EXPERIMENTAL FIRING, AND ANALYSIS OF IMPACTED 17TH– 18TH CENTURY LEAD BULLETS

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ABSTRACT

The analysis of spherical lead bullets recovered from early modern battlefields (1500-1815) has produced valuable data regarding battle location and the extent of the action. Previous experimentation and analysis of individual bullets demonstrate that diagnostic traits can be transferred to the surface of the bullet. However, the nature of impacted bullets and their potential to retain characteristic evidence from the impact surface have yet to be systematically addressed within conflict archaeology. This thesis examines the nature of bullet impact evidence through a series of proof of concept experimental firing trials. To achieve this aim, a reference collection of known bullet impacts which can be used as a comparative tool against archaeologically recovered bullets was established. To build this reference collection, a reproducible experimental firing methodology was created by examining military treatises and scientific publications contemporary to the early modern period, along with previous experimental firing trials and ballistics to identify and define experimental variables and parameters. Experimental designs were developed by examining the reconstructed historic landscape from two case study battlefields to identify common landscape features in which bullets may have impacted during battle. A ballistic modelling program was created through experimentation to enable a regimented experimental firing methodology that would compensate for musket inaccuracy, although with limitations. Experimental firing was conducted over sterile and stony ground surfaces as well as numerous wooden targets to establish a baseline of known bullet impacts. The results from the experimental firing reveal that bullets that impacted the ground surface retain distinct diagnostic characteristics that can be identified within bullets from archaeological assemblages. However, the distinctive characteristics identified on bullets that impacted wooden targets were not observed. This thesis demonstrates that experimentally fired bullets retain diagnostic traits from the impact surface that allow for specific classification and an advanced understanding of archaeologically recovered bullet assemblages.

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Dedications

This thesis is dedicated in memory of my mother, Debra L. Dougherty, without her sacrifices, none of this would have been possible. You will always be loved, and never forgotten.

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Introduction

The majority of battlefield archaeological studies are interested in delineating the boundaries of a battlefield and investigating the spatial relationship of the recovered unstratified battle-related metal artefacts that assist in creating an interpretation of the events of the battle in relation to the primary accounts and historic terrain. The archaeological signature of conflict is principally defined by artefact scatters (Pollard 2009), and the detailed analysis of artefact scatters is an important part in the wider understanding of the entire battlefield landscape (Ferguson 2013: 3). The distribution of artefact scatters can assist and test the historic sources in defining the nature of the military action by suggesting the location, intensity and the extent of the battle that took place (Foard 2008a: 34, 190; Foard 2009: 143-144; Foard & Morris 2012: 22). Battles that occurred before the early modern period deposited unknown quantities of metal artefacts associated with clothing, armour and weapon fragments which are difficult to interpret and to claim with certainty as battle-related artefacts (Foard 2008b: 68; 2012: 35-36). Battlefields dating to the early modern period (1500-1815), while maintaining this trend with artefacts, tend to focus more on the recovered spherical lead bullets fired from small arms as they represent the predominant archaeological find on battlefields in Europe, North America and the United Kingdom (Sivilich 1996: 103; Foard 2008a: 189; 2008b; Smith *et al.* 2009; Butler 2011; Hall *et al.* 2011; Foard 2012). These bullets are not only strong physical evidence tying a battle to a specific location, but they can also provide valuable insight into the detail of the military action when examined individually and as an assemblage.

Established analytical techniques can be used to collect a wealth of information from spherical lead bullets. Current methods in bullet analysis are primarily concerned with the size or calibre of each bullet in the assemblage. The knowledge of the calibre of the bullet can be used in two ways. Firstly, the size of the bullet may enable an advanced understanding of the firearm types and therefore troop types that may have been present at the battle when placed into a calibre graph.

The second method relies on the bullets being placed into a distribution map, where patterns may emerge that enable an understanding of troop locations and movements across the battlefield, but is not detailed enough to give a clear indication of individual movements. The analysis for evidence on individual bullets can expose details about the life span of a bullet, such as how it was manufactured, transported, loaded and fired. However, little comprehensive research on bullet impact evidence exists. Battlefield reports from archaeological investigations generally discuss whether a bullet was impacted or give a minute indication of the level of distortion to a bullet's surface without further discussion or interpretation. The interpretation of impact evidence seen on a bullet's surface has thus far been mainly theoretical and rooted in conjecture based on visual observations of the surrounding landscape in which the bullet was archaeologically recovered (Harding 2012; Sivilich 2016).

The objective of this thesis is to establish how an interdisciplinary approach to the investigation of impacted bullets can be successfully achieved by creating a reference collection of known bullet impacts through a series of proof of concept experimental firing trials. This new avenue of research, then demonstrates for the first time how a proof of concept reference collection of known bullet impacts can be used as a comparative tool against archaeologically recovered bullets to enable an advanced understanding of the nature and character of bullet impact surfaces within the archaeological record. This thesis proves that impacted bullets can retain diagnostic traits from the impact surface to permit for classification, and furthermore provides new insight into the potential site locations of the recovered bullets. This evidence provides a greater understanding of the surface characteristics and alterations noted on archaeologically recovered bullets, and can also provide insight into the potential terrain in which the bullet impacted during battle. In addition to the creation of a reference collection of known bullet impacts, a subjective method for analysing bullets for impact evidence was established building on the foundations of current bullet analysis techniques. A reproducible experimental firing methodology was developed by using military manuals and historic sources to expand upon previous experimental methodologies, along with multiple experimental designs which were instituted by examining the reconstructed historic landscape from two case study battlefields. An external ballistic trajectory modelling program was experimentally produced to enable a rigorous experimental methodology by allowing for the simulation of distance through the manipulation of the gunpowder charge size. However, the inconsistent burn rate of black powder negated that approach, and the modelling program was then used to permit a greater understanding of the distance and velocity of the bullet upon impact.

The need for an inclusive, multidisciplinary experimental firing study with the aim of analysing impacted bullets, is fundamental to advancing the understanding and interpretative abilities of early modern period bullet assemblages and battlefields. Correlating the character of the bullet impact evidence with particular types of impact surfaces is the core aim of this thesis. However, due to the vast experimental scope required to fully complete this objective, numerous future studies would be essential to fully exploit this line of investigation. This thesis demonstrates through a proof of concept the capability of this avenue of research.

This thesis begins by introducing the current methods used in conflict archaeological to examine individual bullets and bullet assemblages. It then focuses on the evidence that can be found on the bullet's surface and how it can be used for interpretation or how it may lead to misinterpretations. This chapter then examines bullet impact evidence within the literature and reveals the need for experimental studies with the aim of collecting and comparing bullet impact evidence. Finally, this chapter ends by proposing a methodology to examine bullet impact evidence, building on current analytical techniques.

Chapter Two examines the ballistics of smoothbore firearms and serves to introduce the basic concepts in the field of ballistics. This is an important issue as any series of experimental firing trials must consider the variables that may affect the bullet before and when it reaches its target. Without this fundamental understanding, the process by which a bullet impacts a target cannot be fully understood. Internal ballistics (Chapter Two) in conjunction with previous experimental firing trials (Chapter Three) are examined to identify specific variables and experimental parameters that need to be further investigated to create a period accurate, comparable, and reproducible experimental firing methodology. All of the identified variables directly affect the way in which a bullet arrives and impacts its target. The variables that could be controlled were subsequently defined throughout these chapters, such as the gunpowder choice, the ratio of bullet weight to gunpowder charge size, bullet composition, and muzzle velocity. Muzzle velocity proved to be the most important starting point as it created not only a scientific baseline in which to compare results, but also provides a direct link into early modern period firing standards. A basic understanding of external ballistics (Chapter Two) is fundamental in the creation of the external ballistic trajectory modelling program developed in Chapter Six, which was created to bolster the experimental firing trials detailed in Chapter Seven.

