5 grams, wadded

It can be seen from Figure 4.6 that the peak pressure was recorded at 7.791 volts (779.1 Bar) and that the peak pressure was recorded at 7.62 μs from the trigger point.

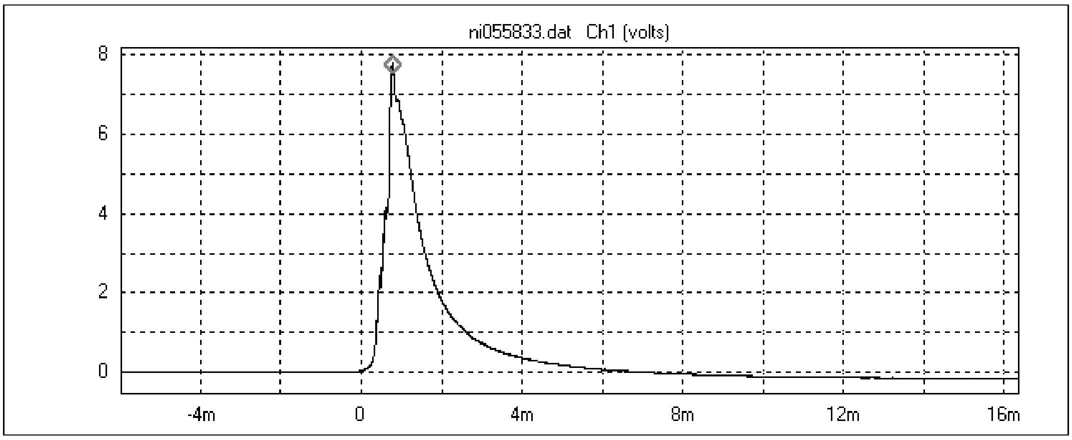


Figure 4.6: Pressure/Time plot for Swiss No.1 powder type, with 12.5grams charge and wadding

4.5.4 Comparative results of the three black powders

Table 4.2 compares three black powder types using 12.5 grams charge weight with wadding.

Table 4.2: Comparison of three types of black powder with wadding

Powder	Velocity (m/s)	Peak Pressure (Bar)
3A	417	227.8
G12	341	176.3
Swiss No.1	453	779.1

Figure 4.7: Retrieved Musket Ball from 12.5 grams of 3A with wadding

Figure 4.8: Retrieved Musket Ball from 12.5 grams of Swiss No.1 with wadding

Figure 4.9: Retrieved Musket Ball from 12.5 grams G12 with wadding

4.5.5 Discussion of Results for wadded trials

By examining the pressure / time graphs the Swiss Number 1 produced a very high pressure with a very fast rise time from the trigger point, which would be unsuitable for the musket as explained in Chapter 2; it could therefore be eliminated as a suitable powder. Swiss Number 1 also had too fast a burning rate. All retrieved musket balls showed visible banding. The Swiss No.1 also produced signs of melting around the banding circumference.

Comparative examination of the musket balls fired with G12 and 3A powders showed it was difficult to differentiate them by their physical appearance.

4.6 Experimental Musket Trials without wadding

The following Results are from firings using a charge of 12.5 grams without wadding.

4.6.1 Powder type: 3A, Charge 12.5 grams, no wadding

It can be seen from Figure 4.10 that the peak pressure was recorded at 2.684 volts (268.4) Bar and that the peak pressure was recorded at 1.86 milliseconds from the trigger point.

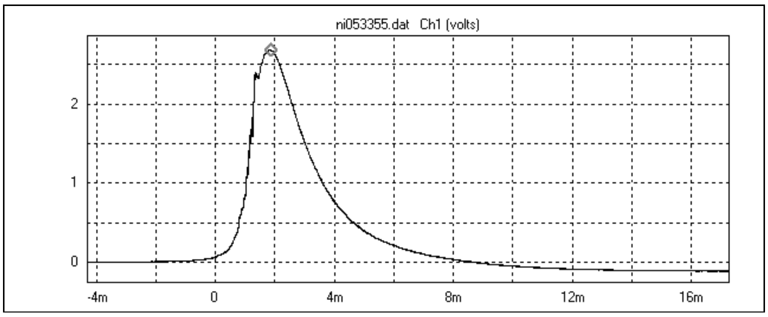


Figure 4.10: Pressure/Time plot for 3A powder type, with 12.5 grams charge with no wadding

4.6.2 Powder type: G12, Charge 12.5 grams, no wadding

It can be seen from Figure 4.11 that the peak pressure was recorded at 1.74 volts (174) Bar and that the peak pressure was recorded at 1.7 milliseconds from the trigger point.

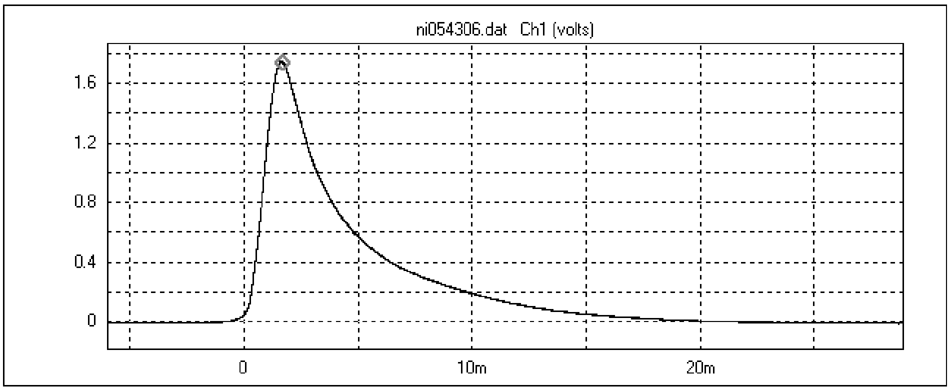


Figure 4.11: Pressure/Time plot for G12 powder type, with 12.5 grams charge with no wadding

4.6.3 Discussion of results for Unwadded trials

Table 4.3, shows the results from firings without wadding with 12.5 grams of black powder.

Table 4.3: Comparison of three types of black powder without wadding

Powder	Velocity (m/s)	Peak Pressure (Bar)
3A	388	268.46
G12	334	174
Swiss No.1	N/A	N/A

Figure 4.12: A retrieved musket ball from 12.5 grams, 3A No wadding

Figure 4.13: A retrieved musket ball from 12.5 grams, G12 No wadding

4.7 Discussion of Powder with and without wadding

Figure 4.14: A picture of a musket ball retrieved from the battle site at Edgehill (Photo from Foard, 2009) which is typical of the large number of musket balls recovered

The musket balls fired without a wad showed similar characteristics to those found on the Edgehill musket ball recovered from the Edgehill battlefield. For example, the pit marks produced from the burning propellant on the base of the projectile where as the wadded musket balls showed no sign of powder pitting. This would indicate from the test results that the Edgehill ball was fired without a wad.

Similar tests were carried out with varied charge weights. These results can be found in Appendix B.

From the Literature Survey the musket ball velocity for 17^{th} Century muskets was in the region of 400 m/s and the weight of propellant would have been approximately 18.6 grams. 18.6 grams of G12 powder produced 430 m/s (No Wad) where 14 grams of 3A produced 423 m/s (no wad). See appendix B. Either G12 or 3A would be suitable to simulate black powder from the 17^{th} Century as they both produced the correct banding on the musket ball. However the G12 velocity gave a closer match to the 17^{th} Century musket with 18 grams of powder and no wad. The pressure / time curve also showed a longer fall off for the G12. (20 milliseconds to return to zero pressure opposed to 8 milliseconds for the 3A). This means it is slower burning than 3A. The 17^{th} Century propellant is likely to be slower burning as it would most probably have been less refined than a modern powder.

4.8 Effect of Barrel Diameter

The following tests were carried out using 18 grams of G12 Powder as it was thought to be the best match to replicate the ballistics of a 17^{th} Century Musket. The nominal diameter for a 10 Bore is 19.685 mm however, this diameter was known to vary due to the manufacturing processes of the time. (see Literature survey).

To study the effects of different barrel diameter, two additional barrels were manufactured that were 48 inches long. One barrel had a bore diameter of 18.7 mm to recreate a very tight fitting musket ball while the other barrel had a bore diameter of 20.4 mm for a loose fitting musket ball. Trials were carried out firing a 12 bore ball of 18.51 mm diameter to investigate the effect of barrel bore diameter on musket ballistics. The results are shown in Tables 4.4 and 4.5 and 4.6.

Table 4.4: Results showing effect of barrel diameter on pressure and velocity of a 12 bore musket ball with 18grams of G12 black powder

Barrel Diameter (mm)	**Wad**	**Velocity (m/s)**	**Peak Pressure (bar)**	**Test Number**
19.49	No	410	269.5	Test 48
19.49	No	420	313.5	Test 49
19.49	No	410	240.2	Test 60
19.49	Yes	427	308	Test 50
19.49	Yes	431	330.7	Test 51
20.4	No	346	182	Test 52
20.4	No	351	203.4	Test 53
20.4	Yes	410	284	Test 54
20.4	Yes	403	283.4	Test 55
18.7	No	452	319	Test 56
18.7	No	465	403	Test 57
18.7	Yes	472	419	Test 58
18.7	Yes	459	393	Test 59

Table 4.5: Mean Velocities and Peak pressures calculated for Musket trials using 18 grams of G12 Black powder with different barrel diameters

Barrel Diameter (mm)	Mean Velocity No Wad. (m/s)	Mean Velocity Wad (m/s)	Velocity increase due to wad (%)	Peak Pressure No Wad (Bar)	Peak Pressure Wadded. (Bar)	Peak pressure increase due to wad (%)
19.49	413.3	429	3.87	273	327	19.78
20.4	349	407	16.62	205	283	38.29
18.7	459	466	1.53	361.5	406.15	12.35

- The mean percentage increase in velocity from all the three barrel sizes due to the use of a wad was 7.34%.
- The mean percentage increase in peak pressure from the three barrels due to the use of a wad was 23.4 %

Table 4.6: Percentage increase in velocity and pressure, when comparing the largest internal diameter barrel with the smallest

	20.4 mm Internal ∅ Barrel	18.7 mm Internal ∅ Barrel	Increase in *v* due to barrel size. (%)	Increase in *P* due to barrel size (%)
Velocity m/s (No Wad)	349	459	31.5	
Velocity Wadded (m/s)	407	466	14.49	
Peak Pressure No Wad.	205	361		76
Peak Pressure Wadded	283.5	406.15		43

4.8.1 Discussion of Results, (Barrel Diameter)

The use of a wad showed less effect on the velocity and peak pressure of the musket ball than the extremes of internal diameter on the barrel. Further data obtained from different barrel diameters with a charge of 14 grams of G12 are shown in the Table 4.7.

Table 4.7: Results showing effect of barrel diameter on pressure and velocity of a 12 bore musket ball with 14 grams G12

Barrel Diameter mm	**Charge G12 grams**	**Wad/No Wad**	**Velocity m/s**	**Ref.**
18.7	14	No Wad	406	T42
18.7	14	Wad	417	T43
20.4	14	No Wad	296	T44
20.4	14	Wad	367	T45

4.8.2 Summary of Results, (Barrel Diameter)

- For a constant charge weight of 14 grams G12 black powder it was found that there was a difference of 110 m/s without a wad between the smallest and largest bore diameter barrels.
- For a constant charge weight 14 grams of G12 black powder there was a difference of 50 m/s with a wad between the smallest and largest bore diameter barrels.
- The use of wadding showed a far greater effect when used with the large bore diameter barrel, increasing the velocity by 71 m/s.
- When using the small bore diameter barrel with a 14 gram G12 black powder charge, the wad increased the velocity by only 11 m/s.

4.8.3 Comparison of recovered musket balls

4.8.3.1 Physical appearance

The recovered musket balls were subjected to visual examination to establish whether any correlation could be found between the markings on the musket ball and the way in which it had been fired. The first comparison was made between the small and large diameter barrels as shown in Figures 4.15 and 4.16.

Figure 4.15: The recovered musket ball fired without a wad with 18 grams of G12 black powder from the 18.7 mm (small bore diameter) barrel

Figure 4.16: The recovered musket ball fired without a wad with 18 grams of G12 black powder from the 20.4 mm (large bore diameter) barrel

More visible banding was evident on the musket ball fired from the small bore diameter barrel (Figure 4.15). The musket ball fired from the large bore diameter barrel was visibly less deformed remaining fairly spherical (Figure 4.16).

The second comparison study was made between musket balls fired from the same barrel 19.49 mm bore diameter (standard size) with a small quantity of powder charge and large powder charge, seen in Figures 4.17 and 4.18.

Figure 4.17: The recovered musket ball fired without a wad with a charge of 14 grams of G12 black powder

Figure 4.18: The recovered musket ball fired without a wad with a charge of 37 grams of G12 black powder

More visible banding could be identified on the musket ball fired with 37 grams of G12 black powder (Figure 4.17) compared to the musket ball with 14 grams of G12 black powder (figure 4.16).

4.8.3.2 Weight loss of balls

All retrieved musket balls had a reduction in mass after firing and a small quantity of lead appeared to remain in the barrel after firing. Table 4.8 shows the average weight loss from the recovered musket balls after firing with 18 grams of G12 black powder both with and without wadding and with different internal barrel diameters.

Table 4.8: Average weight loss from musket balls after firing with a charge of 18 grams of G12 black powder

Powder Charge. (grams)	**Weight loss with wadding (grams)**	**Weight loss without wadding (grams)**	**Barrel size**
18	0.415	1.729	Large bore diameter.(20.4mm)
18	0.538	1.519	Standard 10 bore (19.49mm)
18	0.941	1.505	Small bore diameter (18.7mm)

Less weight was lost from the musket balls fired when using wadding, this was possibly due to less gas being able to escape past the musket ball. More weight was lost from the musket balls as the barrel diameter decreased when using a wad but the opposite occurred when no wadding was used.

4.8.3.3 Diameter Across Banding

The diameter across the banding of the fired musket balls was measured with vernier callipers, the diameter around the circumference varied so readings were taken at the largest and smallest diameter points and the mean value recorded. This value was subtracted from the original musket ball diameter to determine the change in size.

All the readings recorded a reduction in diameter across the banding. From the 18 grams of G12 black powder firings, the maximum reduction from the original musket ball diameter was 0.85 mm and the minimum reduction was 0.18 mm. The diameter reduction from the firings for the 14 grams G12 black powder charge weight showed a maximum of 0.39 mm and a minimum of 0.13 mm.

4.8.3.4 Barrel Fouling

Any large build up of debris left on the internal walls of the musket barrel after firing known as barrel fouling may have an effect on the ballistic properties of the musket ball as the internal diameter would be reduced. It could also cause loading problems if the clearance between the barrel and musket ball is too tight. Tests were carried out to observe the effects of barrel fouling.

The maximum number of consecutive shots without cleaning the barrel during experimentation was 10. The barrel internal diameter was 19.49 mm (10 bore) and the musket ball diameter was a nominal 18.51 mm (12 bore). The clearance was 0.95 mm.

With such a large clearance, the effect of barrel fouling was insignificant. The musket ball could always be slid into the barrel with ease for all ten shots fired. No substantial build up of residue was noted in the barrel. However, it is known that barrel fouling was a problem with 17th Century weapons (see Chapter 2), which is why they had such a large amount of clearance. It is highly likely that the 17th Century powder was not as refined as the powder used in this research and had greater amounts of contaminants compared to modern powders. A high speed Phantom camera was used at 40,000 frames per second to record large amounts of debris exiting the barrel as shown in Figure 4.19. It is not clear if this was debris from the previous shot being expelled or burning propellant grains, or a combination of both.

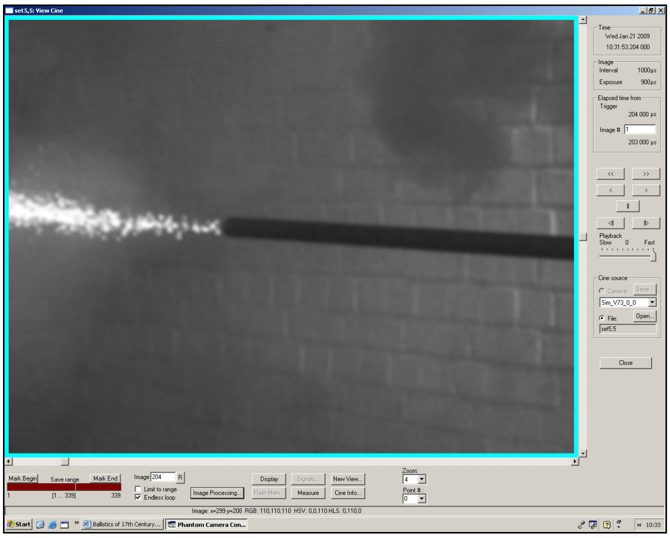


Figure 4.19: High speed video photography of debris leaving the muzzle from a 18.51 mm diameter (12 bore musket ball) fired with black powder from a 19.49 mm internal diameter (10 bore) musket barrel

A cloth was positioned a short distance from the musket barrel and used to capture the debris from a wadded musket ball firing. Another cloth was positioned similarly to capture the debris from a musket ball firing without wadding. The cloths were later analyzed under an electron microscope to try and establish what the debris contained. Both firings used 18 grams of G12 powder.

Lead particles were found, most being sub-micron with some a few microns in diameter. There were substantially more lead particles in the cloth from the firing without wadding most probably due to the wad acting as a barrier between the musket ball and the gases and the powder. It was not possible to establish whether the lead residue had melted before being deposited on the cloth or whether it had been mechanically removed from the musket ball. Also found were large amounts of total residue from both firings.