Chapter Three examines the previous experimental firing trials involving smoothbore firearms and spherical lead bullets. The clear majority of experimental firing studies are focused on the ballistic qualities and the lethality of the firearm and bullet respectively with little to no focus on the wealth of information that can be collected from the impacted bullet itself. This chapter demonstrates the lack of experimentation with the aim of collecting impact evidence from the bullet’s surface.

Chapter Four is a detailed investigation and description of the experimental firing methodology that is used in the experimental firing trials in Chapters Six and Seven of this thesis. This chapter demonstrates how the variables identified in Chapters Two and Three are used in conjunction with early modern period military treatises and scientific publications to create an experimental firing methodology that is in accordance with early modern period firing practises. This chapter will also briefly discuss a second firing methodology that was created using nitro gunpowder. This approach was necessary because of legal changes in the usage of black powder on Ministry of Defence firing ranges.

The experimental designs used in this thesis were created by investigating the tactics and tactical terrain of the early modern period in Chapter Five. Mentions of the terrain are hints at landscape features in which a bullet may have impacted during battle. The two case study bullet assemblages chosen for study are from the Battle of Edgehill fought in the United Kingdom in 1642 during the English Civil War, and the Battle of Oudenaarde fought in Belgium in 1708, during the War of Spanish Succession (1701-1714). These two battlefields have had extensive archaeological investigations conducted on them, as well as the reconstruction of their historic terrain, which allowed for the identification of key landscape features, thus allowing for the creation of multiple experimental firing designs. They are ideal case studies as they demonstrate that the impact evidence found on bullets remains relatively constant despite the difference in sites and locations. This means that the bullet impact evidence collected can be widely applied to battlefields assemblages throughout the early modern period, depending on landscape features on each site. Common landscape features mentioned on both battlefields included the open terrain, chiefly arable and pasture fields and hedged enclosures. Due to the complexity of the ground surface and hedge enclosures, it was decided to begin experimental firing by creating a baseline for future comparison by examining bullet impact evidence against the most basic of ground and wooden surfaces. Ground surface firing included the bounce, roll and ricochet of bullets against sterile soil and stony soil conditions in a simulated ploughed field. The variety of wooden surfaces tested included different species of wood, along with living wood and dead wood. This chapter ends with a discussion on the problems and limitations with firing live ammunition in an experimental study, such as legal and costing issues that can prevent an inclusive study, so that future researchers may have greater ease in overcoming these obstacles.

The experimental designs (Chapter Five) were further bolstered by research into musket range and accuracy in Chapter Six. The experimental firing trials investigate bullet impact evidence at varying distances along the maximum range of the musket (0m to193m). Musket accuracy at medium to long ranges (75m to 193m) proved problematic, and this problem was overcome with the creation of an external ballistic trajectory modelling program. For the first time a modelling program specific to ‘musket balls’ was created for use in this thesis. The modelling program can predict a given velocity at predetermined distances along the musket’s maximum range. The knowledge of a bullet’s velocity at predetermined distances enables the alteration of the gunpowder charge size to simulate distance and therefore collect impact evidence without having to sacrifice impact accuracy or velocity. This data was used to inform the experimental firing trials in Chapter Seven.

The methodologies created in Chapters Four and Five, along with the modelling program data from Chapter Six are then used in conjunction to create a series of experimental firing trials which is the central focus of this thesis and the basis of Chapter Seven. The results of the experimental firing trials discussed in Chapter Seven, created the known bullet impact reference collection, and the first test for the bullet impact analysis methodology created in Chapter One.

Finally, the known bullet impact reference collection was used in conjunction with the bullet impact analysis methodology created in Chapter One to investigate the bullets from both the Edgehill and Oudenaarde archaeological bullet assemblages for diagnostic characteristics in Chapter Eight. The usage of the reference collection of known bullets impacts demonstrates their effectiveness as a comparative tool to investigate impact evidence from bullets within the archaeological assemblages. This chapter reveals the importance of experimental firing and the creation of a known bullet impact reference collection in assisting with the interpretation of impact evidence seen on bullets within the archaeological assemblages.

The thesis concludes by discussing the potentials and limitations of the experimental firing trials as well as the bullet impact reference collection and offers suggestions for future avenues of research for experimental firing.

Chapter 1: Bullet Analysis and Evidence in Conflict Archaeology

Before the creation of a proof of concept reference collection of known bullet impact evidence (Chapter Seven), and the analysis and comparison of that evidence to bullets within the archaeological assemblages (Chapter Eight), a thorough assessment of current bullet analysis methodologies is needed. The first aspect of any research is to identify and understand a standard terminology which will be used moving forward throughout this thesis. With an established terminology, the current methods for bullet analysis will be investigated to address how bullets are discussed and what specifically is examined on the bullets' surfaces. This will then lead into the issue of non-impact related evidence seen on the bullets' surfaces, evidence such as manufacture, transport, loading, firing, and any other surface modifications and intentional alterations. These multiple forms of non-impact related evidence create a knowledge base that enables interpretive, diagnostic bullet analysis and what can be ruled-out when viewing archaeological bullet assemblages for impact evidence. Then, how impact evidence is already discussed in published battlefield reports will be explored, while acknowledging the scant attention paid to impacted bullets in the overall literature. This chapter will propose an alternate methodology to examine bullet impact evidence that is built on the foundations of the previous research. This chapter will conclude by discussing the urgent need for a series of comprehensive experimental firing trials that aim to collect bullet impact evidence from known impact surfaces. This line of investigation will enable not only a better understanding of bullet evidence, but will also enable a greater understanding of the archaeological bullet assemblages from conflict archaeology sites.

1.1 Terminology

Conflict archaeology publications refer to bullets in different manners although they are still referring to the same concept. Bullets can be referred to by their bore, calibre, diameter, and weight in any combination or variation of units of measurement, be it metric or imperial units. In some battlefield studies, bullets can be referred to simply as 'musket shot', without any further description or analysis (Bonsall 2007). For clarification in this thesis, the term bullet refers to the classic spherical lead ball unless otherwise stated. The term ‘shot’ refers to ordnance fired from cannons and other types or artillery. Case shot is fired from cannons and can be easily confused for bullets within archaeological assemblages, so it is important not to confound the two. There will also be a brief discussion about the problem with case shot in section 1.3.5.4 below.

Bore is an older term seen in military manuals and first-hand accounts dating to the 16th -18th centuries, but is sometimes still used in modern battlefield publications, including this thesis. Bore is a way of referring to both the firearm and the bullet it fired. This is because in the early modern period a firearm was usually defined by the size of the bullet it fired. Bore can refer to how many bullets could be cast from one pound of Avoirdupois lead (Harding 1999b: 156), although it is important to point out that the weight of one pound of lead could change, depending on country and locale (Schürger 2015: 74). In England for example, a 12-bore bullet means that 12 bullets could be cast from one pound of lead, each bullet weighing roughly 37g. Bore can also refer to the internal diameter of the gun barrel. From the late 17th until the mid-19th century there were three principal bore sizes used in small arms for the British Army that were manufactured or purchased by the English Board of Ordnance, known as musket, carbine and pistol bore (Harding 1999a: 156). This will be discussed in further detail in Chapter Four, section 4.6. The term bore is still in use today in reference to modern firearms, although it is generally used to indicate shotgun gauges (Pollard & Oliver 2003: 95; Branstner 2008: 171).

Calibre is a term that was intermittently used in the 17th century but became more popular during the modern era. Calibre, like bore, can mean both the internal diameter of the gun barrel of the firearm and the diameter of the bullet. Calibre is usually expressed in either imperial inches or metric millimetres. A bullet can be described as having a 0.64-inch diameter (0.64 calibre bullet) or as having a diameter of 16.26mm. Finally, bullets can be discussed by their weight which is generally expressed in grams (g); however, some studies refer to bullets in grains (gr) instead. How bullets are described are ultimately interchangeable, and to prevent confusion and to provide consistency bullets in this thesis will be referred to either by their weight in grams (g) or their bore size.

Finally, windage is the difference between the diameter of the bullet and the internal diameter of the firearm barrel (Foard 2012: 41; Sivilich 2016: 18). A further discussion on windage can be found in Chapters Two (section 2.1.3) and Four (section 4.6) of this thesis where the ballistics of a firearm are examined.

1.2 Current Methods for Bullet Analysis in Battlefield Archaeology for the Early Modern Period

The origins of battlefield archaeology can be attributed to an accidental brush fire in August 1983 at the Little Bighorn Battlefield National Monument. The brush fire burned away the thick vegetation that had long since obfuscated the ground surface of the battle of the Little Bighorn (June 25-27 1876); with the vegetation cleared, artefacts from the battle became exposed (Scott & Fox 1987: 7; Sivilich 2016: xxi-xxii). The initial survey, carried out by Richard Fox and Douglass Scott, uncovered a variety of battle-related artefacts and the following report endorsed further investigation (Scott & Fox 1987: 7). The subsequent field seasons dealt with a major archaeological paradox; battles are not contained to small plots of land but can extend for miles and traverse wide areas of the surrounding landscape. In-depth archaeological investigations do not allow for a quick, detailed investigation of so much land in a timely manner. Time being an issue, how does one reconcile the problem of investigating an unknown length and breadth of the landscape in an in-depth and detailed method? The solution to the problem, in the case of the Little Bighorn, was the deployment of metal detectors to locate metal artefacts within the soil, and with the success of this idea came the creation of the concept of battlefield archaeology (Scott & Fox 1987: ix; Sivilich 2016: xxi-xxii).

The archaeological investigation of the Little Bighorn battlefield recovered a vast collection of artefacts. The contextual and spatial relationship of these artefacts allowed for an advanced interpretation of the events of the battle. Artefacts from battlefields are human material culture and, as such, are physical evidence of human activity (Scott & Fox 1987: 49). A large ensemble of artefacts recovered from the Little Bighorn battlefield were pieces of equipment belonging to soldiers, such as buckles, buttons, pieces of broken firearms, as well as the human remains of the soldiers that had fought and died (Scott & Fox 1987: 86-107; Scott *et al.* 1989: 89-103).

However, the bullets and their cartridge cases were the most illuminating artefacts recovered because they were the most abundant, and therefore had the most potential to provide a clearer interpretation of the events of the battle (Scott & Fox 1987: 52; Scott *et al.* 1989: 153).

Firearms-identification analysis is a modern forensic technique that was used to identify the signatures of the bullets and cartridge cases recovered from the Little Bighorn battlefield (Scott *et al.* 1989: 153). This technique allows the comparison of bullets and cartridge cases, which permits the identification of the firearm type associated with the bullets and cartridge cases (Scott & Haag 2009: 104). Class and individual characteristics of the firearm are imprinted onto the bullet and cartridges cases, such as the firing pin impressions left on the cartridge cases after being fired, and the number of lands and grooves imparted on the bullet from the rifling of the firearms (Scott & Haag 2009: 104-107). Knowing this information, it was then possible to determine the number and types of firearms that were present on the battlefield by examining the bullets and cartridge cases recovered during the archaeological investigation (Scott *et al.* 1989: 153; Scott & Haag 2009: 104). With this technique, it was even possible for Douglass Scott and team to track the movement of individual firearms across the battlefield.

As effective as this method is, it cannot be applied universally to all battlefields that involve firearms due to fundamental technological progressions within the firearms and bullets respectively. The bullets from the Little Bighorn battlefield are a modern style conical bullet, where the bullet is physically connected to the cartridge case which contains the gunpowder charge that propels the bullet. Modern firearms have rifled barrels which contain lands and grooves as well as a firing pin that detonates the bullet's charge inside the cartridge casing. These characteristics allow for modern forensic techniques to be used to collect the evidence needed for an advanced interpretation of the events of the battle.

Muzzle loading smoothbore firearms used in the early modern period do not impart the same type of individual characteristics on the bullet as modern firearms do. As a result, smoothbore firearms must be investigated differently. Early modern period bullets consist of the conventional spherical lead bullet, although there were also other obscure variations of the conventional spherical bullet as will be seen in section 1.3.5. Smoothbore firearms have no rifling and thus no lands and grooves which can be imparted onto the bullet, nor do they contain a firing pin to ignite the propellant charge. A smoothbore firearm barrel consists of a long smooth tube attached to a wooden shoulder stock. The gunpowder is poured into the muzzle of the firearm, and then the bullet is rolled into the chamber or pushed into the chamber of the firearm via a ramrod. Cartridges existed in the early modern period, although they were typically made of paper. The bullet and gunpowder charge were packed into a paper tube which was folded at one end and tied at the bullet-end with twine. The folded end was typically torn open, a small amount of powder was poured into the priming pan, and the bulk of the powder poured down the muzzle. The bullet was either rammed down the barrel still wrapped in paper, or the bullet was squeezed out of the paper cartridge and dropped or rammed down the barrel until it was seated on the powder charge in the chamber; in this case, the paper was discarded. The paper cartridge would generally not be preserved in the archaeological record, since being an organic material would be subject to rapid decay.

The preliminary methods used to analyse bullet assemblages dating to the early modern period are primarily focused on the overall size of the bullet as well as its level of deformation or distortion. Knowledge of the size of a bullet allows for potential identification of the firearm used to fire it. This is completed by taking the measurement of the bullet's diameter and by taking the weight of the bullet to discern its calibre (Sivilich 1996; Branstner 2008; Foard 2008b: 99; Smith *et al.* 2009; Foard 2012: 51). Knowledge of the calibre of the bullet can also assist in discerning the troop types that fired the bullet (Foard 2008a: 191; 2008b: 79; Foard & Morris 2012: 5), and in some cases it can differentiate which army fired it, thereby revealing a clearer picture of the events on the battlefield (Sivilich 2009). Along with mapping bullet distributions during a battlefield archaeological survey, these methods have become standard practice in bullet analysis (Babits *et al.* 2003; Sivilich 2005; Branstner 2008; Smith *et al.* 2009; Foard 2012).