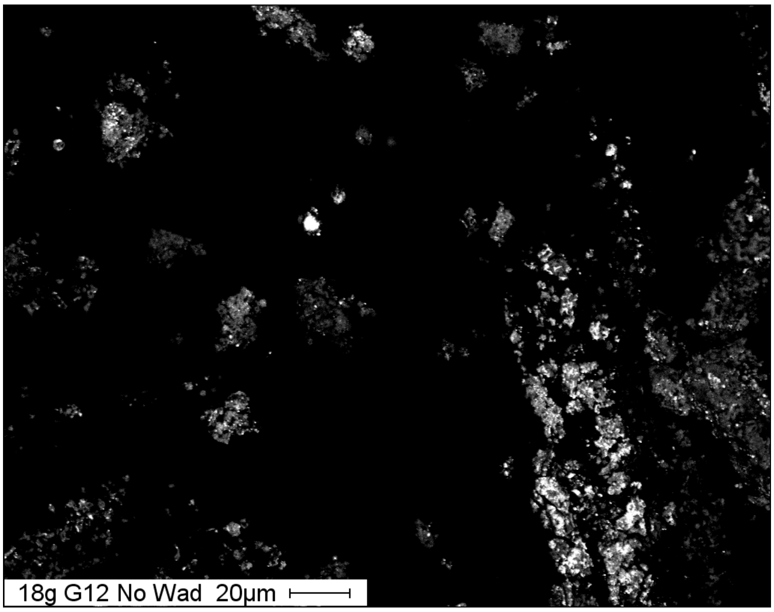


Figure 4.20: An image taken from the electron microscope of the firing without wadding. The lighter areas show the lead particles.

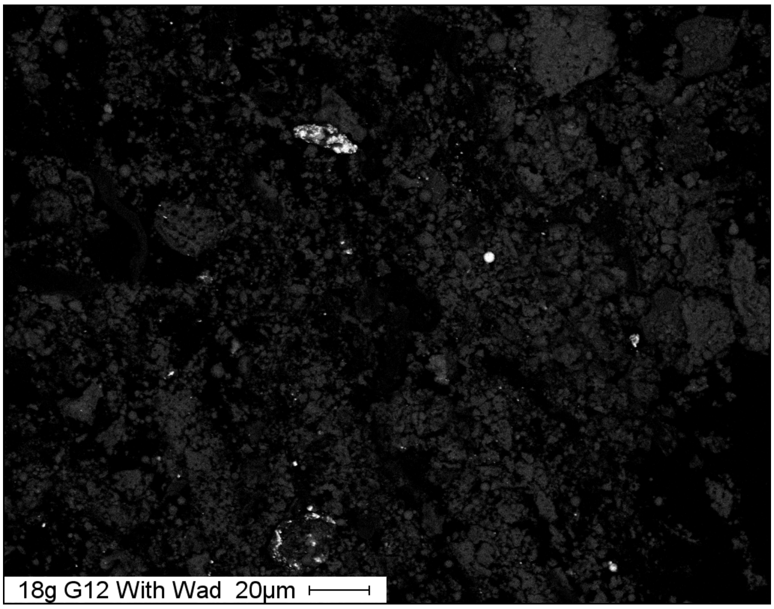


Figure 4.21: An image taken from the electron microscope of the firing with the wadding. The lighter areas show the lead particles.

4.9 The cause of the banding

The significance of 'banding' on the musket ball was an important factor for this research as its presence questions whether or not the ballistic properties were changed by its occurrence. Banding was also a characteristic that could be replicated with that of recovered 17th Century musket balls. For many years prior to electrical pressure transducers lead/copper crushers were used to measure pressures in firearms, as the soft malleable properties would deform proportionally to the pressure exerted upon them. Tests were carried out to try and establish what causes the banding.

Possible causes of banding are thought to be:

1. The pressure behind the musket ball pressing it against the internal wall of the barrel.
2. The passing of gases between the musket ball and the inner wall of the barrel.
3. Rubbing against the inner wall of the musket barrel as it is accelerated along the barrel.
4. A combination of all or some of the above.

The following experiment was carried out to determine whether escaping gases alone could cause banding, by preventing the musket ball from moving. The powder charge (5 grams of G12 black powder) and musket ball were loaded into the barrel without wadding, then a ram rod was inserted into the barrel until it came into contact with the musket ball. The other end of the ramrod was butted up against an 8mm plate of steel attached to a target frame which would prevent any forward motion of the musket ball when fired. Pressure was recorded at 383 Bar. The setup is shown in Figure 4.22.

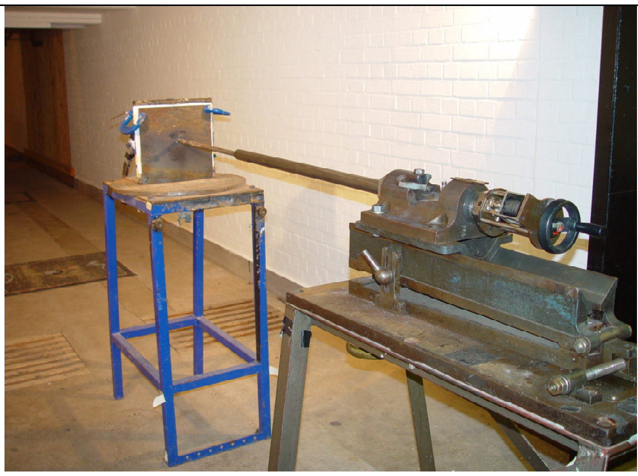


Figure 4.22: Arrangement used for investigating the effect of gas flow past the projectile by preventing movement of the musket ball by the use of a ram rod abutting against a fixed surface

4.91 Results of banding testing

After firing, the musket ball was removed from the barrel and examined. The result of the firing is shown in Figure 4.23.

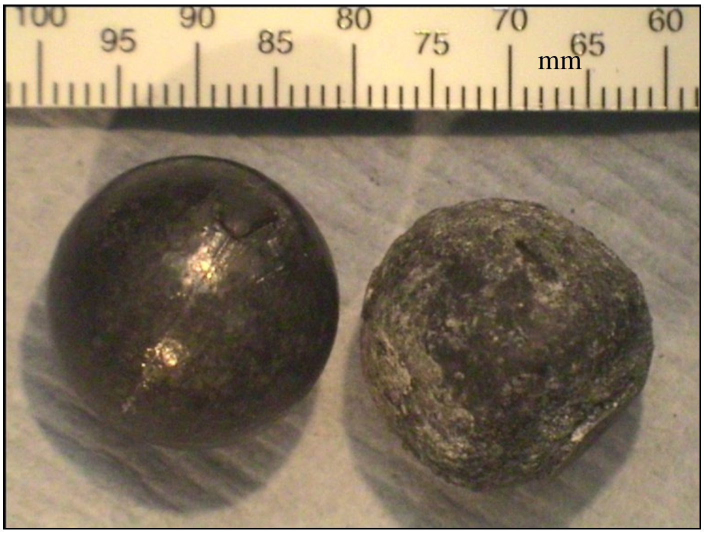


Figure 4.23: The musket ball before and after firing with 5 grams of G12 black powder and the movement of the musket ball prevented by a fixed ramrod.

Banding was clearly visible after firing. There were also pit marks from the powder and blackening. This would indicate that one cause of banding was due to the gases escaping past the musket ball. The peak pressure was 283 Bar which is similar to the pressure of an unrestricted musket ball exiting at 415 m/s with 18 grams of G12 black powder. There was a large weight loss from the musket ball (2.464 grams) and a small quantity of lead was left in the barrel.

Banding was also present from musket balls fired with wadding. This would have reduced the amount of gases escaping past the musket ball therefore it would seem likely that banding was also caused by the musket ball rubbing against the sides of the inner walls of the barrel. Increased pressures produced more banding, an extreme example of this is shown in chapter 3. It is most probable that a combination of these factors produce the banding marks seen on the musket ball.

Chapter 5: TRAJECTORY PREDICTIONS

5.1 Introduction

It is unknown whether the distorted shape of the musket ball will have an effect on its ballistic properties. The following predictions were calculated to compare against actual results from test firings carried out at Ashdown House. They were also used to determine the most influential variables that can affect the distance the musket ball travels such as velocity, height and angle of elevation. The predictions were calculated using a Trajectory Model generated in Excel as discussed in Chapter 2. The drag co-efficient used was that for a perfect sphere.

5.2 Methodology

The predictions shown in Table 5.1 are for a 18.51 mm diameter (12 bore) Musket Ball fired at a height of 1.39 metres with a horizontal trajectory parallel to the ground. This represents the same conditions as the actual experimental firings carried out at Ashdown Park. (The height of 1.39 metres was the mean height from ground to shoulder measured from a number of volunteers). The muzzle velocity was varied between 330 m/s and 490 m/s in 20 m/s increments (a spread of 160 m/s). The model was used to establish the predicted distance the musket ball would travel before impacting the ground and the velocity it would be travelling at upon impact. Figure 5.1 shows the results of muzzle velocity against impact distance plotted as a graph.

5.3 Results

Table 5.1: The predicted data for a 12 bore Musket Ball fired at different muzzle velocities at a height of 1.39 metres with a horizontal trajectory parallel to the ground

Velocity m/s	**Ground Impact Velocity m/s**	**Distance to Ground Impact. m**
330	214	146
350	219	154
370	224	160
390	228	166
410	232	171
430	236	177
450	239	182
470	241	187
490	244	191

Velocity Range = 330 to 490 = 160 m/s

Ground impact velocity spread = 214 m/s to 244 m/s = 30 m/s

Spread of Range (distance) = 146 m to 191 m = 45 m.

This equates to a 3.5 metre change in range per m/s.

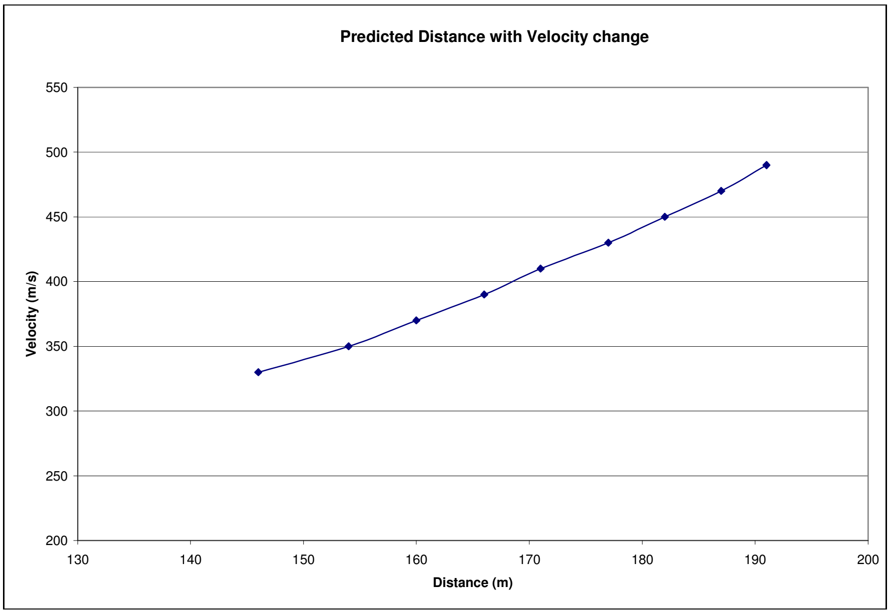


Figure 5.1: The predicted distances the musket ball would travel before impacting the ground against velocity

A musket ball is only effective when it can hit a man sized target. Table 5.2 illustrates the predicted distance a musket ball would travel before it would pass over the head of a six feet tall (1.83m) person when fired at 400 m/s at shoulder height at varying elevations. It also shows the musket ball velocity at ground impact and the distance it would travel before impacting the ground.

Table 5.2: The predicted distance a musket ball would travel before it would pass over the head of a six feet tall (1.83m) person when fired at 400 m/s at shoulder height at varying elevations

Elevation (Degrees)	**Distance travelled to height of 1.83 m (6 feet person) (m)**	**Velocity at Ground Impact (m/s)**	**Distance to Ground Impact (m)**
0		230	169
1	27	163.7	315.95
2	12.9	128.12	427.78
3	8.99	107.28	509.4
4	5.99	92.91	576.7
5	4.98	83.5	628.7
10	1.96	61	799
15	N/A	55.46	890.44
20	N/A	54.85	943.79
25	N/A	56	970.49
30	N/A	57.69	977.33
35	N/A	59.31	966.78

1° of elevation would miss a 6 foot person standing 27 metres away.

Increase in distance for 1 degree of elevation = 146 metres.

Increase in distance for 2 degrees of elevation =258.78 metres.

Increase in distance for 5 degrees of elevation =459.7 metres.

Maximum distance 977 metres with 30 degrees of elevation.

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Figure 5.2 shows the distance travelled by a 12 bore musket ball when fired at a muzzle velocity of 400 m/s at a height of 1.39 m above the ground for different launch angles to the ground

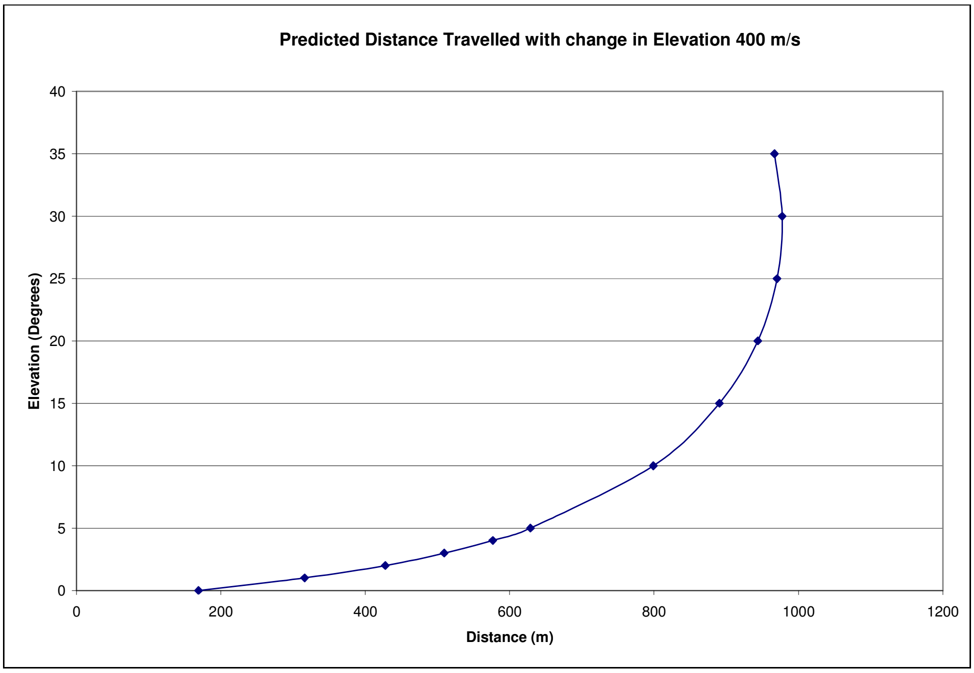

Figure 5.2: The predicted distance a musket ball would travel when fired from shoulder height (1.39 m) at 400 m/s with change in elevation.

It can be seen that the maximum distance travelled is 977 metres at an angle of 30° and that greater angles than this would result in a reduction in range.

Table 5.3 shows the predicted distance of impact and the impact velocity when firing a 18.51 mm diameter (12 bore) musket ball at a muzzle velocity of 400 m/s at a height of 1.39 m above the ground for different negative angles of elevation.

Table 5.3: Predicted distance of impact and the impact velocity when firing a 18.51 mm diameter (12 bore) musket ball at a muzzle velocity of 400 m/s at a height of 1.39 m above the ground for different negative angles of elevation.

Elevation (Degrees)	**Velocity at Ground Impact (m/s)**	**Distance to Ground Impact (m)**
-1	309	68.99
-2	345	37.98
-3	361	25.96
-4	370	18.95
-5	376	14.94
-6	379	12.93
-7	382	10.92
-8	385	8.91
-9	387	7.9
-10	389	6.89

Figure 5.3 shows the predicted distance to ground impact when firing a 18.51 mm diameter (12 bore) musket ball at a muzzle velocity of 400 m/s at a height of 1.39 m above the ground for different negative angles of elevation.

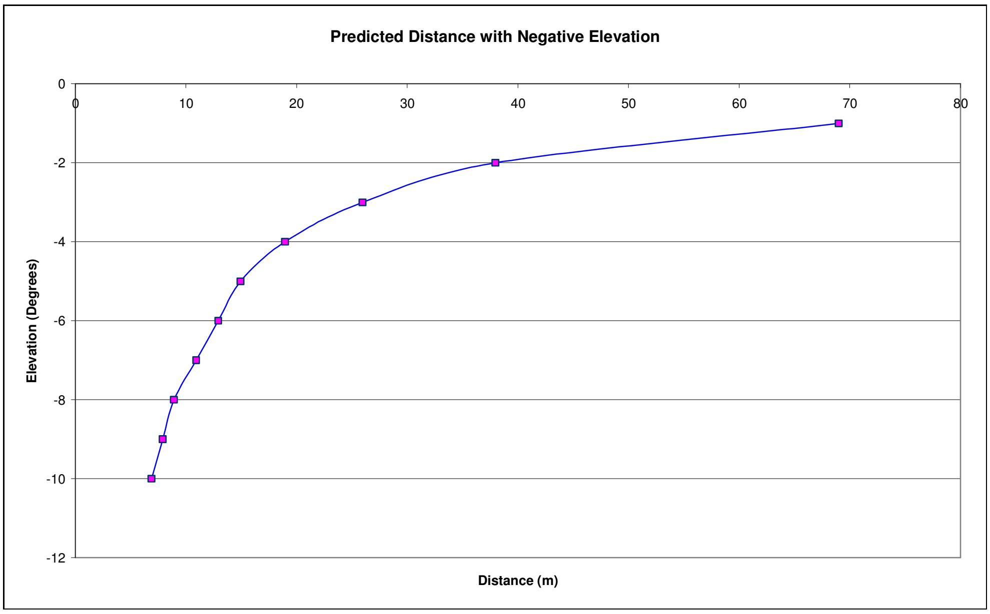

Figure 5.3: Predicted distance to ground impact when firing a 18.51mm diameter (12 bore) musket ball at a muzzle velocity of 400 m/s at a height of 1.39 m above the ground for different negative angles of elevation.