The physical composition of the bullet itself enables an in-depth diagnostic analysis. Due to the malleable nature of lead, distinctive features can be transferred onto the bullets' surfaces allowing for diagnostic analysis on an individual scale (Branstner 2008: 182; Smith *et al.* 2009; Foard 2012). Conflict archaeology publications and battlefield reports commonly note the transfer of characteristic traits onto the bullet's surface upon impact or contact with another surface. The bullet's surface retains impressions transferred throughout the bullet's life span from, the manufacture of the bullet to the loading and firing of the bullet (Eyers 2006; Scott & Haag 2009; Sivilich 2009; Smith *et al.* 2009; Foard 2012). Experimental firing has confirmed the transfer of characteristic traits onto the bullet's surface from impact with trees, logs and other wooden surfaces (Linck 2005; Scott *et al.* 2017), as well as abrasions from ground impacts (Miller 2009; Foard 2012), although systematic experimentation to collect and analyse impacted bullets was not the major focus for the majority of these experiments and the impact evidence observed in those studies was not fully exploited, nor were they used for comparison to bullets from the archaeological assemblages. These experiments will be discussed in further detail in Chapter Three of this thesis.

1.2.1 Establishing Bullet Calibre

Establishing the calibre of a bullet can be determined in two ways. First, if the bullet retains its spherical shape the diameter of the bullet can be measured. However, if the bullet has become deformed and no longer retains its spherical shape, which is often the case, then diameter measurements become futile. If the bullet has been deformed through either impact or improper manufacture, then the only way to determine its calibre is through weight.

Measuring the diameter of a bullet is carried out using a set of callipers. Calliper measurements can be taken on the mould seam or perpendicular (at a 90°angle) to the mould seam (Babits & Mannesto 1994: 4; Sivilich 1996: 103; Foard 2009: 5). Research by Babits and Mannesto indicate that diameter measurements perpendicular to the mould seam are better at approximating the true diameter of the bullet (Babits & Mannesto 1994: 4). Foard states the reason for this is that it more accurately establishes the depth of the mould chamber in which the bullet was cast (Foard 2009: 5). Certain types of manufacturing errors can cause the mould seam to be offset, thereby causing an overall increase in the bullet's diameter (Babits & Mannesto 1994: 4; Foard 2008b: 100; 2012: 51), which is generally caused when the bullet mould is not lined up properly; this is discussed in further detail below in section 1.3.1. However, the largest problem with determining the diameter measurement of a bullet from the archaeological record is the distortion of the bullet due to firing and/or impact. 41% of the bullets recovered from Edgehill and 79% of the bullets recovered from the Oudenaarde archaeological survey are impacted; this subject will be discussed in more detail in Chapter Eight.

The second method used to establish a bullet's calibre is by measuring its weight; however, this method is not without its limitations. Manufacturing errors can occur leaving a void in the bullet: this can create a bullet that is the same size as expected, but the weight will be lower than expected (Branstner 2008: 171; Foard 2008b: 100; 2012: 51; Harding 2012: 28). The weight of a bullet can also be affected by the amount of flashing or sprue that remains on the bullet after the manufacturing process. The total fluctuations in weight are not as significant as to cause the calibre to be misinterpreted. Weight fluctuations can also occur due to the material composition of the bullet when it is cast, as not all bullets are made of pure lead. Sometimes, tin and pewter impurities could be mixed with the lead during casting, which could cause the bullet to weigh less than expected. The total amount of these impurities within the bullet could cause calibre confusion as the specific weight of tin is substantially lower than that of lead (Schürger 2015: 128-129; Sivilich 2016: 24).

For impacted or otherwise distorted bullets, bullet weight can be used to discover the bullet's diameter. This can be done by using an equation that over the years has become known as the Sivilich formula: (Sivilich 1996: 104; 2005: 8; 2009: 87; Smith *et al.* 2009: 55). This formula does mix imperial and metric units, although this problem is simply fixed by converting the diameter in inches to millimetres.

Diameter in inches = 0.2228 x (weight in grams) ^$\frac{1}{3}$

It is important to note that some bullet weight loss can occur from the compression and melting of the bullet during the firing process (Foard 2008b: 99-100; 2009: 6; 2012: 51; Harding 2012: 28). Experimental firing completed by Dave Miller in 2009 showed that the degree of weight loss due to firing is variable depending on if a wad was used. Miller's experiments revealed that weight loss is on average 1.5g without a wad and 0.5 to 0.94g with a wad (Miller 2009: 99). Bullet weight loss can also be attributed to corrosion (Homann & Weise 2009: 34), although this area of study has not been closely examined. Finally, bullet weight loss from the firing and impact processes can be very significant, as noted in the experimental firing trials in Chapter Seven of this thesis, where some bullets lost over 12g due to impacting stones within the soil.

1.2.2 Bullet Calibre Interpretations

Knowledge of the bullet's calibre can be used to infer the types of firearms used in a battle (Foard 2008b: 99; 2012: 51), and in some instances, it can be used to infer which army fired the bullet (Sivilich 2009; 2016: 28). This information is generally exhibited in two ways; the calibre graph and the calibre distribution map. However, recent research by Schürger (2015) has called into question the validity of using the weight and diameter of bullets for the allocation of firearm types, stating that the actual weight for certain calibres was intentional manufactured lower than reported within early modern period military manuals due to a lack of standardisation (Schürger 2015: 128-137, 371-372). For further discussion on this subject, it is advised to consult Schürger (2015) as this subject is outside the scope of this thesis.

1.2.2.1 Calibre Graph

For bullet assemblages that come from archaeological sites dating to the 17th century, it is advised to cross reference a bullet's weight in grams to bore size. This enables an understanding of the patterns within the entire assemblage. The peaks in the graph enable an understanding of what firearm types were present in the battle. As firearms were not standardised in the 17th century, there is a wider range of peaks present revealing the diversity of firearms present. Knowing firearm types, one can then distinguish troop types present at a battle. Foard (2008) notes to be careful in the consideration of bullet weight loss due to firing and impact (Foard 2008a: 133; 2009: 7). Figure 1.1 below illustrates this concept.

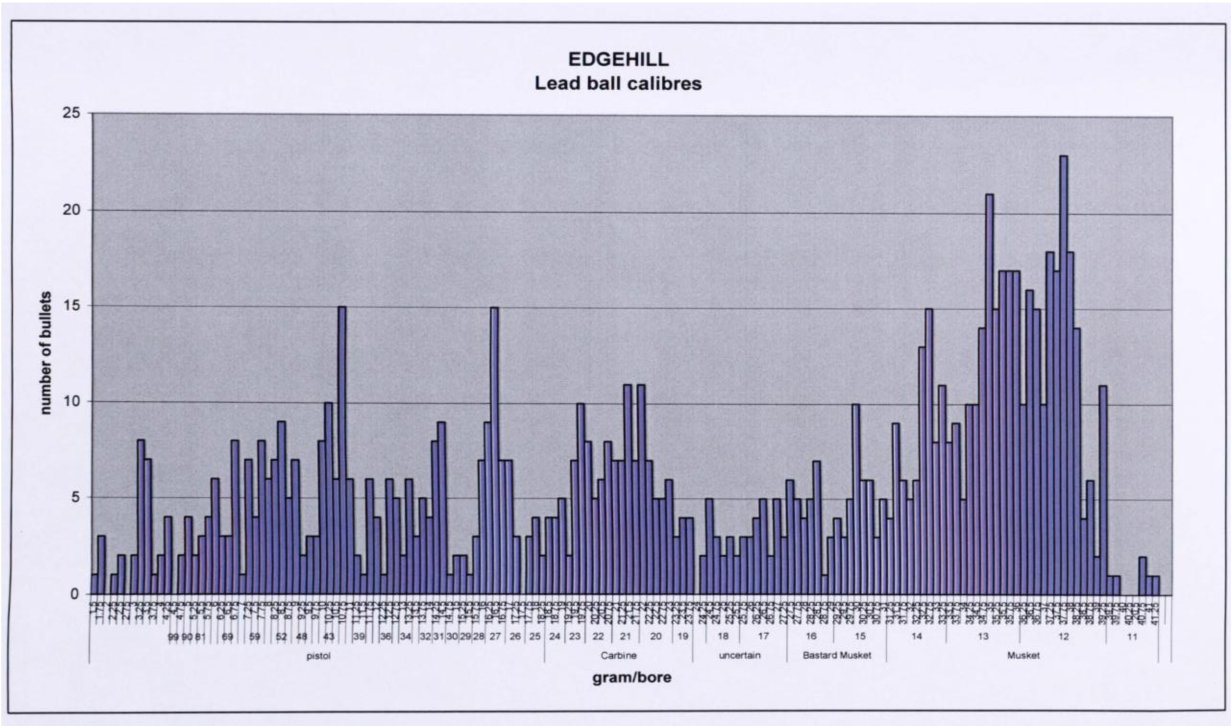

Figure 1.1: Edgehill battlefield calibre graph of all bullets, courtesy of Foard 2012: 157.