The distance travelled by a musket ball when fired parallel to the ground will vary depending on the height above the ground at which the musket was fired. The maximum height will depend upon the height to the shoulder when firer is standing and the minimum practical height will be for when the firer is kneeling. Table 5.4 shows the predicted effect of firing a 18.51 mm diameter (12 bore) musket ball at a muzzle velocity of 400 m/s parallel to the ground and at different heights on the distance to impact with the ground and the impact velocity. Figure 5.4 shows a graph of the predicted effect of firing a 18.51mm diameter (12 bore) musket ball at a muzzle velocity of 400 m/s parallel to the ground and at different heights on the distance to impact.

Table 5.4: Predicted effect of firing a 18.51 mm diameter (12 bore) musket ball at a muzzle velocity of 400 m/s parallel to the ground and at heights of 0.9 m (a kneeling man) to 1.7m (a tall standing man) on the distance to impact with the ground and the impact velocity.

Height (m)	**Velocity at Ground Impact (m/s)**	**Distance (m)**
1.7	222	182.99
1.5	227.8	173.99
1.3	233.2	163.99
1.1	240.17	152.97
0.9	248	139.99

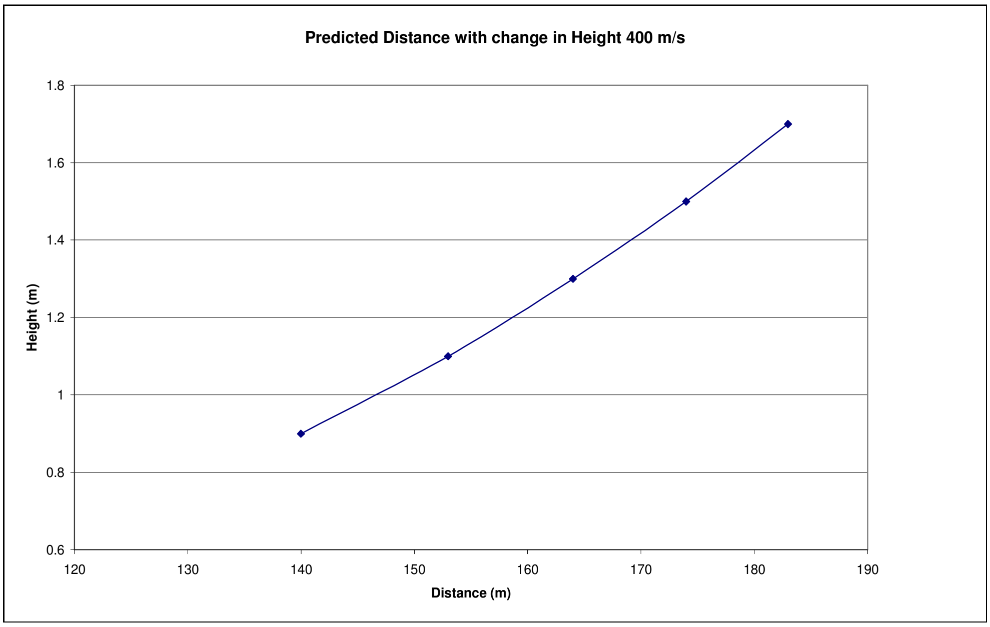

Figure 5.4: Predicted effect of firing a 18.51mm diameter (12 bore) musket ball at a muzzle velocity of 400 m/s parallel to the ground and at different heights on the distance to impact.

It can be seen that extremes in height 1.7 m to 0.9 m (kneeling) produce a spread of 43 m from182.99 m to 139.99 m.

If a musket was fired at a positive angle of elevation relative to the ground the musket ball would rise until it reached its maximum height and then fall until it impacted the ground. This is shown in Figure 5.5 which is the trajectory diagram for a 18.51 mm diameter (12 bore) musket ball with a muzzle velocity of 400 m/s fired at 1.39 m above the ground and at an angle of 5 degrees.

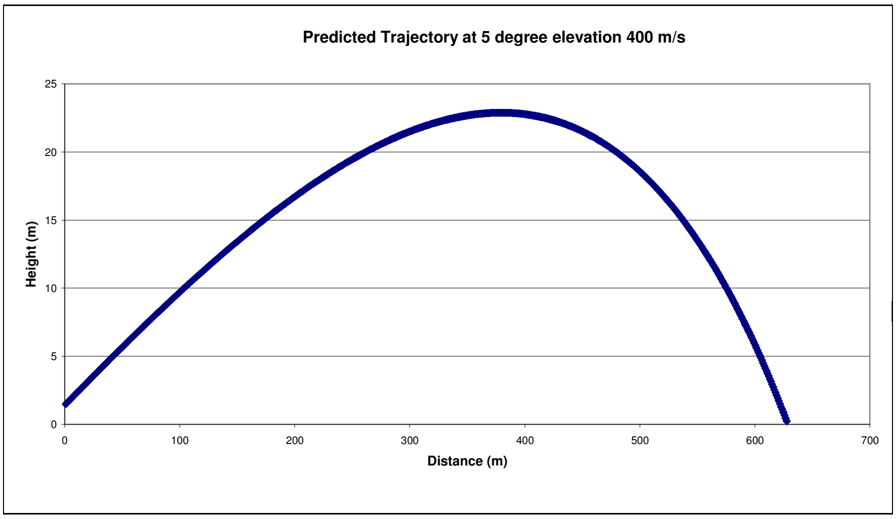

Figure 5.5: Trajectory diagram for a 18.51 mm (12 bore) musket ball with a muzzle velocity of 400 m/s fired at 1.39 m above the ground and at an angle of 5 degrees.

From Figure 5.5 it can be seen that if the musket was fired at a 5 degree angle it would pass over the head of a 6 feet (1.83 m) person at a distance of 5 m and would only become effective again after 620 m (1.9 m high) shortly before ground impact at 629 m.

5.4 Discussion

Small changes in elevation have far more influence on the distance a musket ball travels before impacting the ground than changes in height or velocity due to firing. A number of factors affect velocity loss with range and therefore range to ground impact.

Maximum range if fired in a vacuum is given by:

$$R = \frac{V^2}{g}\sin(2\theta) \qquad (5.1)$$

$$\text{For } 45° \text{ Sin } 2\theta = 1 \therefore R = \frac{v^2}{g} = \frac{400^2}{g} = 16300m \qquad (5.2)$$

It can be seen that aerodynamic drag therefore has a considerable effect on the maximum range due to the velocity loss with range.

Velocity loss with range is given by:

$$\frac{\Delta V}{\Delta S} = \frac{Cd.2m.\rho}{V.A} \qquad (5.3)$$

Where V= Velocity

m= Mass

ρ = Density of air

A= Cross sectional area of the projectile.

Cd= Drag coefficient.

$\frac{\Delta V}{\Delta S}$ is directly proportional to mass. The mass loss of the musket ball is small, approximately 1.5 grams. If the mass of a projectile is reduced by 1 gram the range to ground impact is reduced by 1m.

The Drag Coefficient (Cd) is dependant on the shape of the projectile and although distortion in the barrel during firing occurs the change in shape is negligible. A 10% increase in drag coefficient will only reduce the range by 3 metres. Distortion of the musket ball will also increase the cross sectional area but again this effect will be small. A 10% increase in cross sectional area will reduce the range by 3 m/s. Thus it can be seen that changes in the musket ball due to the firing process will have a small effect on the range of the musket ball fired from the shoulder parallel to the ground.

5.4.1 Angle of Elevation

A simple experiment was undertaken to observe angles of elevation on a musket barrel. This would be useful in determining the likelihood of what angles of deviation from the horizontal might occur when the musket was fired. The barrel was placed in the proof housing and a target positioned 5 metres away. This is shown in Figure 5.6 below.

Figure 5.6: Proof mount with target showing elevation of the barrel

The barrel was first positioned horizontally using a spirit level and a laser sight was used to spot a position on the target. Trigonometry was then used to calculate the distance from this mark to measure 1 degree steps on the target. A levelled camera mounted on a tripod recorded the image of the barrel at the elevations. A horizontal line of tape was positioned on the rear wall to act as a reference. The results are shown in Figure 5.7.

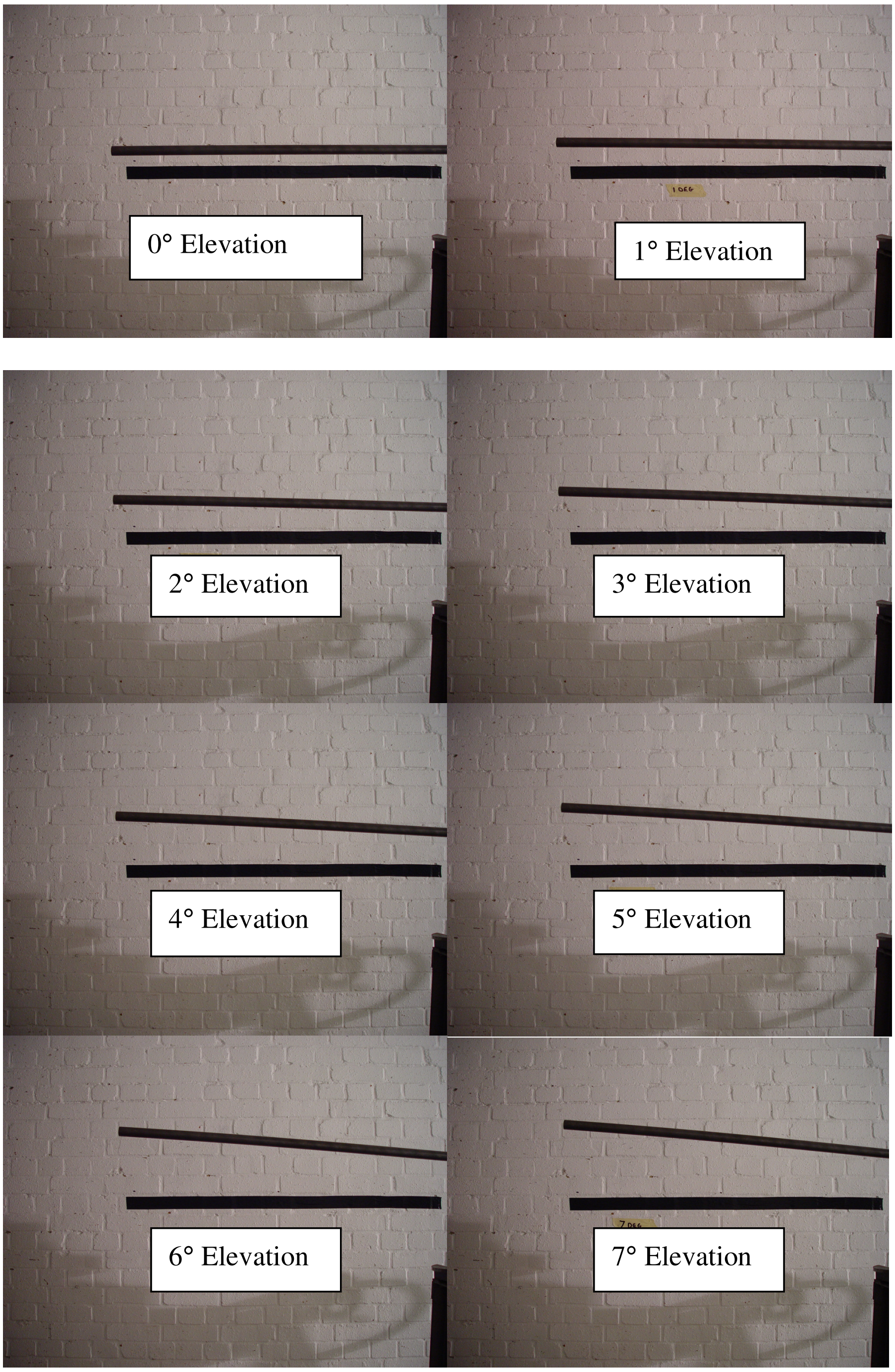

Figure 5.7: Photographs showing levels of barrel elevation

It can be seen from the above pictures that an angle as small as one degree is quite apparent to the human eye and that an elevation greater than 7°, even in the most inexperienced hands, would be unlikely.

Figure 5.8: Impact positions from varying degrees of elevation upon a Figure 11 target placed five metres away from the muzzle

5.5 Conclusions

The predictions show that the most influential factor in determining the distance a musket ball will travel to the point of ground impact is the angle of elevation. If it varies from between 0° to 5° then the range varies from 169 m to 629 m, a variation of 460 m. The velocity of the musket ball impacting the ground at 0° elevation was predicted to be 230 m/s. The velocity of the musket ball impacting the ground at 5° was 83.5 m/s. The slower velocity at impact combined with a steeper angle of descent will greatly reduce the distance of bounce and roll after impact with the ground. Thus variations in elevation will have a smaller effect on the total distance travelled by the musket ball than would be implied if only the distance to the impact point with the ground was considered.

Chapter 6: PREDICTIONS FOR BOUNCE AND ROLL.

6.1 Introduction

On impacting the ground the musket ball will still be travelling at a considerable velocity. Depending on the ground conditions it will then skid, bounce and roll a number of times until all of its energy is used up at which point it will come to a final resting position. It is this final resting position at which fired musket balls are normally found on the battle field. The distance that musket balls bounce and roll, as well as the distance that a musket ball travels from muzzle to ground impact, is therefore of high importance to any work interpreting where musket balls may have been fired from on the battle field.

6.2 Results

Work on the bounce and roll of masonry debris was carried out by Knock (2004). The aim was to develop a modelling programme to study what happens at the first impact of the debris with the ground. Three levels of ground hardness were created using clay. Both spherical and angular projectiles were used. It was concluded that a rigid body model could not be applied to the collected experimental data as there was no consistency in the values of the coefficients of restitution and the friction obtained from the data. Instead it was found that the impact could be successfully modelled using simple empirical equations relating the ratio of the reflected velocity to the impact velocity to the impact angle and the change in angle of flight to the impact angle. Cubes and spheres gave very similar results; the cubes losing slightly more velocity on impact than the spheres. An analysis of the rotational data showed that the post impact rotation rate was difficult to predict. The results also suggest that after impact, the spin rate will be high enough for the Magnus effect to be significant.

The programme model required the following data:

The velocity immediately before and after ground impact and the entry and exit angles before and after ground impact. From a series of bounce and roll trials carried out using 18.51 mm diameter (12 bore) musket balls (Section 7.2.5), only shots A3 and A6 had all data for the modelling programme. The velocities before and after impact were obtained from the Doppler radar trace. They are tabulated in Table 6.1.

Table 6.1: Experimental data for using prediction model

Shot number.	V1	V2
A3	239	152
A6	289	217

Paper witness screens were used at intervals down range to record the trajectories of musket balls before and after their impact with the ground. By using the coordinates from the witness screens directly before and after the first ground impact, the angle that the musket ball impacted the ground at and the angle it exited the ground after skidding was calculated using trigonometry. The pre and post impact velocities and the length of the skid on the ground are given in Table 6.2.

Table 6.2: Impact and exit angles with skid length for the shots with usable data.

Shot Number	Entry angle (degrees)	Exit Angle (degrees)	Skid length (m)
A3	2.29	1.80	3
A6	1.03	1.96	4

The trajectory prediction model calculated the angle at impact to be 1.10° for a musket ball fired at 420 m/s on a flat trajectory at a height of 1.39 m. The required data was entered into the bounce and roll prediction model but unfortunately, the results were totally different to the recorded results. A possible explanation for this was that the model was designed for large objects travelling at slow velocities. Further work to the modelling programme using new data would be required to use the model successfully.

Although the data used did not give meaningful results for the modelling programme it is useful for observing energy values from the firings. Results from long range trials established the velocity loss of the musket ball impacting the ground at 239 m/s skidded for 3 m and exited at 152 m/s, a loss of 87 m/s and a decrease in velocity of 36%. This equates to an energy loss of 630 joules which is 59.6% of the impact energy. The impact angle was 2.29 degrees.

Chapter 7: LONG DISTANCE FIRINGS-ASHDOWN HOUSE

7.1: First Long Range Firing Trials (0ctober 2007)

In Chapter 6, the trajectory of a projectile, (external ballistics) were studied. The distance from the fired weapon to the point at which it first impacted the ground was considered. A simple trajectory model was used but this was dependent on the use of a drag coefficient (Cd) for a perfect sphere. However, it is known that the soft musket ball is modified in shape in the barrel which may affect the trajectory. Trials were carried out to examine the distance travelled by a musket ball from the muzzle to the point that it impacts the ground and to compare this with the predicted values. Two shots using steel ball bearings were also fired to compare results with those of a projectile that would not be modified in shape.

The musket balls found on a battlefield are not at the position where they impacted the ground because upon impact they bounce and roll. These tests were also designed to capture data on the distance that the musket balls bounced and rolled and also the variation in these values on a shot to shot basis.

All the trials were fired along the main grass ride at Ashdown wood. This ride was 18 m wide and 1500 m long. The ride is almost flat for the first 300 m and is almost completely free of metallic debris, a requirement for finding the musket balls post firing using a metal detector.

7.1.1 Setup

The musket barrel was mounted in a number 3 housing as described in Chapter 3, Soft Capture of musket balls. The number 3 housing was attached to a modified light weight car trailer. All firings were conducted with the barrel set using a spirit level to zero elevation. The angle of elevation of the barrel was adjusted by means of an adjustable jockey wheel fitted to the trailer tow bar. The height of the barrel was 1.39 m above the ground. The height of 1.39 m was the mean figure taken by measuring from ground to shoulder for a number of volunteers (this being pre-determined by the firing rig manufactured for experimental research in collaboration with the Battlefields Trust (Pollard, 2008). The horizontal position was sighted to the 20 m target by looking along the barrel. The ground surface was near level. The grass length was approximately 30mm and the soil was damp. There was virtually no wind present (calm). To measure impact positions cartridge paper witness screens were used, these witness screens were placed at 20 m intervals from the gun to a total of 200 m. An optical level as shown in Figure 7.7 was used to mark the witness screens with a 0,0 coordinate at 1.39 m high and centred to enable drop and sideways movement to be measured. A Weibel Doppler radar model W700 was used to record the velocities and was powered by a portable generator. A metal detector was used to find the musket balls after firing. The musket balls were marked for later identification with a letter stamp.

Ground hardness was measured with a Cone Penetrometer. This is an instrument suitable for use in soft soils such as clay loam and silt. Its primary use is for ascertaining the ground hardness suitability for military vehicles and aircraft. It was used in accordance with the user hand book. The higher values relate to higher ground hardness, for example a cone index (C I) range of 80 to 99 is suitable for rear wheel drive vehicles intended primarily for highway use.

Musket ball recovery was by metal detecting as the musket balls could not be found by visual searching due to the length of the grass. Searching beyond the 18 m width was not possible due to shrub and tree cover. Figure 7.1 shows the view along Ashdown main ride showing the witness sheets at 20 m intervals to a distance of 200 m and with the number 3 housing mounted on the light weight trailer and Doppler radar antenna for measuring projectile velocity.

Figure 7.1: The view along Ashdown main ride showing the witness sheets at 20 m intervals to a distance of 200 m and with the number 3 housing and Doppler radar antenna for measuring projectile velocity

7.1.2 Results

The muzzle velocities of each firing, the position of the musket ball travelling through the witness screens, the impact distance and the final resting position are given in Table 7.1

Table 7.1: The muzzle velocities of each firing, the position of the musket ball travelling through the witness screens, the impact distance and the final resting position for the six shots fired.

Distance From Muzzle, m	**X and Y coordinates of impact on witness sheet, mm**					
	Shot 1 410 m/s muzzle velocity	**Shot 2 361 m/s muzzle velocity**	**Shot 3 298 m/s muzzle velocity**	**Shot 4 438 m/s muzzle velocity**	**Shot 5* 326 m/s muzzle velocity**	**Shot 6* 486 m/s muzzle velocity**
20	X 64, Y -135	X 100, Y -65	X 35, Y -45	X 160, Y -76	X 113, Y -65	X 2, Y -67
40	X -27, Y -200	X 8, Y -82	X -34, Y -71	X 184, Y-110	X 127, Y -144	X -172,Y -62
60	X -145, Y -292	X -107, Y -153	X -87, Y -192	X 212, Y -220	X 190, Y 46	X -400 Y -96
80	X -280, Y -390	X -273, Y -295	X -140, Y -460	X 245, Y -370	X 323, Y 219	Missed witness sheet
100	X -411, Y -460	X -412, Y -465	X -215, Y -864	X 230, Y -581	Missed witness sheet	Missed witness sheet
120	X -437, Y -550	Missed witness sheet	Ground impact 115 m	X 215, Y -855	Missed witness sheet	Missed witness sheet
140	X -388, Y -625	Missed witness sheet		X 162, Y 1198 Ground impact 146m	Missed witness sheet	Missed witness sheet
160	X -261, Y -740	Missed witness sheet	Missed witness sheet after impact Reading taken After impact @146m	X 110, Y 1000	Missed witness sheet	Missed witness sheet
180	X -8, Y -937	Missed witness sheet	Missed witness sheet	Missed witness sheet	Missed witness sheet	Missed witness sheet
200	X 313, Y -1240	Missed witness sheet	Missed witness sheet	Missed witness sheet	Missed witness sheet	Missed witness sheet
	Ground impact 213 m					
Final Position	288m 2.3m right	Not found	323m 5.7m left	310m 2.5m right	Not found	Not found

* = 19mm steel ball bearings

7.1.3 Comparison of valid shots

The results in Table 7.1 are incomplete because the width of the paper witness sheets were 1.2 m and this was not always sufficient due to the large deviations in the directions of the musket ball in flight and after impact. Their height was also limited to 2m and some musket balls passed over the top. Also, the working width of the firing range was only 18 m and at the longer ranges the deviation of some of the musket balls were such that they could not be contained within this width. Additionally, the witness sheet screens were made of steel tubing and some of the musket balls struck them, especially the base cross members.

Table 7.2 shows the muzzle velocity distance to impact and the maximum distance travelled by the musket ball for shots 1, 3 and 4 (the shots for which the data was recorded)

Table 7.2: Muzzle velocity, distance to ground impact and final resting position for shots 1, 3 and 4

Shot No.	**Muzzle Velocity (m/s)**	**Distance to ground impact (m)**	**Distance to final resting point (m)**
1	410	213	288
3	298	115	323
4	438	146	310

Shots 1 and 4 had muzzle velocities of 410 m/s and 438 m/s, a velocity spread of 28 m/s, the distance travelled before ground impact varied from 213 m (shot 1) to 146 m (shot 4) the reason for such a large variation was due to the way in which the two shots differed in their trajectories. This can be seen from Figure 7.2 which shows the predicted trajectory of the musket ball and the actual trajectory as recorded by the paper witness sheets for shots 1 and 4.

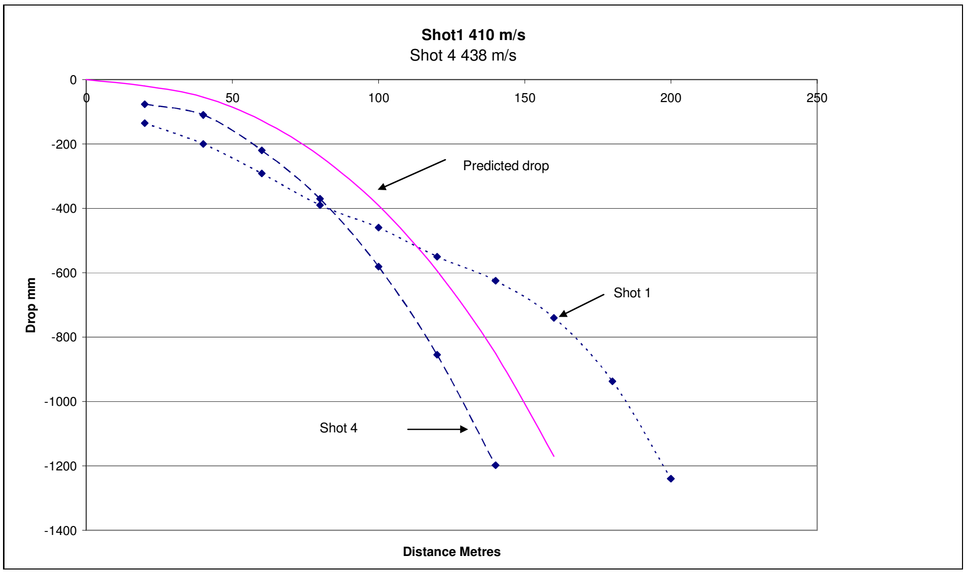

Figure 7.2: Recorded trajectory for shots 1 and 4 and for the predicted trajectory

.

It can be seen that shot 4 has a similar trajectory characteristic as the theoretical curve. However, the trajectory for shot 1 has a very different characteristic to the predicted curve. There should be very little deviation of the path of the musket ball from that of a straight line in the horizontal plane (plan view) but Figure 7.3 shows that this is not the case for shot number 1. It can be seen that in the horizontal plane the musket ball moves to the left during the first 100 m of its flight. It then starts to move back towards the centre and crosses the centre line at about 180 m. If the movements of the musket ball from shot number 1 in the vertical and horizontal planes are combined it can be seen that the musket ball from shot no 1 is cork screwing as it is passing down range.

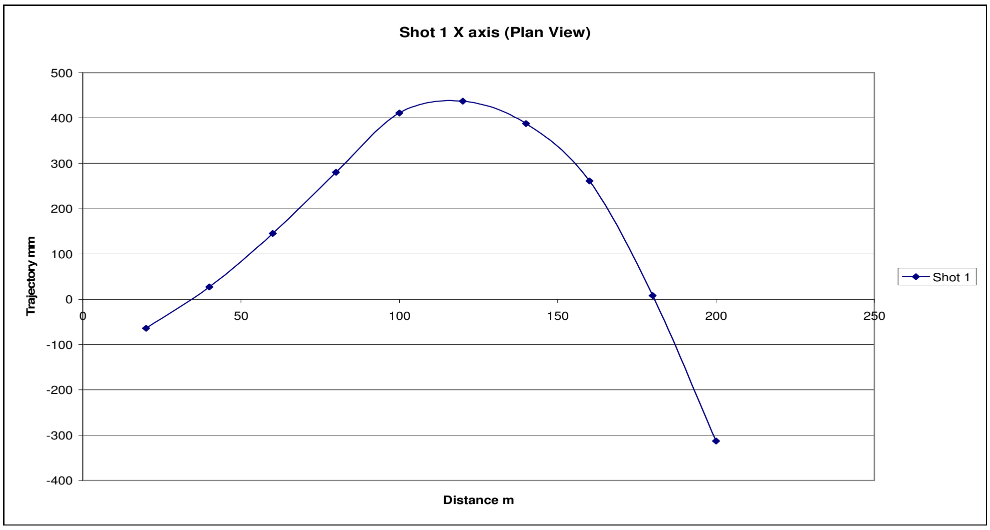

Figure 7.3: A plan view of the trajectory path of shot 1

The trajectories for all six shots are plotted in Figure 7.4 (vertical plane) and Figure 7.5 (horizontal plane).

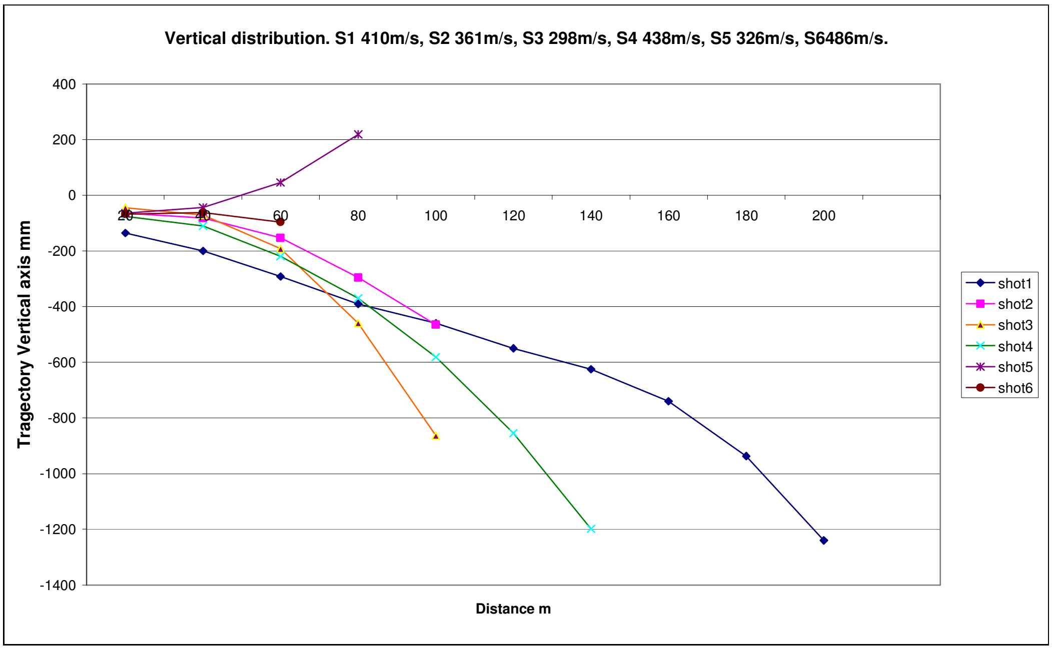

Figure 7.4: The path of all the shots from 1 to 6 in the vertical plane

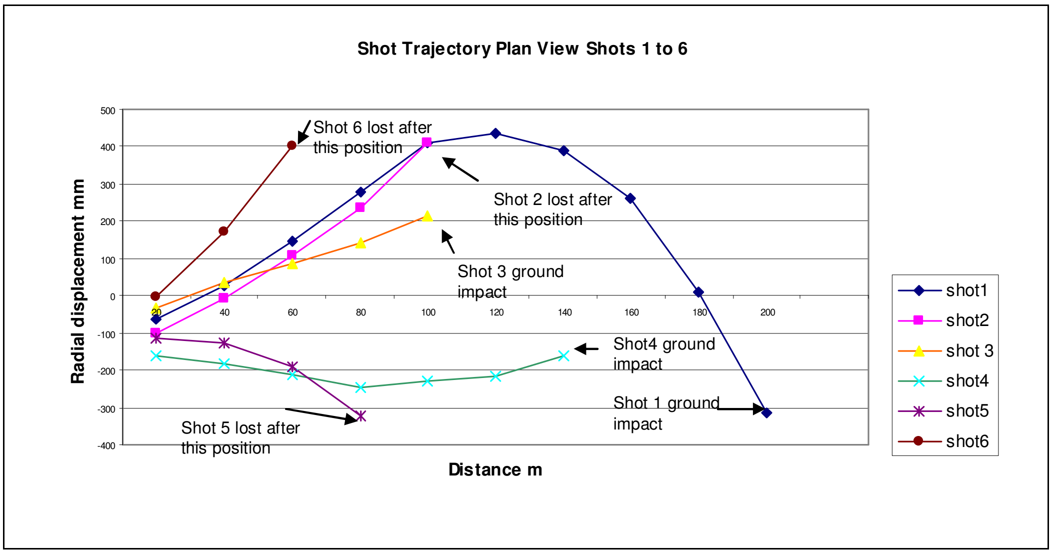

Figure 7.5: The trajectory plan view of shots from 1to 6 in the vertical plane

It can be seen from Figures 7.4 and 7.5 that all of the musket balls showed characteristics similar to those of shot number 1 as they did not travel in a perfectly straight line. It can also be seen that the two steel ball bearings (shots 5 and 6) had the greatest deviation from that of a straight line.

7.1.4 Musket Ball final Resting Positions

Figure 7.6 is the horizontal trajectory (plan view) and shows the first impact position and final position (maximum distance travelled) for shots number 1, 3 and 4 (the only shots for which the musket ball was found).

Dispersion mm

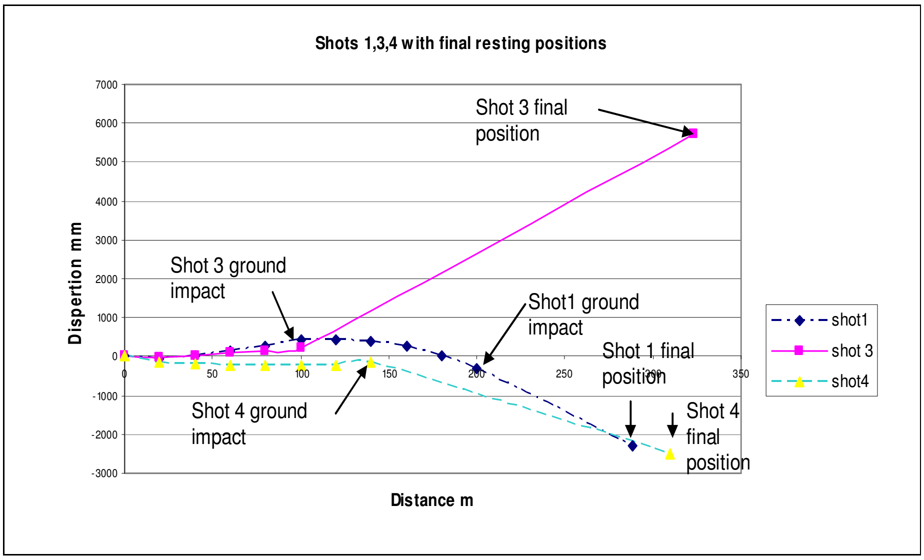

Figure 7.6: The horizontal trajectory (plan view) and showing the impact position and final position (maximum distance travelled) for shots number 1, 3 and 4

7.2 Second Long Range Firing Trials (May 2008)

For this trial the propellant charge weight used for all firings was 18 grams of G12 black powder. Three different barrel bore diameters were used to investigate the effect of barrel bore diameter on the trajectory and maximum distance travelled by the musket ball.

Shots A1 to A5 used a 48 inch barrel internal diameter 19.49 mm (10 bore).

Shots A6 and A7 used a 48 inch barrel reduced internal diameter 18.7 mm.

Shots A8 and A9 used a 48 inch barrel enlarged internal diameter 20.4 mm.

All musket balls were identification marked with a number stamped into their surface. A thin coating of white paint applied to them to increase their visibility on the field after firing. They were also weighed and measured. The data is tabulated in Appendix D.