With 18th century battlefield archaeological sites, one can use the same type of graph. With sites dating to the American War of Independence, such as from the Monmouth battlefield State park two distinct peaks will form on the calibre graph as seen in figure 1.2. These peaks are the result of the distinctively different firearms being used by opposing armies; this is due to the relative standardisation of firearm types by this period (Sivilich 2005: 8; 2009: 87).

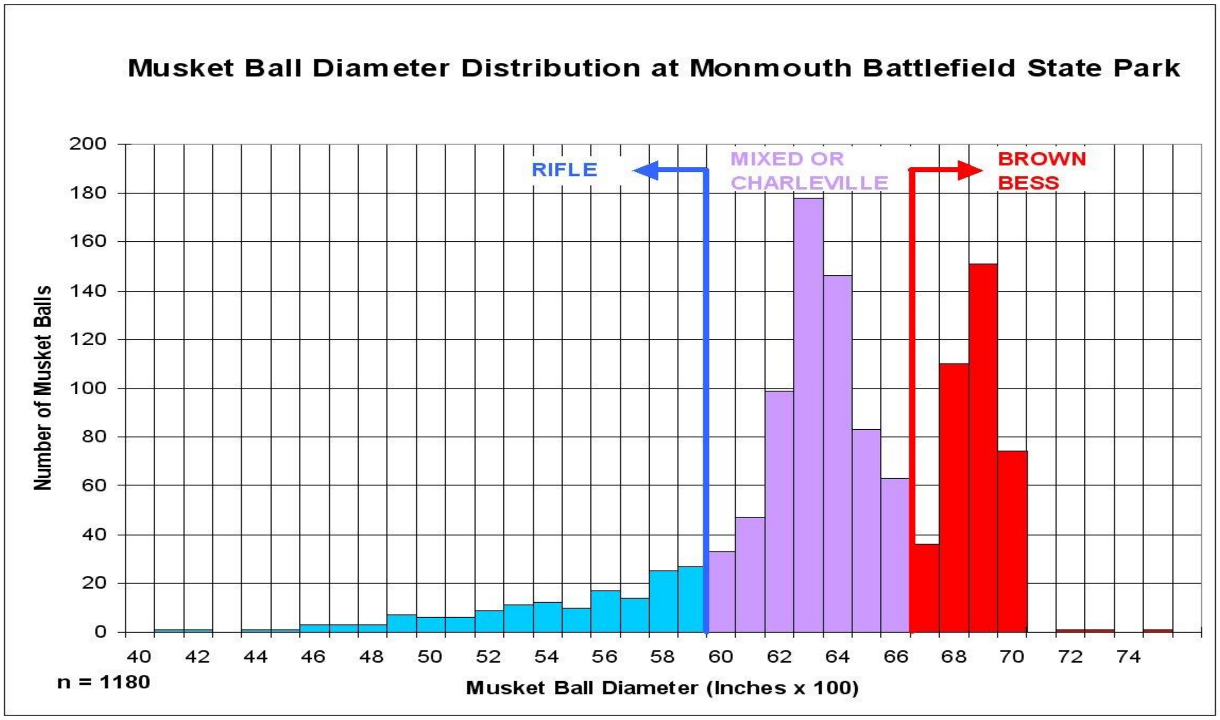

Figure 1.2: Monmouth battlefield calibre graph of all bullets, courtesy of Sivilich 2016: 32.

1.2.2.2 Calibre Distribution Map

A calibre distribution map is similar to an artefact scatter map, except only the bullet calibres, are present. The key to understanding the distribution of bullets across the battlefield is understanding the firearms that were used during the battle (Schürger 2015: 70). This gives the bullet context within the battlefield and reveals any patterns that may be present. These patterns can allow for an advanced interpretation of troop movements or to track certain actions, such as a rout or a flanking manoeuvre. Distinct, individual patterns can emerge on distribution maps especially when two armies meet using distinctly different calibre bullets. An example of this can be found in the distribution map below (figure 1.3), which shows that the bulk of the infantry action, denoted by musket calibre bullets, occurred in the centre of the battlefield. Distribution maps can also allow for a more advanced understanding of the events of a battle within the battlefield landscape as the scatters of bullets can allow for the identification of the location, intensity and the extent of the battle.

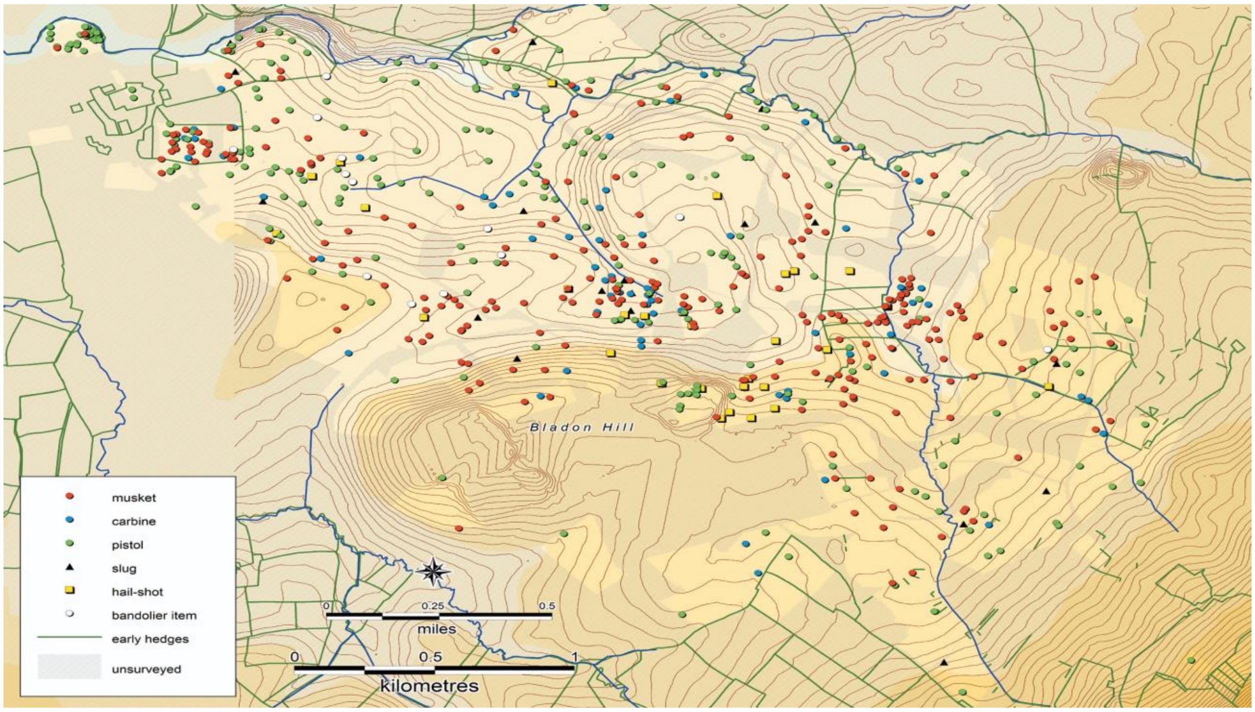

Figure 1.3: Edgehill battlefield calibre distribution map of all bullets, courtesy of Foard 2012: 174, DTM copyright Intermap Technologies Inc. 2007, provided by Getmapping PLC.

1.3 Bullet Evidence- Eliminating Non-Impact Related Evidence

Distinctive characteristics can be transferred onto a bullet's surface, allowing for individual diagnostic analysis. The evidence seen on a bullet's surface varies in degree and are likely not all from impacting a target on the battlefield. To fully understand the evidence found on bullets, it is important to investigate all potential evidence that could appear on a bullet throughout its life span, beginning with the manufacturing of the bullet, to the transportation of the bullet, to the loading and firing of the bullet. Much of this evidence has been confirmed through either experimental firing or other forms of experimentation by Dan Sivilich (1996-2016), and Glenn Foard (2008- 2013).

It is important to understand these types of evidence for two reasons. First, so that specific types of surface evidence and alterations can be recognised for what they are and eliminated as non-impact related evidence and secondly because these types of evidence can obfuscate and overlap with impact evidence which could confuse interpretative analysis.

1.3.1 Manufacturing Evidence

The manufacturing process of bullets can leave distinctive diagnostic characteristics on the surface of the bullet (Foard 2008b: 141; 2009: 15; 2012: 94). These manufacturing characteristics must be explored and identified so they are not confused with traits that are related to impact damage. This is especially important once corrosion has set in on a bullet's surface, as corrosion degrades the surface characteristics making them difficult to identify.

Bullets in the early modern period were manufactured by melting lead and other metal alloys such as tin and pewter that have a low melting point, into either a single two-part mould or a larger gang mould. Figures 1.4. is a single two-part mould from a Springfield musket used in the American Civil War. Bullet moulds like the one pictured below were issued to soldiers throughout the early modern period, so they could cast their own bullets in the field. Figure 1.5 is a larger gang mould used for manufacturing bullets of multiple calibres. Once the lead cooled, the mould was opened, and the bullet was removed from the mould. A mould seam is present around the circumference of the bullet derived from the location of where the two halves of the mould joined, this is illustrated in figure 1.6. How precisely the two halves of the mould fit together can influence the size of the mould seam. Moulds that have a tight fit can leave little evidence of a mould seam (Foard 2008b: 145-146; 2009: 18; 2012: 98-99), this can be seen in figure 1.7.

Figure 1.4: Single cavity bullet mould with sprue nippers built into the handle.

Figure 1.5: Gang mould from Fort Paris, New York, photo courtesy of Dan Sivilich.

Figure 1.6: Bullet showing mould seam and extended sprue.

Figure 1.7: Bullet with no mould seam, cast by the author.

A loose-fitting mould, where the two halves do not seat tightly will allow excess lead to seep around the mould seam causing a more robust and easier defined mould seam. If too much lead seeps through the loose mould, then the surplus lead can form beyond the mould seam. This surplus lead is called flashing (Foard 2008b: 146; 2012: 98) and is pictured in figure 1.8.

Figure 1.8: A bullet exhibiting flashing on the mould seam.

Alternatively, if the two halves of the mould did not join up properly, then the two halves of the bullet would not match up, thereby creating an offset bullet. An offset bullet varies with the degree in which the two halves of the mould did not match up appropriately to create a sphere (Sivilich 2005: 7; Foard 2008b: 146; 2009: 19; Sivilich 2009: 84; Foard 2012: 99). Figure 1.9 illustrates an offset bullet.

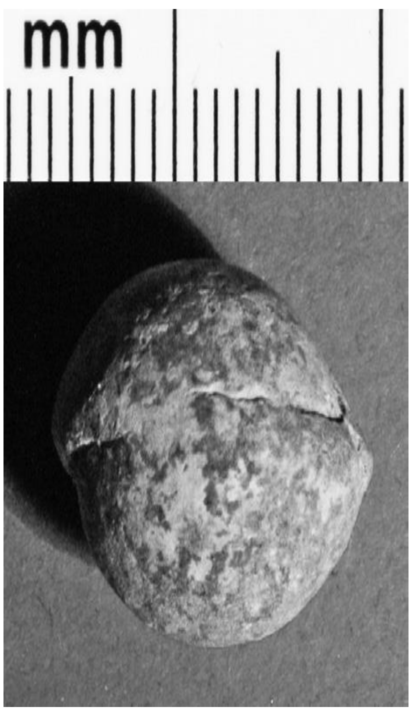

Figure 1.9: Edgehill 2268, an offset bullet, courtesy of Glenn Foard.

Once the bullet is cast and removed from the mould, a set of nippers that are either attached to the bullet mould itself or a separate instrument altogether are then used to clip off the casting sprue from as close to the surface of the bullet as possible. The casting sprue is an elongated piece of lead extending from the top of the bullet and is pictured in figure 1.6. The sprue is the scrap lead from the opening channel in the top of the mould that was used to pour the molten lead into the mould (Sivilich 2005: 7; Foard 2008b: 142; Sivilich 2009: 85; Foard 2012: 94-97; Sivilich 2016: 16-17). Single two-part moulds leave a single casting sprue attached to the bullet that sits on top of the mould seam. A gang mould would be used to produce multiple bullets in one attempt, in this case, each bullet is still left with one casting sprue. However, all the casting sprues will be conjoined by a single strip of lead (Foard 2008b: 143; 2009: 16; 2012: 97).

The removal of the casting sprue will leave a distinctive half-moon depression where the sprue once was located, although the indentation from the removal of the sprue can be deeper from bullet to bullet (Foard 2008b: 144; 2009: 16; 2012: 97). Figure 1.10 is an example of different impression that can be left from the removal of the sprue by different instruments. The bullet on the left contains a raised lip with a circular indentation, whereas the bullet on the right contains a half moon impression.

Figure 1.10: Different tools leave different impressions, two bullets with removed sprue with different evidence.

During the manufacturing process, numerous casting faults can occur. Casting faults can leave distinctive evidence on a bullets' surface. Most of these casting faults occur when the bullet mould is cold or not filled properly. A cold bullet mould will leave a disorganised wave-like appearance on the surface of the bullet; the appearance of this can vary from bullet to bullet as seen in figure 1.11 below. This is due to the molten lead cooling in stepped layers instead of cooling in a uniform appearance. Latitudinal lines are a series of evenly spaced lines that run along the bullet's surface. The lines in the mould result from how the mould itself was created (figure 1.12) (Foard 2008b: 147; 2009: 20; 2012: 99-101). A potlid casting fault can occur because there was not enough molten lead in the ladle as it was poured into the mould; this would require the individual casting the bullet to fill the bullet mould twice. This results in a bullet with two or more obvious layers, as can be seen in figure 1.13. Figure 1.14 displays incomplete bullets; this can occur when the bullet mould was not filled completely. The most common type of casting fault is caused by the presence of air bubbles in the lead that creates a void in the bullet. This feature is not generally seen on the surface of the bullet but can be seen when the sprue is removed (Foard 2008b: 146; 2009: 19; 2012: 98-99).