7.2.1 Experimental Setup

The musket barrel and fixed number 3 housing were mounted to a scissor jack table. The firings were on a flat trajectory checked with a spirit level and the barrel height was 1.39 m. The horizontal position was sighted to an aiming cross on the first witness screen using a telescopic sight attached to the barrel. The first witness screen was placed 50 m from the muzzle. Seven further witness screens were placed at intervals of 30 m to a total of 260 m then a further two sets of screens set at 20 m intervals to a total of 300 m. The screens were made wider as the distance increased to help capture the results from the musket ball. An optical level set at the same height as the gun barrel was used to give the zero point on each witness sheet and the witness screens were marked with a 0,0 coordinate to enable drop and sideways movement to be measured. Average ground hardness was measured at 195 CI. (California Bearing Ratio CBR 9). The wind was calm. A Doppler radar was used to record the musket ball velocities and a metal detector used to find the musket balls after firing. A photograph of the setup can be seen in Figure 7.7. The weapon was re-zeroed onto the 0,0 coordinates on the first witness sheet at 50 m before each shot was fired.

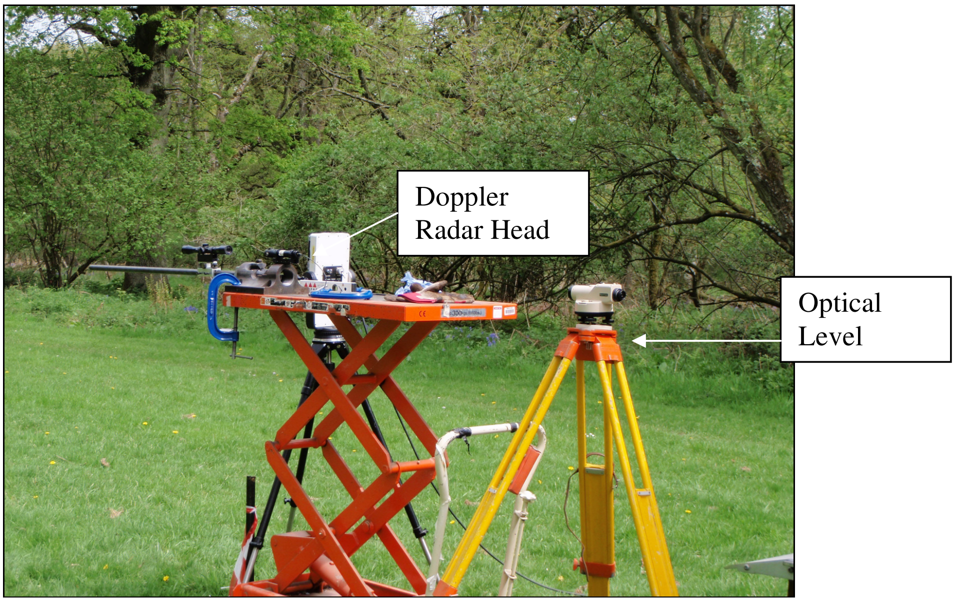

Figure 7.7: The Gun Barrel and No.3 housing clamped to the scissor lift table. Behind it is the optical level mounted on a tripod. The Doppler Radar Head can also be seen behind the table

7.2.2 Results A1-A5 (19.49 mm bore Barrel)

The X and Y coordinates from the witness screens were measured both before and after ground impact after each shot was fired. Data on the number of bounces and height of the bounces of the musket balls could then be recorded for analysis as well as the trajectories.

Figure 7.8 shows the witness sheet at 110 m from the muzzle and the impacts of the musket balls from shots A1 to A5

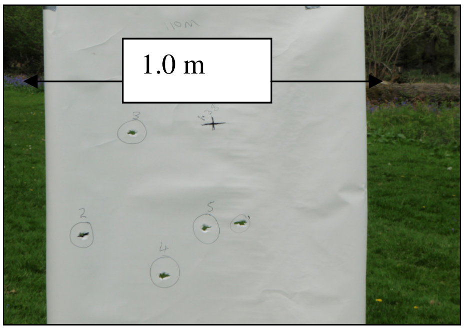

Figure 7.8: A photograph of the witness screen positioned at 110 m from the firing point after shots A1 to A5 were fired

All of the measured coordinates measured from the witness sheets for all firings are given in Appendix D. Table 7.3 gives the muzzle velocity, impact velocity, ground impact distance, number of bounces and the maximum distance travelled for shots A1 to A5. It should be noted that the bounce mark was identified by the skid mark on the grass. At the longer ranges the impact velocity of the musket ball with the ground would have decreased to a low value and the impact mark was increasingly difficult to see so there may have been more bounces than could be identified.

Table 7.3: Muzzle velocity, impact velocity, ground impact distance, number of bounces and the maximum distance travelled for shots A1 to A5

Shot No.	Velocity m/s	Velocity at ground impact m/s Doppler	Distance to Ground Impact. m	Number of Bounces.	Total Distance to final resting position m
A1	429	259	170	Hit Frame 0	
A2	423	266	166	4 (3 definite)	402
A3	423	239	203	3 definite	330 + unfound after this point
A4	412	264	153	4	296
A5	412	250	170	Hit Frame 0	

7.2.3 Analysis of Results shots A1 to A5 (19.49 mm bore barrel)

Shots A1, A2, and A5 all had similar trajectories, A1 and A5 both hitting the base of the frame at 170 m. Shot A2 impacted the ground at 166 m. The velocity of A1 was 429 m/s (the highest of the serial) and shot A5 was 412 m/s (lowest of the serial) giving a difference between maximum and minimum muzzle velocities of only 17 m/s.

The furthest distance to ground impact was shot A3, which was 203 m and the least distance was shot A4, which was 153 m. The velocity of shot A3 was 423 m/s and the velocity of shot A4 was 412 m/s. It should be noted that the trajectory of shot A3 was slightly higher than the others and shot A4 slightly lower. This small change in trajectory produced a change in range from 153 m to 203 m, a difference of 50 m. The average distance to ground impact was 172.4 m

Only two musket balls were found, shot A2 which travelled 402m and shot A4 which travelled 296 m. Thus the average distance travelled was 349 m with a difference of 106 m between maximum and minimum distances.

Figure 7.9 shows the trajectories of shots A1 to A5 in the vertical plane and Figure 7.10 shows the trajectories of shots A1 to in the horizontal plane.

Figure 7.9: Vertical trajectories of shots A1 to A5 to ground impact

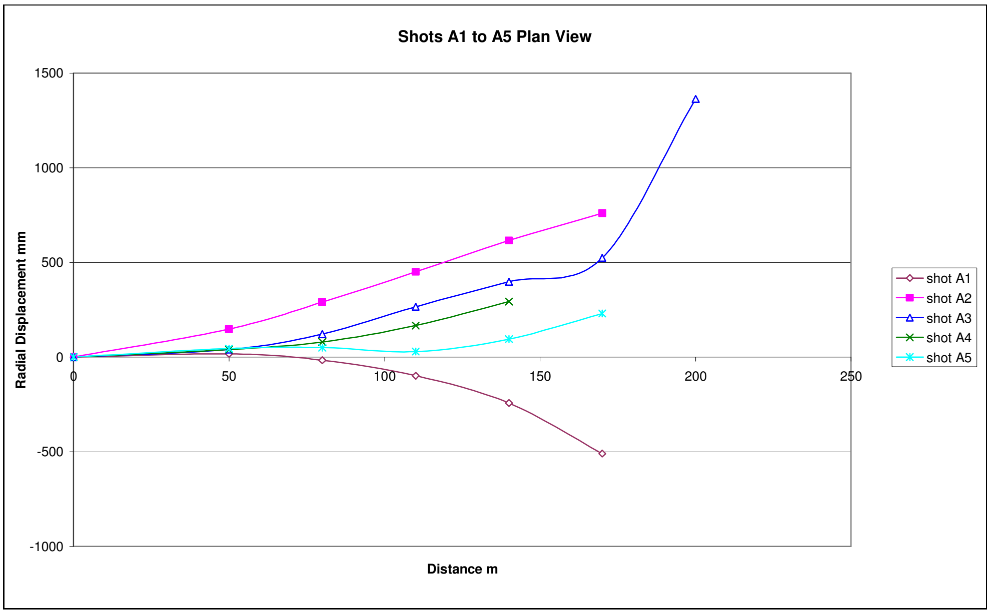

Figure 7.10: Horizontal trajectories of shots A1 to A5. (Plan View)

Figure 7.11: shows the horizontal trajectories (plan view) combining the results of shots A1 to A5 both before and after ground impact (the broken lines signify the path of the musket balls after the first ground impact).

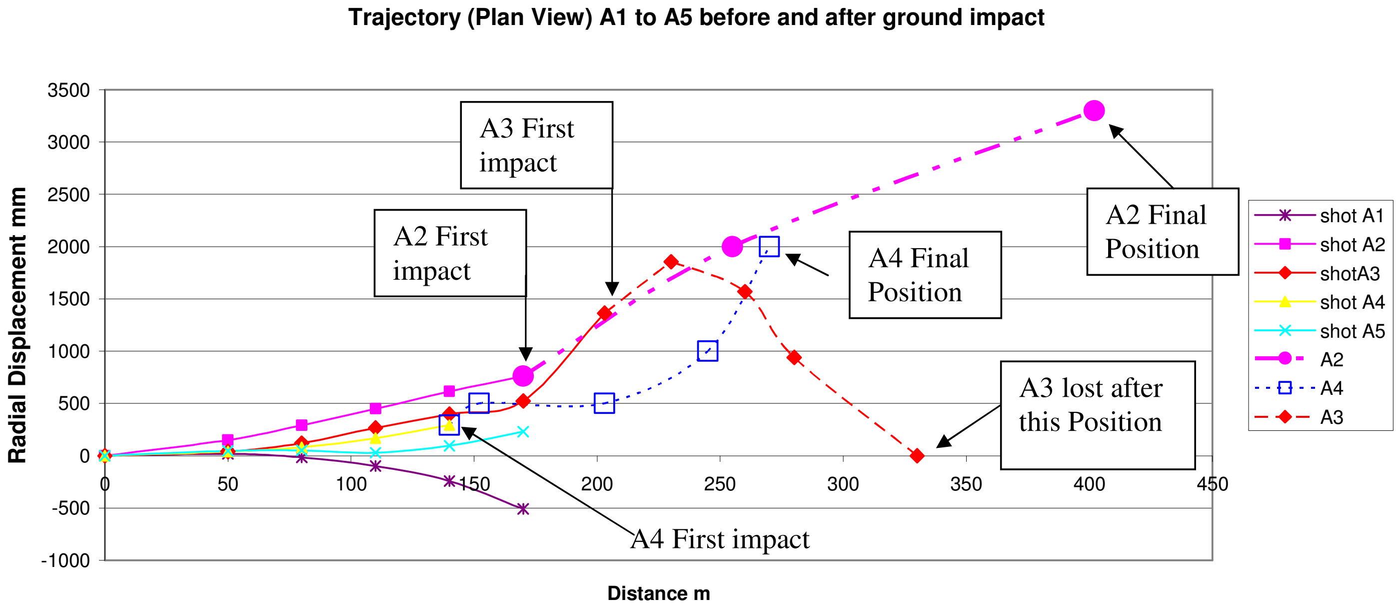

Figure 7.11: Horizontal trajectory (Plan View) of shots A1 to A5 before and after ground impact

7.2.4. Results A6 to A7 (18.7 mm bore Barrel) and A8 to A9 (20.4 mm bore Barrel)

Table 7.4 shows the muzzle velocity, first ground impact velocity, distance to first impact and the number of bounces by the musket ball (where known) obtained for shots A6 to A9. None of the musket balls were found so there are no values for the total distance that the musket ball travelled.

Table 7.4: Muzzle velocity, first ground impact velocity, distance to first impact and the number of bounces by the musket ball

Shot No.	Velocity (m/s)	Velocity at ground impact (m/s)	Distance to ground impact (m)	Number of Bounces	Total distance to final resting position (m)
A6	467	289	140	2 then lost	Lost after 303
A7	484	266	182	Unknown	Lost after 302
A8	339	208	Lost after 110m over screens	Unknown	unknown
A9	351	217	234	2 then lost	Lost after 300

Figure 7.12 shows the vertical trajectories of shots A6 to A9 to the point they first hit the ground (or were lost) and Figure 7.13 shows the horizontal (plan view) of shots of shots A6 to A9 to the point they first hit the ground (or were lost).

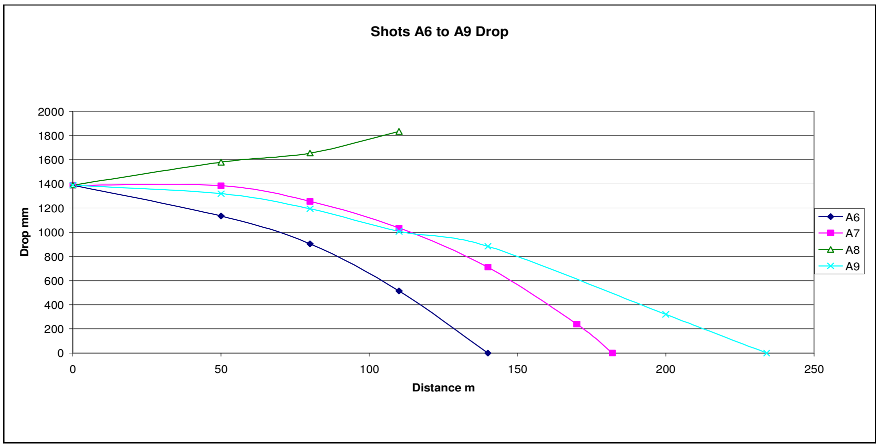

Figure 7.12: Vertical trajectories of shots A6 to A9 to the point they first hit the ground (or were lost).

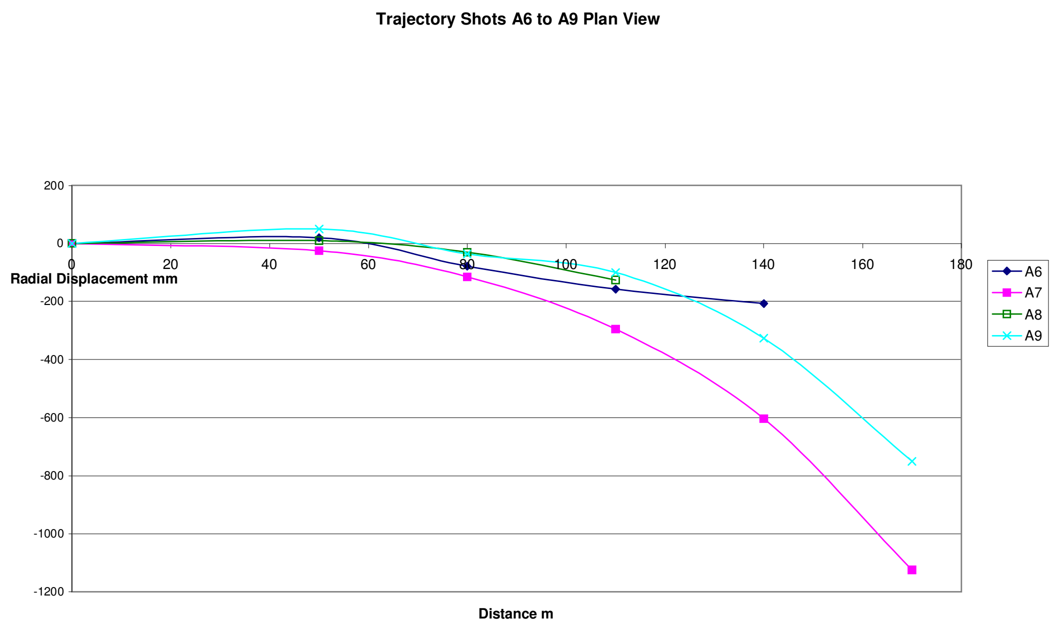

Figure 7.13: Horizontal (plan view) of shots A6 to A9 to the point they first hit the ground (or were lost).

Figure 7.14 shows the horizontal trajectories (plan view) of shots A6 to A9 before and after ground impact.

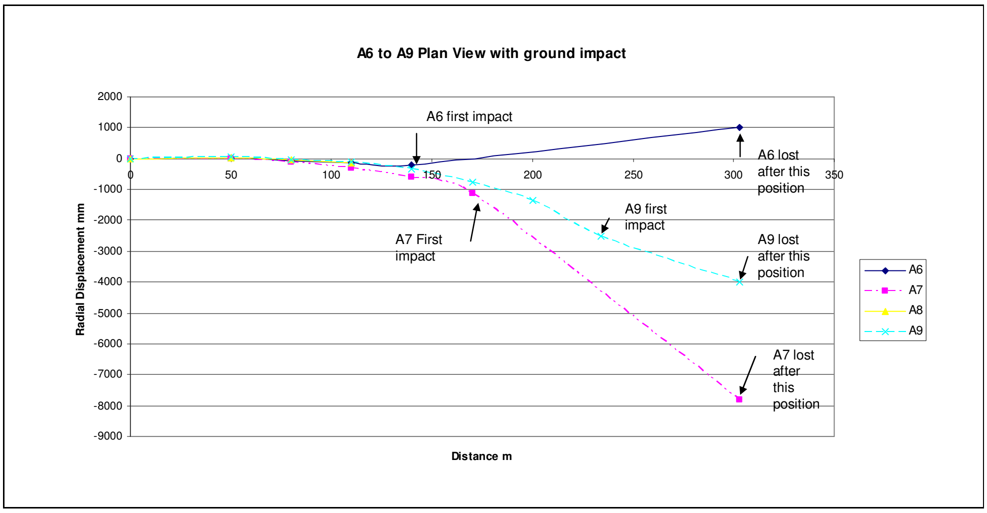

Figure 7.14: Horizontal trajectories (plan view) of shots A6 to A9 before and after ground impact

7.2.5 Bounce and Roll

After impacting the ground the musket balls skidded and then bounced. The coordinates of their positions were measured from the paper witness screens.

Figure 7.15 shows the vertical trajectory and subsequent bounce of shots A2, A3 and A4 (The original barrel with a 19.49 mm bore). (Note some smoothing was required in producing the chart to take into account the missed data between the witness screens).

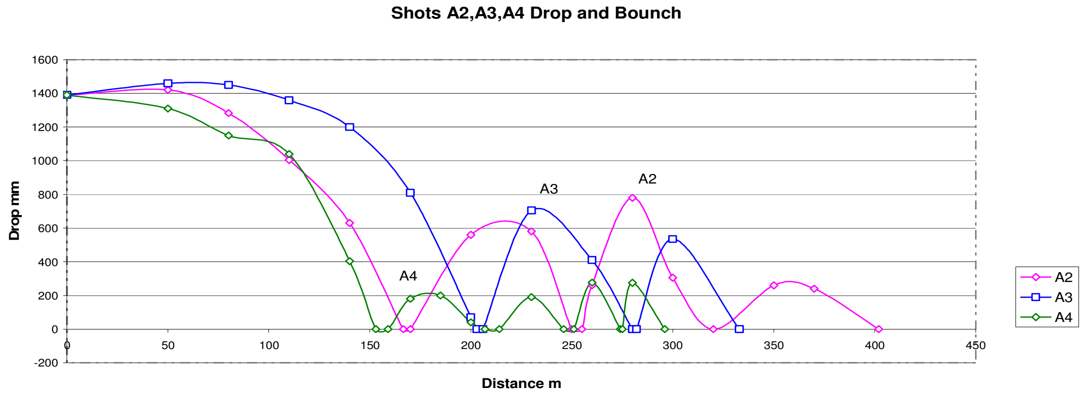

Figure 7.15: Vertical trajectory and subsequent bounce and roll for shots A2, A3 and A4

The vertical trajectory plus bounce and roll for Shot A6 (The only shot from A6 to A9 with usable Data) is shown in Figure 7.16. The bounce has had a smoothing interpolated line added because it is probable that the bounce went higher between the screens.

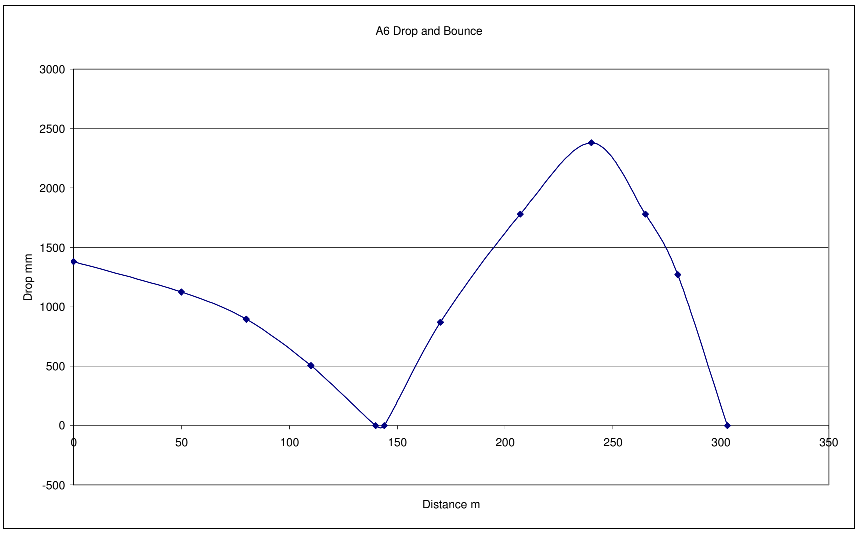

Figure 7.16: Vertical trajectory plus bounce and roll for Shot Number A6

7.2.6 Analysis of results for impact and bounce from shots A1-A5 and from shotsA6–A9

Shot A6 produced the maximum height of bounce (first bounce) predicted to be 2.38 m, well above the witness screens at a distance of 240 m from the firing point and shot A4 produced the lowest first bounce of 0.260 m at 180 m from the muzzle.

Shot A4 recorded the most bounces, four in total. Shot A2 recorded 3 bounces but Figure.7.15 indicates that it is possible that a fourth bounce at approximately 360 m occurred but was not visible. Shots A2 and A4 showed an increase in bounce height with distance. No bounces were recorded after the last witness screen at 300 m but it is probable that the musket ball would continue to bounce at decreasing increments before coming to a halt. Figure 7.17 shows the Final position of all the recovered musket balls and the first impact point. (The chart excludes intermediate impacts).

Figure 7.17: Final position of all recovered musket balls and their first impact point

7.2.7 Distance To Musket Ball Final Position

The minimum distance to final resting position was Shot Number 1 and was 288 m with the first ground impact point occurring at 200 m. The muzzle velocity was 410 m/s and the musket ball hit 135mm low at the 20 m marker.

.

The maximum distance to final resting position was Shot Number A2 and was 402 m with the first ground impact point occurring at 170 m. The muzzle velocity was 423 m/s and the musket ball hit 40 m high at the 50 m marker. This gives a difference of 114 m between the minimum and maximum final position.

The average distance to the final resting position from all recovered musket balls was 323.8 m. It should be noted that a number of musket balls were not recovered because their final resting place was in the undergrowth where they had deviated by more than 9 m from the centre line of the firing range. If the angular deviation was similar it would be expected that it would be the musket balls that travelled the furthest that would be lost thus skewing the results.

Figure 7.18 shows all the first ground impact positions for all shots fired and their horizontal position. (Plan View) Note: this does not include the impact points for the 19 mm steel ball bearings which were outside the width of the witness sheets.

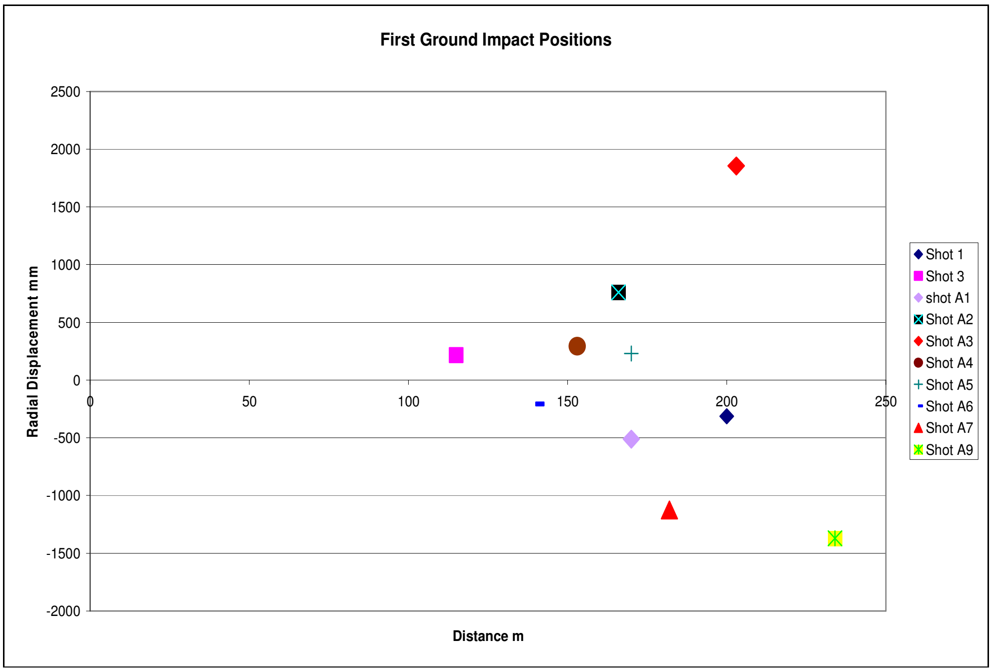

Figure 7.18: First ground impact positions for all shots fired and their horizontal position (Plan View).

7.2.8 Distance to Ground Impacts

The minimum distance to ground impact was for Shot Number 3 and was 115 m. The muzzle velocity was 298 m/s which was the lowest velocity recorded. The musket ball impacted 45 mm low at the 20 m target. The maximum distance to ground impact was for Shot number A9 and was 234 m. The muzzle velocity was 351 m/s and the musket ball impacted 70 mm low at the 20 m Witness screen. The average distance to ground impact for all shots fired was 159.1 m with a variation of 85 m from minimum to maximum. The average velocity was 419.6 m/s.

7.2.9 Maximum Variation of recorded ground impacts (left to right)

The greatest distance a musket ball impacted to the left of the centre line occurred with shot number A2 with a ground impact distance of 760 mm to the left. The greatest distance a musket ball impacted to the right of the centre line occurred with shot number A7 with a ground impact distance of 1125 mm to the right. It should be noted that the 19 mm diameter steel ball bearings impacted the ground outside of the width of the witness sheets.

7.2.10 Maximum Variation of recorded final recovery position (left to right)

The maximum recorded distance from the left of the centre line was for Shot Number 3 which was 5.7 m to the left. The maximum recorded distance from the right of the centre line was for shot number 4 which was 2.5 m to the right. It should be noted that the results will be clipped to a maximum distance of 9 m each side of the centre line because that was the width of the firing range.

Table 7.5 shows the musket ball's final resting positions for all of those that were recovered. Those musket balls that were not recovered will skew the results because of the range being a maximum width of 9 m each side of the centre line.

Table 7.5: Final resting positions for all of those musket balls that were recovered

Shot number	Distance travelled (m)	Spread (m)
1	288	2.3 Right
3	323	5.7 Left
4	310	2.5 Right
A2	402	3.3 Left
A4	296	2.0 Left

7.2.11 Musket Ball Skids

When the musket ball impacted the ground it produced a skid mark several metres long. This impact absorbed some of the kinetic energy of the musket ball resulting in a reduction in its velocity. Figure 7.19 shows a Doppler trace from shot A6. The split in the line indicates where the musket ball hits the ground. Using these traces it is possible to establish velocities before and after ground impact.

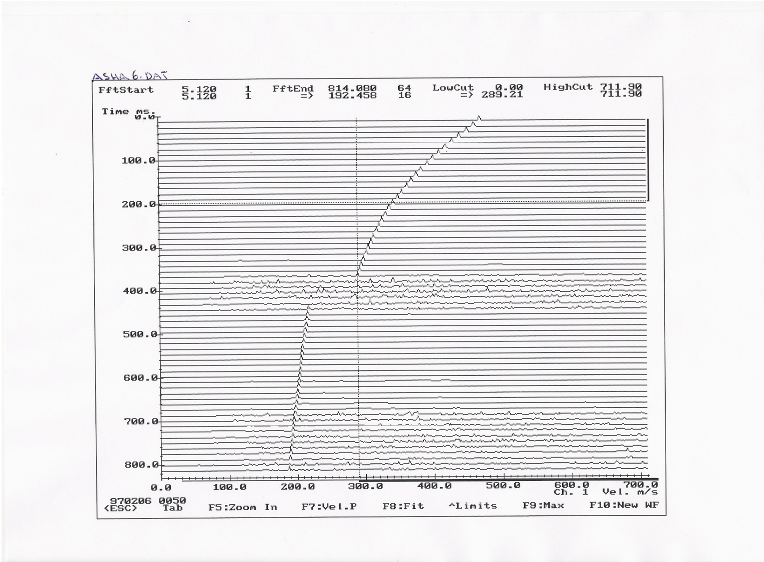

Figure 7.19: Doppler radar trace for shot number 6 showing the reduction in musket ball velocity when it impacted with the ground.

Table 7.6 shows recorded skid lengths and velocities before and after impact with the ground for those shots where the data was recorded.

Table 7.6: Recorded skid lengths and velocities before and after impact with the ground for those shots where the data was recorded.

Shot number	Skid length m	Velocity before skid m/s	Velocity after skid m/s	Velocity Loss m/s
1	2			
2	4			
A2	3.5			
A3	2.6 (second skid 2)	239	152	87
A4	5.5 (second skid 7) (third skid 5) (fourth skid 1)			
A5				
A6	4 (second skid 2)	289	216	73
A7		266	178	88
A9	7			

7.3 Third Long Range Firing Trials (July 09)

This trial was undertaken to increase the amount of available data on final resting positions of the musket balls.

7.3.1 Setup

The musket barrel and proof housing were mounted on the modified car trailer as in the first long range firings. This was for convenience because the firings were carried out in conjunction with a cannon firing trial which also used the trailer as a mount. All the firings were conducted at the same position as previous firings with Zero elevation. Ten musket balls were fired using 18 grams of G12 black powder (no wads were used). The musket balls were coloured bright orange with spray paint to help recovery. A witness sheet of paper was positioned 100 m from the barrel and a cross marked on it as a point of aim by bore sighting. A telescopic sight was then positioned on the barrel and adjusted to the cross so each shot would have the same aiming mark. The firings were carried out in accordance to those previously done. Ground hardness was measured at 2.5 CBR (85 CI). This was much softer than the previous firings. The ground was damp and the grass was approximately 30mm high. The wind conditions were a light breeze. There was only a limited amount of time to carry out the firings so to reduce set up time and reduce the time between firings no instrumentation was used and only one witness sheet was set up. Velocity was predicted to be 413 m/s taken from previous firings.

7.3.2 Results

The coordinates from the paper witness screen were plotted (Table found in Appendix D). They were entered into a computer programme (663A) by M.S.Instruments PLC. The programme was used to calculate the following statistics: shown in Table 7.7

Table 7.7: Results from witness sheet set at 100 m from the muzzle.

	X	Y
Mean point of Impact (mm)	-569	-518
Group Rectangle (mm)	1210	923
Standard Deviation (mm)	317.61	252.03

Extreme Spread (mm) 1223.32

Group Circle (mm) 1223.32

All the firings hit the target low and left (as shown from the mean point of impact). This was due to errors in the initial aiming. The aim was not re-adjusted to ensure all the firings were subjected to the same offset. (The sight was always positioned on the cross prior to each firing).

A screen shot of the plotted coordinates is shown in Figure 7.20 (Note the shot positions have been brought to the centre by offsetting the mean point of impact).

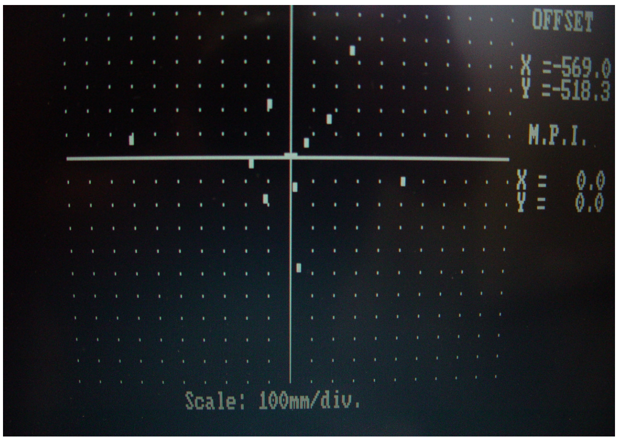

Figure 7.20: Screen shot of results of firing trial entered into the shot position computer program.

The ground was searched with metal detectors. Six of the musket balls were recovered. The remaining four unrecovered musket balls are thought to have been lost in the undergrowth on either side of the firing range.

Table 7.8 shows the distances travelled to the final resting place where the balls were recovered and the deviation from the central firing position. (The ball ref. is defined by the order in which they were found the 3 refers to the third long distance firing at Ashdown).

Table 7.8: Distance travelled to the final resting place and the distance from the centre line of the range.

Ball Ref.	Distance to final resting position. (m)	Deviation from centre.(m)	Direction from centre.
3.5	227.89	1.2	Left
3.6	265.39	2.2	Right
3.4	266.39	3.4	Left
3.3	270.29	0.6	Left
3.2	312.49	4.6	Left
3.1	329.99	1.35	Left

The results from Table 7.8 are shown plotted in Fig. 7.21

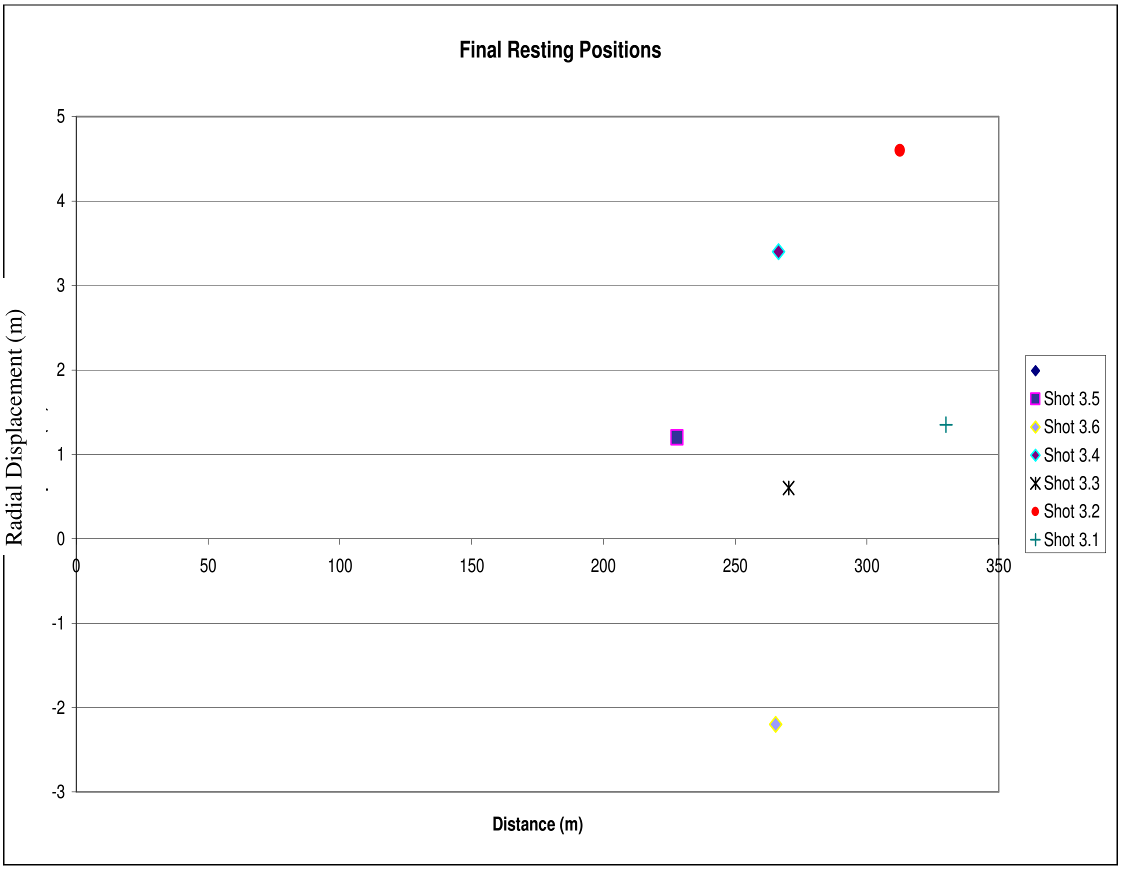

Figure 7.21: The distance travelled to their final resting place for shots 3.1 to 3.6

The distance travelled by the musket balls from these firings were less than previous ones and may have been due to the much softer ground conditions. The average distance was 290.175 m compared to 307 m for the first firing and 349 m for the second firing.