Figure 1.11: Casting faults from a cold mould showing disorganised surface texture.

Figure 1.12: Latitudinal lines.

Figure 1.13: Edgehill 871 showing a potlid casting fault.

Figure 1.14: Casting faults showing incomplete bullets

Bullets were manufactured in many situations and locations. Bullets could have been manufactured by the soldiers themselves in camp or garrison, by a local magazine or by an arsenal depending on circumstances. No attempt is made in this thesis to differentiate where a bullet was manufactured based on the associated manufacturing evidence. However, it is a recommendation of this study to investigate bullet assemblages recovered from garrisons, sieges, battlefields and arsenals to explore if this information can indeed be inferred.

Military manuals and primary accounts allude to the manufacture of bullets in the field by soldiers on campaign. It was normal for soldiers in the 17th and 18th centuries, when issued with their firearm, to also be issued with their own bullet moulds, melting pots, ladles and sprue nippers to ensure that the bullets fired from those firearms were of the correct calibre (Foard 2008b: 142; 2012: 94-97). An English military manual written by Markham (1625) states that part of the responsibility of English army Corporals was to oversee soldiers casting their bullets if needed and to teach any soldiers who did not know how to cast their bullets (Markham 1625: 8). This is also demonstrated during the American Revolutionary war (1775-1783), where American riflemen active during the battle of Cowpens (January 17, 1781) were issued one-pound lead bars which were to be melted into bullets. Because the American riflemen carried their personal rifled musket, there was no standard calibre between them as each rifle varied from soldier to soldier. As a result, each soldier would need to create their bullets in the field to ensure they fit within their musket during battle. They would use the issued lead bars instead of using any pre-manufactured bullet supplied by local magazines or arsenals which would not be guaranteed to fit all soldiers' rifles (Babits 1998: 14).

Eldred (1646) details the provisions an army would need for 15 days in the field. Eldred lists 2000 'hundredweight shot' of lead, 2000 for both harquebuses and muskets, which infers pre-manufactured bullets. Eldred also explains that an army would carry all manner of melting ladles and moulds for manufacturing bullets in the field, for both artillery and small arms (Eldred 1646: 116-117). Eldred also details the provisions an army would need if defending a town while under siege which consists of at least 200 common muskets with accompanying moulds and roughly 25,000 hundredweight of lead, all for making bullets (Eldred 1646: 167-168). A hundredweight is a term meaning a ton (Foard 2012: 94).

Some English towns would have local magazines where ammunition and supplies would be stored for the army and, if the army required further munitions the local populace would be contracted to help. Howes (1992) investigated how the parliamentary garrison of Gloucester (who were isolated and without resupply), during the English Civil War survived a month long siege using only locally acquired resources to manufacture ammunition (Howes 1992: 37). Mr Baker, who was a local bell founder was paid for making bullets and stocking the local magazine both during and after the siege. Robert Holford was paid by the Gloucester city council for acquiring 500 pounds of lead and accompanying bullet moulds, and the local bookseller was paid for white paper which was used for making cartridges for the cavalry (Howes 1992: 38).

Besides soldiers casting bullets in the field and local citizens assisting in the maintenance of local magazines, bullets were also cast at Royal arsenals. An ammunition laboratory was established in the Royal arsenal at Woolwich in 1695. It was reported that the inside of the ammunition laboratory contained moulds for casting 'bullets and balls' of all sizes from one pound to two hundred and fifty pound shot (Anonymous 2012: 24). Moulds were also reported in various forms for casting grape, canister and chain shot, which are related to artillery (Anonymous 2012: 24).

The manufacturing process of a bullet can leave a multitude of different characteristics on the surface of the bullet. Whether a bullet was manufactured by a soldier in the field before battle, or by a local magazine or at an established arsenal, these manufacturing characteristics are the first evidence seen on the bullet during its lifespan. Knowing the distinction between manufacturing evidence and impact evidence is essential to accurately analysing and recording archaeological bullet finds and assemblages. However, manufacturing evidence is not the only evidence that can be found on bullets that are unrelated to impact evidence.

1.3.2 Transportation Evidence

Once the bullets were manufactured, they were typically stored in barrels in store houses, for local magazines and arsenals, or in the case of an individual soldier making his own bullets, in his bullet or cartridge pouch. In some cases, munitions were purchased from other nations, and those munitions had to be imported. Such a case can be found in the English Civil War, where Dutch merchants supplied both the Parliamentary and Royalist armies (Kenyon & Ohlmeyer 1998: 251-252). In the American War of Independence, the English army was resupplied with lead and bullets from England (Sivilich 2005: 7; 2009: 85-86). In both cases, the bullets would have been packed into barrels or crates and loaded onto a transport or merchant ship. After the docking of the ship to port, the barrels of bullets would then be loaded onto wagons. Foard (2008, 2012) notes that during the English Civil War bullets were usually supplied to the army from local magazines in barrels and those barrels were then loaded onto wagons as part of army’s baggage train. From there the bullets were then distributed to the soldiers, where they would remain in their bullet pouches until used (Foard 2008b: 148; 2012: 101).

During the transportation of the bullets by either baggage train, ship or in the bullet or cartridge pouches carried by soldiers on the march or some overall combination of all factors considered, the bullets would be constantly, yet gently bumping against each other. The bumping of the bullets against each other leaves multiple tiny, shallow, circular depressions on the surface of the bullet, termed micro-dimples by Dan Sivilich. This constant bumping can even cause certain evidence from the manufacturing process to be obfuscated and even erased. Evidence such as flashing, the mould seam and even the sprue and sprue cut can be worn down by the constant friction (Sivilich 1996: 103; 2005: 7; Foard 2008b: 148; 2009: 21; Sivilich 2009: 85-86; Foard 2012: 101).

1.3.3 Loading Evidence

The loading of a bullet into a firearm can leave distinctive evidence on the surface of the bullet. This evidence comes in the form of a shallow circular depression or facet, much larger than those found from the bumping caused by transportation; this depression can be found in figure 1.15. This impression comes from the use of a metal ramrod to properly seat the bullet onto the powder in the firearm's chamber or breech (Scott & Haag 2009: 113; Foard 2012: 105; Sivilich 2016: 36). Sivilich (2005, 2009) notes that if the bullet were to slightly rotate inside the chamber each time the bullet were struck with the ramrod, then multiple ramrod impressions will be left on the bullet's surface (Sivilich 2005: 9; 2009: 88).