Figure 7.22 combines these final resting positions with previous ones to view all the musket ball final resting positions from all the long range firings.

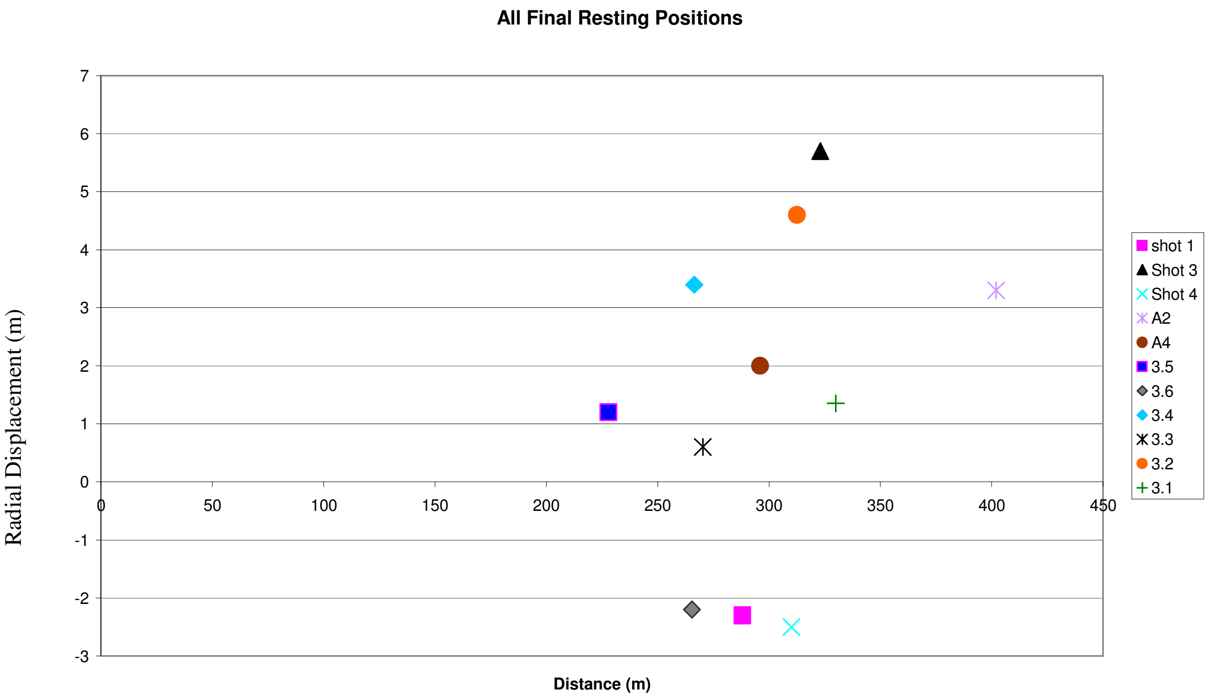

Figure 7.22: Plot of all of the musket balls fired during the 1st, 2nd and 3rd long range firing trials showing their final resting positions.

The final resting positions of the recovered musket balls are tabulated in ascending order of the distance travelled in Table 7.9

Table 7.9: Final resting positions of the recovered musket balls in ascending order of the distance travelled.

Distance to final resting position (m)	Radial displacement (m)	Shot Number
227.89	1.2 Left	3.5
265.39	2.2 Right	3.6
266.39	3.4 Left	3.4
270.29	0.6 Left	3.3
288	2.3 Right	1
296	2.0 Left	A4
310	2.5 Right	4
312.49	4.6 Left	3.2
323	5.7 Left	3
329.99	1.35 Left	3.1
402	3.3 Left	A2

7.4 Effects of Ground Hardness

The ground hardness was measured for each of the three long range firings. Table 7.10 shows the average distance of the musket balls final resting position from each of the 3 firings and the ground hardness (the higher number indicates harder ground).

Table 7.10: Average distance of the musket balls final resting position from each of the 3 firings at Ashdown House and the ground hardness (the higher number indicates harder ground)

Long Range Firing No.	Average Distance to final resting position	Ground Hardness	
		Cone index (CI)	California Bearing Ratio (CBR)
1	307	110	3.75
2	349	195	9
3	290	85	2.5

Although there is limited data from three firings it would appear that the ground hardness has a significant effect on the distance travelled to the musket balls final resting position. The average distance musket balls travelled increased by 59 m when fired on harder ground compared to the soft.

Chapter 8: DISCUSSION

The main aim of this research was investigate the ballistics of 17th Century muskets so as to assist battlefield archaeologists in the analysis of battle fields of that period. After more than 300 years there are few artefacts left on the battlefield to aid researchers in their studies but one of the most prolific are spent musket balls. These are found where they have landed having been fired during the battle. To be able to answer the question of where they were fired from would be of considerable benefit and it is to help answer this question that is the purpose of this work.

A definitive muzzle velocity for the musket of the 17th Century could not be obtained so estimations from previously published research were used. There will have been considerable variations in muzzle velocity due to variations in bore diameter, the use or otherwise of wads and variations in the propellant charge weight used and all of these have been investigated on the indoor firing range. Data collected from long range firings on the effects of variations in muzzle velocity and the subsequent effects on the external ballistics and bounce and roll is more limited because of the much greater scale of the effort required to generate and collect the data.

A large amount of experimental research was conducted to successfully identify a soft capture system that would enable the examination of fired reproduction musket balls under a wide range of conditions. This made it possible to produce a good match of the distortion that occurs in the barrel of the musket when it is fired to 17th Century musket balls found on the battlefield. This included the pitting of the base of the musket ball by the black powder when a wad is not used. Results proved that, on average, the distance to the first ground impact was in good agreement with the predictions for spherical undistorted musket balls suggesting that distortion due to firing has little effect on the "distance to ground impact" of the musket ball. This was confirmed by investigating the theoretical effect of changes in drag coefficient, mass loss and changes in cross sectional area of the musket ball.

During the first long distance firing at Ashdown House, two shots were fired using steel ball bearings, (shots 5 and 6). The hard steel ball bearings would have remained spherical during firing and being 19 mm in diameter compared to 18.51 mm for the lead musket balls were a better fit in the barrel. Therefore, it was thought that they would be the most accurate however they were both lost from the witness screens before they hit the ground and thus proved to have the greatest dispersion of all of the long range shots fired. The reason for this is not known, but could be related to the elastic interaction between the hard steel ball with the steel barrel compared to the plastic interaction of the soft lead ball and the steel barrel.

During trials the average distance of the musket ball to ground impact agreed well with theoretical predictions. However there were some significant differences. For example Shot Number 1 from the first long distance firing at Ashdown House travelled 43 m further to ground impact than was predicted. The trajectory of Shot Number 1 was also unusual when viewed from above as it initially veered to the left by approximately 0.5 m over a distance of 125 m, before changing direction and moving 0.75 m over 75 m to the right before ground impact, as shown in Figure. 8.1.

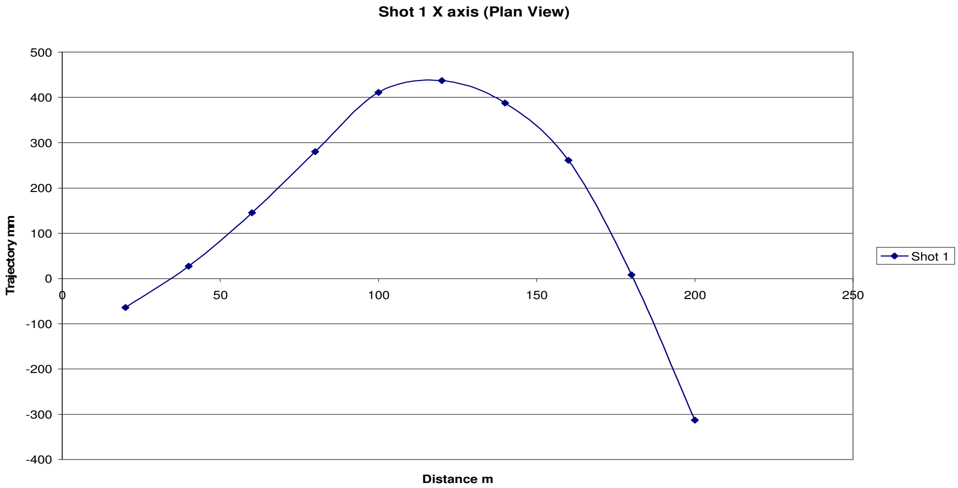

Figure 8.1: Horizontal (plan) view of Shot Number 1 Trajectory. (The amount of variation is emphasized by the scaling of the chart).

The musket ball is clearly cork screwing as it moves down range. It is unclear exactly what may have caused this effect. A possible explanation is that some musket balls were slightly more distorted (or had slightly larger "sprues" left on them) therefore, producing a turbulence that would affect the trajectory. Another explanation may be that spin may be imparted to the musket ball due to the large clearance between the ball and bore resulting from one side of the ball being in contact with the barrel and the other with clearance through which the high velocity gases could flow. A high speed video was used to check for spin (see Appendix C, High Speed Video Tests). No spin was observed but the musket ball could only be observed over a short distance so if the spin rate was low it may not have been seen but could still influence its trajectory over a long distance. Visual comparisons between retrieved musket balls from the Long range firings were made. Figure 8.2 shows shot number 1 and figure 8.3 shows shot number 3.

Figure 8.2: Shot number 1 from first long range firing

Figure 8.3: Shot number 3 from first long distance firing

A comparison between these two musket balls was chosen as shot number 1 travelled the greatest distance to ground impact from the first set of long range firings and produced the most significant deviation from the predicted trajectory of all three firings. Shot number 3 travelled the least distance from the first long range firings and its trajectory was similar to predictions. Shot number 1 showed significantly more banding than shot number 3 but had a smaller sprue. Shot number 1 also had the largest amount of banding compared to all other retrieved musket balls from the long range firings which would indicate the reason for its erratic trajectory in flight.

It was found that musket balls initially impacting the ground closer to the firing position (i.e. before the expected 170 m) could, in some cases, exceed the distance to their final resting position to those impacting the ground at greater distances (170 m plus). Additionally, it was noted that musket balls with higher than average muzzle velocities in some cases travelled shorter distances to their final resting places than musket balls with lower than average velocities. Clearly the differences will be affected by the unevenness of the ground, whether stones or other objects were struck and by the surface covering, which in this case was grass. The cork screwing of the musket ball will also affect the impact distance and the impact angle and will have a significant effect on the maximum distance that the musket ball will travel. The nature of the ground at the point of initial and subsequent impacts will significantly affect the velocity loss of the musket ball during its impact with the ground.

It can be seen that variables such as velocity variations (due to variations in internal barrel diameter, powder charge weights and the use or otherwise of a wad), that were initially thought to be critical to establishing firing positions, are potentially less influential than other variables such as the cork screwing of the musket ball and the nature of the ground during bounce and roll.

All of the firings were carried out using an adjustable fixed mount set to give a flat trajectory of 0° and with the barrel 1.39 m above the ground. In reality the elevation would vary depending on the firer. It was established by calculation that an elevation of 2 degrees increased the first impact point of the musket ball from 170 m to 428 m giving an increase of 258 m. It was calculated that the maximum distance to ground impact was 967 m for an angle of 30° elevation (angles greater than this resulted in a shorter distance to impact with the ground). Also, the distance travelled by a musket ball after initial impact will be reduced at increased angles of elevation due to the sharper angle at which it impacts the ground. An additional consideration is that the energy at impact of a projectile fired at high angles of elevation will have less energy at impact than a projectile fired at low elevation. This is illustrated by Shot Number A3 (fired at 0°) which impacted the ground at 239 m/s (impact energy1056.7 joules) whereas the predicted impact velocity of a musket ball fired at a 2° angle of elevation would be 128 m/s (impact energy 303 joules) so that the subsequent bounce and roll would be less for the musket ball fired at the lower angle. Figure 8.4 is a simple illustration to show this.

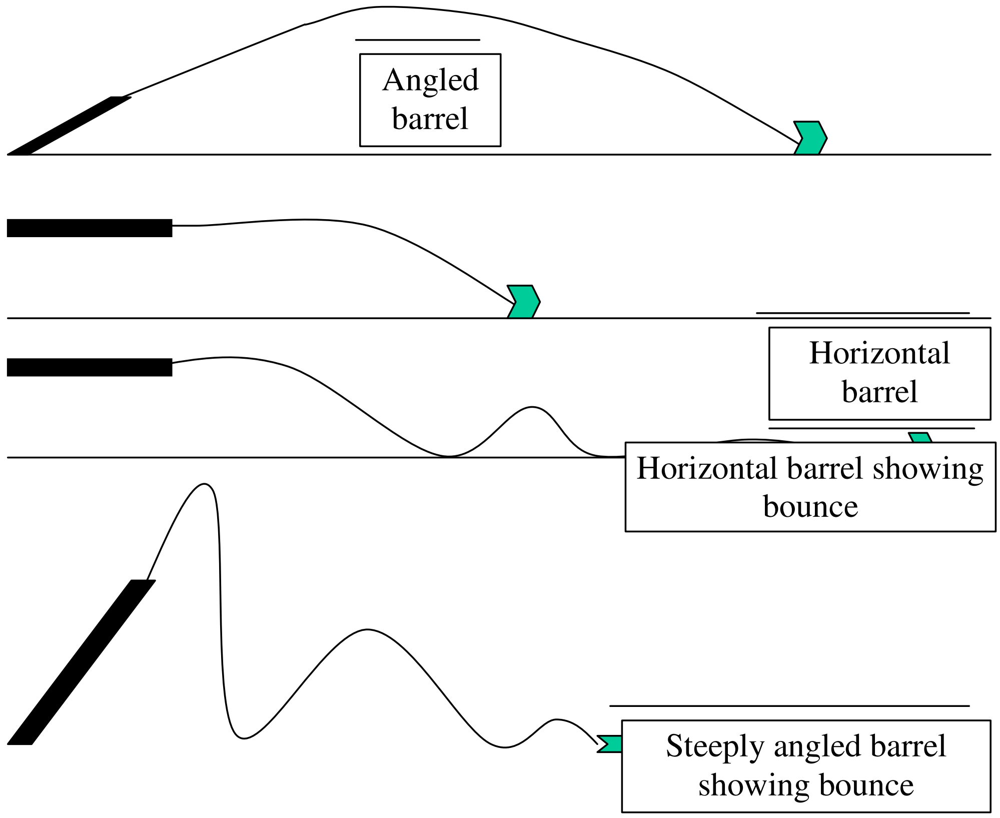

Figure 8.4: Diagram showing the effect of elevation on the initial impact & final resting place of the musket ball.

The skid lengths of the impacted musket balls were shown to be up to 7 m long and the maximum height for the bounce of the musket ball was estimated to be 2 m. Skids on the grass surface, marked with flags, are shown in Figure 8.5.

Figure 8.5: Skid marks of musket balls on the grass firing range.

The majority of the initial recorded bounces were between 0.2 m and 0.8 m high and would strike personnel at longer ranges than the initial impact. The musket ball of Shot NumberA3 retained 427 joules of energy after initial ground impact and was travelling at over 152 m/s. It was traditionally claimed that 80 joules would incapacitate an unprotected man but recent research (Champion, et el, 2009) suggest that this figure is too simplistic and that the ability of a projectile to incapacitate is dependant upon where it impacts the body and how much energy is absorbed during the impact. A higher figure of 200 joules would be necessary to incapacitate when struck in the thorax. 427 joules of energy is well above the newly recognised figure and the fact that a musket ball is made of soft lead which is known to spread on impact, suggests that a great deal of that energy would be transferred to the body.

Barrel fouling is a product of the combustion of black powder (mainly potassium carbonate) which can reduce the internal diameter of the barrel making it difficult to load a musket ball and was thought to be a common problem in the 17th Century. However, no noticeable effects were found from barrel fouling during the trials as there was no significant reduction in barrel diameter and it was always easy to load the musket ball. This may have been due to the use of higher quality black powder during these trials as opposed to the black powder used in the 17^{th} Century.

It was found that variations in bore diameter of the musket produced an average velocity variation of 110 m/s between the largest bore diameter and smallest bore diameter (no wadding). This showed a significant variation in velocity but produced a fairly insignificant outcome to the final resting position of the musket ball. The average velocity variation when using wadding was greatly reduced to 60 m/s therefore, the effect of wadding is more beneficial with increased windage. One variable that was not tested is that of variations in the diameter of musket balls. This would have given greater variation in muzzle velocities and pressures produced because a larger musket ball will give less windage and will be heavier so that the burning rate of the black powder would be greater producing high pressures and muzzle velocities.

It should be noted that a significant number of the musket balls were not recovered during the long range firings at Ashdown House. They were lost in the undergrowth along the edges of the firing range because the firing range was only 18 m wide. Thus the results of the distance of the horizontal dispersion from the centre line of the range have been chopped to 9 m to left and right. This will also have resulted in skewing the results of the maximum range of the musket balls because it is the longer range results that are likely to have been lost in the undergrowth.

Chapter 9: CONCLUSIONS

There has been little previous research into the ballistics of 17th Century muskets, especially the bounce and roll of musket balls which is crucial in establishing possible positions that a musket ball may have been fired from on the battlefield. This research has reproduced the firing of 17th Century muskets and the firing marks found on musket balls recovered from battlefields of the 17th Century and has investigated a number of important variables affecting ballistics of weapons from that period.

Musket balls found on the battlefield are known to have been distorted by the firing process which changes the shape of the musket ball. These changes were replicated and used to investigate the subsequent effects.

It was found that the average distance travelled by the musket ball before it impacted the ground was in good agreement with predictions using a simple single point model and that the drag co-efficient of the musket ball was little affected by its distortion/alteration in shape during firing.

The average distance to the musket balls final resting position (after bounce and roll) was approximately 315 m – almost doubling its distance from its initial landing point. This value is likely to be greater because of the limitation of the width of the range which almost certainly resulted in the musket balls travelling the furthest being lost in the undergrowth so not being included in the results.

Wadding was originally thought to have been used by 17th Century musketeers. However, it was shown that the musket balls fired without wadding showed a closer resemblance to some of the original 17th Century musket ball than those fired with the wadding. It was thought that wadding would have increased the muzzle velocity of the musket by preventing gas leakage past the musket ball in the barrel. This was found to be the case but the effect was surprisingly low. Variations in bore diameter showed a significant variation in velocity, especially when fired without a wad because of the change in gas leakage past the ball but produced little change on the outcome of the final resting position of the musket ball. After ground impact the musket balls were capable of skidding up to 7 m and bouncing to a height in excess of 2 m.

Chapter 10: RECOMMENDATIONS FOR FURTHER WORK

This work has made a considerable contribution towards understanding the effect of a number of different and important variables on the ballistics of 17th Century muskets and the total distance that a musket ball will travel when fired on the battlefield. There are however, a number of important areas that would benefit from investigation. The possible variations in musket ball diameter should be investigated because this, combined with the full range of barrel bore variations, will have a significant effect on muzzle velocities and peak pressures developed in the barrel during firing. This in turn may have a significant effect of the maximum range a musket ball travels. It is important that future firings should be carried out on a significantly wide firing range to ensure all the musket balls are located and that the data is not skewed by not recording all of the data.

It has been shown that small increases in the elevation of the musket gives a large increase in the distance travelled by the musket ball before it first impacts the ground. However, trials need to be carried out to show the effect of this on the maximum distance that the musket ball will subsequently travel.

The results on the effect of the ground hardness indicate the maximum distance a musket travels increases as the ground hardness increases. A greater number of different ground conditions need to be tested to identify the full effect that they have on maximum musket ball range. It would also be beneficial to increase the number of witness screens and reduce the distance between them to increase the resolution of the data collected.

An important variable affecting horizontal and vertical dispersion is that introduced by the firer. Actual hand firings of reproduction muskets by a number of firers under identical conditions would identify the effect on horizontal and vertical dispersion and the subsequent effect on the maximum distance travelled by the musket ball.

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12: Appendix A -Trials with wadding

The Tables below show the data from the experiments conducted comparing different powder types with wadding.

Table 12.1: Comparison of powder types with wadding showing pressure and velocity

Powder	Charge (grams)	Weight (grams)	Velocity (m/s)	Pressure (Bar)	Comments.
Swiss No.1	12.5	37.277	453	779.1	
Swiss No.1	10.2	37.478	393	453.5	
Swiss No.1	7.0	37.129	310	241.6	
3A	14.5	37.275	489	366.7	Bullet not found.
3 A	14.5	37.414	462	256.8	Ball oval.
3A	12.5	37.291	417	227.8	
3A	6.75	38.240	246	105.8	
G 12	12.5	37.261	341	176.3	Ball not found.
G 12	17	37.179	410	276	

Table 12.2: Comparison of powder types with wadding showing pressure, weight loss and musket ball diameter across banding.

Powder	**Charge (grams)**	**Pressure (bar)**	**Weight loss of Ball (grams)**	**Diameter of pre-fired (mm)**	**Diameter across banding (mm) (Max)**	**Diameter across banding (mm) (Min)**	**Diameter across banding (mm) (Average)**
Swiss No.1	12.5	779.1	1.683	18.53	18.13	17.61	17.87
Swiss No.1	10.2	453.5	2.473	18.55	17.88	17.56	17.87
Swiss No.1	7.0	241.6	0.693	18.51	18.32	17.94	18.13
3A	14.5	256.8	0.061	18.55	19.36	19.21	19.285
3A	12.5	227.8	0.318	18.54	18.48	18.29	18.385
G 12	17	276	0.556	18.57	18.4	17.93	18.165
G12	12.5	176	Not recovered	18.5			

13: Appendix B -Trials without Wadding

Data from Tests with 14 gram charge with no wadding.

Table 13.1: Velocity and pressure from 3A and G12 Powder

Powder	Velocity (m/s)	Peak Pressure (bar)
3A	423	276
G12	369	191

Table 13.2: Results from No Wad firings using a 48 inch Barrel

19.49 mm internal diameter showing pressure and velocity

Powder (no Wad)	**Charge (grams)**	**Velocity (m/s)**	**Peak Pressure (Bar)**
G12	18.824 Half ball mass	430	No reading
G12	18	410	269.5
G12	18	420	
G12	18	410	240.2
G12	14	396	168
3A	14	423	276
G12	37.49 (Proof Charge)	623	549
3A	37.521 (Proof Charge)	655	645
G12	12	334	174

Table 13.3: 39 inch Barrel 19.9 mm diameter showing velocity and pressure

Powder (no Wad)	Charge (grams)	Velocity (m/s)	Pressure (Bar)
G12 lead bullet	14	289	170

14: Appendix C - High Speed Video Tests

The long range firings produced several results where the musket ball behaved differently to predicted trajectories. One possible reason for this would be if the musket ball was spinning. High speed video using a Phantom 7 camera was used to establish whether any spin was apparent. The musket balls were marked with a white line to aid analysis. The 10 bore musket barrel was used with 12 bore musket balls.

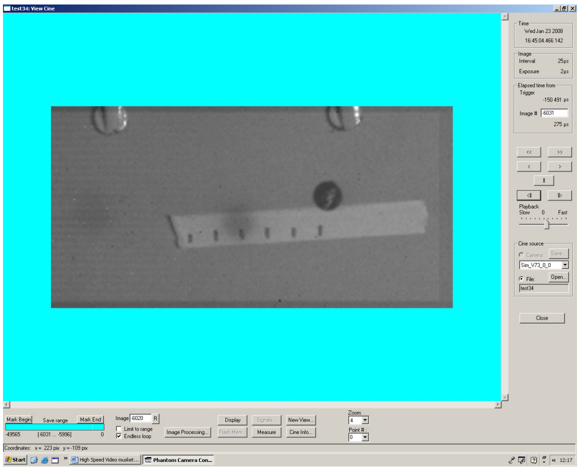
Table 14.1: shows the charge of powder, the velocity of the musket ball and whether a wad was used or not.

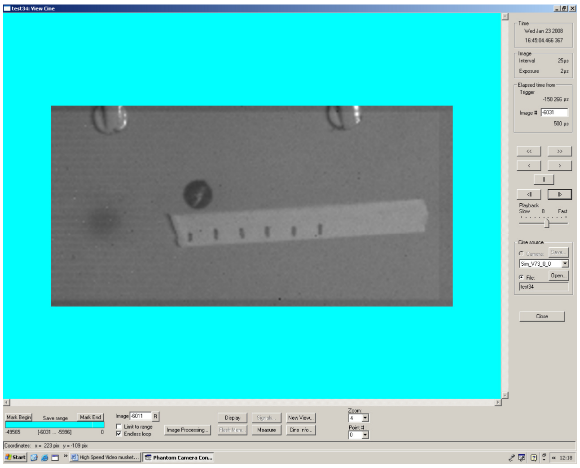
Table 14.1: Results from high speed video firings

Charge G12	Velocity (m/s)	Wad / No Wad	Comments
12.5	329	Wad	No video
14	365	Wad	No Video
14	368	Wad	No video
14	367	Wad	No usable Video
14	366	Wad	Video
14	370	Wad	Good Video
14	368	No Wad	Video
14	361	No Wad	Video
14	372	Wad	Good Video
14	360	No Wad	Good Video
18	417	No Wad	No Video
14	367	No Wad	No Video
14	367	No Wad	Good Video
14	379	Wad	No Video
14	379	Wad	Good Video
14	No Wad	378	Good Video

<u>Test 1 Settings</u>

Frame rate. 40000 frames per second. Resolution 224 × 112. Velocity 372 m/s G12 Wadded.



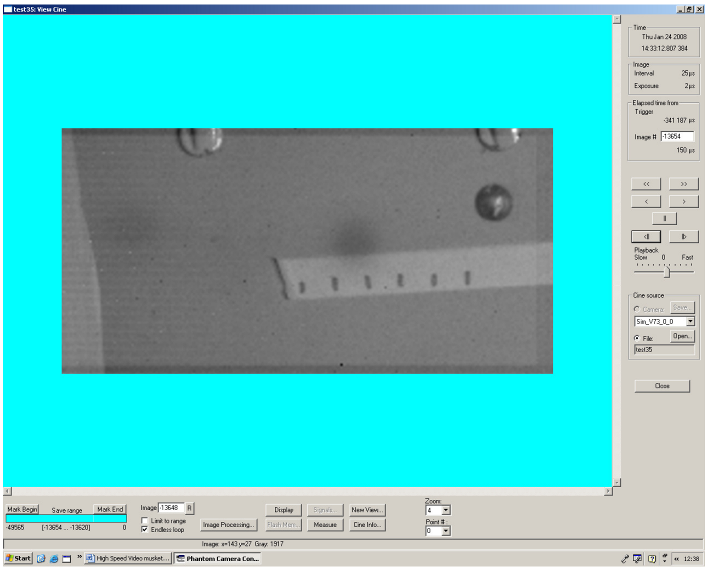


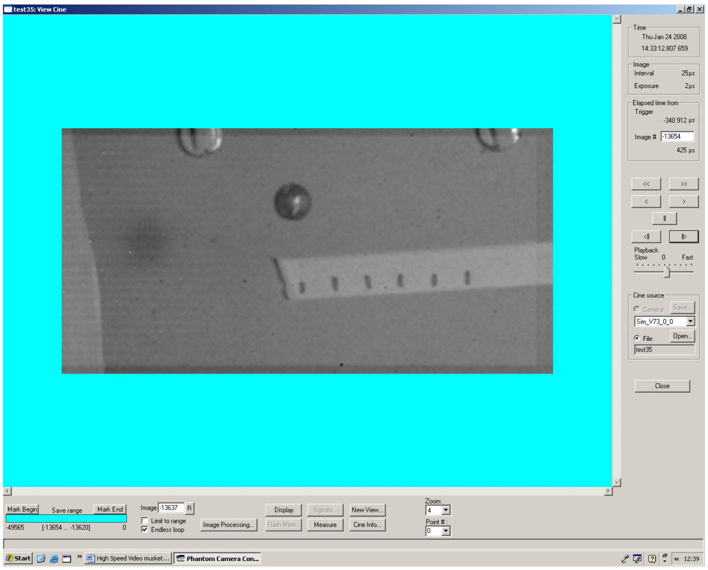
The white line has not moved indicating no spin is apparent.

<u>Test 2 Settings</u>

Frame rate. 40000 frames per second. Resolution 224 × 112. Velocity 360 m/s G12

No Wad.





No visible spin was apparent.

15: Appendix D-Tables from Long Range Trials.

Table 15.1: Shots A1 to A5 10 bore barrel id 19.49 mm

Distance (m)	Shot A1 429 m/s	Shot A2 423 m/s	Shot A3 423 m/s	Shot A4 412 m/s	Shot A5 412 m/s
50	X -17,Y 35	X -148, Y 40	X -40,Y 70	X -40, Y -80	X -45, Y -17
80	X 16,Y -100	X -290, Y -97	X -121, Y 60	X -80,Y -240	X -50, Y -17
110	X 99, Y -354	X -450,Y -375	X -266, Y -30	X -166,Y -350	X -29, Y -115
140	X 243, Y -712	X -615,Y -750 First Impact 166.5 m	X -398, Y -190	X -293,Y -986 First impact 153 m	X -95, Y -692
170	X 510, Y -1380 Impact bottom of frame.	X -760, Y -1380	X -524, Y -580	X -310, Y -1210	X -230, Y -1380 Impact bottom of frame.
200		x -1100, y -820 (first Impact)	X -1364,Y -1320 (first impact 203m)	X -410 Y -1350	
230		X -1620,Y -800	X -1855, Y -685	X -930, Y -1200	
260		X -2115 Y -1119 (second impact)	X -1570, Y -980	X -1500 Y -1114 Third bounce	
280		X -2510 Y -600	X -940 Y -960	X -1780 Y -1115	
300		X -4400? Y -1075	X -1800? Y -855		

Table 15.2: Shots A6 and A7 barrel id 18.7 mm Shots A8 and A9 barrel id 20.4mm

Distance (m)	**Shot A6** **467 m/s**	**Shot A7** **484 m/s**	**Shot A8** **339 m/s**	**Shot A9** **335 m/s**
50	X -20 Y -256	X -25 Y -4	X -10 Y 190	X -50 Y -70
80	X 78 Y -485	X 115 Y -134	X 30 Y 265	X 36 Y -195
110	X 157 Y -875	X 295 Y -354	X 126 Y 444	X 100 Y 383
140	X 207 Y -1258 1st Impact	X 603 Y -680	Lost over screen.	X 326 Y -506
170	X 330 Y -510	X 1125 Y -1150		X 1370 Y -807
200	X 340 Y 220	Off Screen RHS 182m		X 1370 Y -1070
230	Over top of screen			1st impact 234m
260	Over top of screen			
280	X 455 Y -110			2nd impact 293m
300		Probable 2nd impact at 302 m		Lost RHS 8m skid

Table 15.3: Summary of Results Shots A1 to A5

Shot No.	Velocity m/s	Velocity at ground impact m/s Doppler	Distance to Ground Impact. m	Number of Bounces.	Total Distance to final resting position m
A1	429	259	170	Hit Frame 0	
A2	423	266	166	4 (3 definite)	402
A3	423	239	203	3 definite	330 + unfound after this point
A4	412	264	153	4	296
A5	412	250	170	Hit Frame 0	

Table 15.4: Musket ball data from second long range firings

Identification No.	Weight (grams)	Diameter (mm)
1	37.48	18.55
2	37.432	18.49
3	37.487	18.56
4	36.854	1857
5	37.213	18.5
6	37.213	18.51
7	37.701	18.62
8	37.819	18.57
9	37.759	18.63

Table 15.5: Results from third long range firing 100 Metre range

Shot Number	X Coordinates (mm)	Y Coordinates (mm)
1	-300	-80
2	-680	-700
3	-660	-300
4	-550	-650
5	-60	-630
6	-400	-360
7	-740	-550
8	-1270	-450
9	-500	-460
10	-530	-1003

16: Appendix E- Weights and dimensions of musket balls pre and post firing

Table 16.1: Weights and dimensions of musket balls using 19.49 mm internal diameter barrel.

Powder	Charge (grams)	Weight pre-firing (grams)	Weight post firing (grams	Diameter pre-firing (mm)	Diameter across bands post firing (mm)
3A (wad)	12.5	37.291	36.973	18.55	18.38
G12 (wad)	17	37.179	36.623	18.53	18.16
Swiss No.1 (wad)	12.5	37.277	35.594	18.51	17.16
Swiss No.1 (wad)	10.2	37.478	35.005	18.56	17.87
Swiss No.1 (wad)	7.0	37.129	36.436	18.52	18.13
3A (wad)	14.5	37.414	37.353	18.54	18.17
3A	12.5	37.275	35.936	18.54	17.90
G12	17	37.292	35.448	18.49	18.07
G12	18	37.648	36.565	18.54	18.36
G12 (wad)	12.5	37.40	37.260	18.5	18.4
G12 (wad)	14	37.390	37.130	18.54	18.4
G12 (wad)	14	37.160	37.060	18.49	18.36
G12	14	37.391	36.250	18.51	18.38

G12	14	37.568	35.91	18.47	18.32
G12	14	37.850	36.790	18.5	18.18
G12	14	37.467	36.451	18.55	18.18
G12	14	37.457	35.910	18.58	17.65
G12 (wad)	14	37.700	37.126	18.64	18.02
G12	18	37.450	36.070	18.60	18.30
G12	18	37.67	36.012	18.62	18.40
G12 (wad)	18	37.435	36.989	18.59	17.95
G12	18	37.57	36.941	18.58	17.73
G12	18	37.336	36.425	18.50	18.20