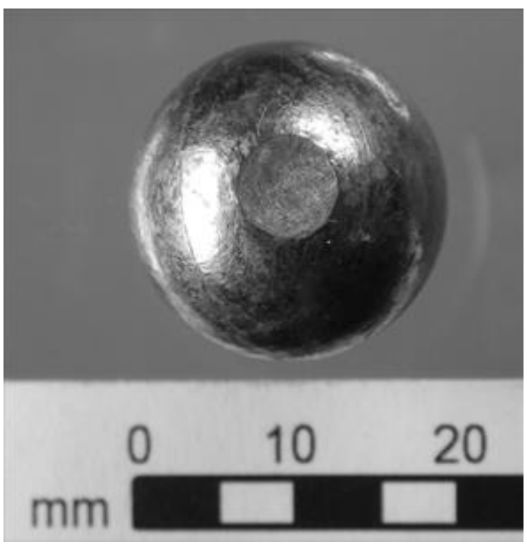

Figure 1.15: Ramrod indentation, photo courtesy of Dan Sivilich

During the early modern period, the loading procedure of the firearm changed. During the English Civil War, the powder charge was poured into the barrel mouth from a bandolier, then the bullet was taken from the soldier's pouch or mouth and rolled down the barrel and into the chamber of the firearm. Sometimes, due to either bullet size and firearm windage or due to firearm fouling, the bullet would have to be forced down the barrel with a ramrod until it was seated properly on top of the powder charge (Foard 2012: 104-105). It is important to note that during the English Civil War a ramrod would have been made of wood, as Eldred (1646) suggested that the rammer should be made of a strong, hard wood (Eldred 1646: 23; Foard 2012: 105). Experimentation conducted by both Harkins (2006) and Foard (2008) with wooden ramrods reveal that they do not leave the same shallow circular depression on the bullet's surface as metal ramrods, they, in fact, leave no loading evidence (Harkins 2006: 45; Foard 2012: 105).

By the time of the American War of Independence, firing procedures had changed. Metal ramrods had taken the place of wooden ramrods and cartridges became the common method to load a firearm. Once the cartridge was torn open, and the powder was poured down the muzzle, the bullet was then either rammed down the barrel still wrapped in paper or dropped into the barrel after the remaining paper was discarded. In either case, the bullet was then rammed into position on top of the powder charge using a metal ramrod (Foard 2008b: 155; Sivilich 2016: 36-37). Bullets that were rammed into position using a metal ramrod would take on a circular depression as seen in figure 1.15. However, Smith et al (2009) and Sivilich (2016) state that when the bullet was rammed into the chamber still wrapped in cartridge paper, that the paper would act as a soft insulator and the ramrod indentations would not be transferred onto the bullet's surface (Smith *et al.* 2009: 55; Sivilich 2016).

On occasion, a firearm would misfire, and the bullet would be stuck in the chamber. If this happened, then the bullet would have to be pulled. This was accomplished with a device that attached to the opposite end of the ramrod called an extraction screw. These screws were often used in combination with a worm. A worm is a metal tool with a double helix shape, each arm of which has a corkscrew like appearance. A worm is used to remove the wadding from the barrel and combining a worm and screw into a single tool made fewer implements a soldier had to carry. However, this dual-purpose tool was generically referred to simply as a worm. The screw mechanism of the worm would be used to drill into the bullet's surface, creating a hole with threading marks around the inside surface of the hole. Both the worm and the resultant threading marks can be seen in figures 1.16 and 1.17 below. Foard (2012) states that worms dating to the

17th century leave a coarse thread and that worms used in the 18th century have a finer thread pattern (Foard 2008b: 155; 2012: 105-106; Sivilich 2016: 36-40).

Figure 1.16: Musket Worm, photo courtesy of Dan Sivilich.

Figure 1.17: Pulled bullet, photo courtesy of Dan Sivilich.

1.3.4 Firing Evidence

When a bullet is fired there is a possibility that several distinctive characteristics will be imparted onto the bullet’s surface. This firing evidence can be a source of confusion, as most battlefield reports use firing evidence alone or in conjunction with impact damage for interpretive purposes. However, depending upon certain factors, a fired bullet could contain no distinctive firing evidence on the bullet’s surface at all, as noted by Miller (2009) in his experimental firing studies, which are discussed in further detail in section 1.4 below. Furthermore, this is a subject discussed in Chapters Seven and Eight of this thesis, where experientially fired bullets contain no evidence of firing. Throughout Chapter Eight it is noted that some bullets contain evidence of impact, but no evidence of the firing process and alternatively, some bullets can contain firing evidence but no impact evidence. This can lead to potential misidentification and misinterpretation of the evidence seen on the bullet's surface. The conditions in which the bullet was under during the firing process seems to determine whether this type of evidence is imprinted on the bullet. There are different types of firing evidence such as banding, melting and powder pitting, as well as impressions from smoothbore barrel walls and rifled barrels. Each type of firing evidence will be explored further below.

1.3.4.1 Banding Evidence

Banding evidence (figure 1.18), also known as barrel banding, and compression banding, produces a smooth band that can run around the circumference of the bullet, and is the most distinctive and common form of firing evidence (Scott & Fox 1987: 52; Sivilich 1996: 104; Foard 2008b: 157; 2009: 23-24; 2012: 108; Foard & Curry 2013: 168; Sivilich 2016: 48-49). The banding effect is variable from one bullet to another, even with bullets fired from the same firearm. There are many potential causes of the banding effect.

Figure 1.18 Bullet showing banding evidence, photo courtesy of Dan Sivilich.

One possible cause of the banding effect is the peak pressure from the internal ballistics cycle. This peak pressure is the result of the gunpowder's ignition and the resultant gases expanding within the chamber of the firearm. Experimental firing by Harkins (2006) determined that the banding effect found on the surface of the bullet is from the bullet 'setting up' due to high peak pressure in the barrel as the powder was ignited. The process of setting up causes the bullet to expand to fit the bore of the barrel (Harkins 2006: 42). The second potential cause is called in-bore sliding friction wherein the bullet is forced and compressed into the barrel wall by the expanding gases from the gunpowder's ignition (D'Antoni 1789: 122; Greenwood *et al.* 1987: 174). As experimental firing has shown, this can be a contributing factor for the banding effect seen on fired bullets (Miller 2009: 103-105). A third cause for the banding effect could be due to windage. Experimental firing conducted by Dave Miller (2009) demonstrated that when the same size bullet is fired from different bore size firearms, the distortion and banding seen on the bullet's surface are more pronounced with smaller bore diameter barrels. When the same size bullets were fired from larger bore diameter barrels, the bullet was less visibly deformed and remained more spherical in shape (Miller 2009: 96-98). As a result, Miller (2009) concluded that the greater the windage, the less banding that will occur on the bullet. The last possible cause of the banding effect can be a combination of the above factors acting on the bullet.

To investigate the cause of the banding effect seen on the bullet's surface, Miller (2009) loaded a musket with a 12-bore bullet (37g), using a 5g gunpowder charge without a wad and inserted a ramrod into the barrel of the gun. The other end of the ramrod was pressed up against a steel plate which would prevent the ramrod from discharging out of the barrel. No wad was used as it was previously thought that the gases escaping past the bullet during the internal ballistics cycle was the cause of the banding, although Miller also notes that bullets fired with a wad can also contain a band. The results from this experiment reveal that a band was clearly visible on the bullet. Miller concluded that the banding effect is caused by both the gas escaping around the bullet and the bullet rubbing up against the barrel that combine to create the overall banding evidence on the bullet (Miller 2009: 103-105).

It is important to keep in mind that there are many bullets from the archaeological record that have clear signs of impact damage, but no banding evidence. Bullets fired experimentally with the same firearm demonstrate that not all fired bullets will have banding evidence.

1.3.4.2 Melting and Pitting

When a bullet is fired, it can be subject to gross melting across its surface, caused by the ignition of the gunpowder charge in the chamber of the firearm. The bullet's surface will take on a disorganised, pitted appearance, as seen in figure 1.19. Pitting is represented as a rough surface texture on one hemisphere of the bullet, while the opposite hemisphere of the bullet appears unaffected. The hemisphere of the bullet that shows this evidence is the hemisphere that was in direct contact with the gunpowder when it was ignited (Harkins 2006: 42; Foard 2008b: 159-160; Scott & Haag 2009: 113; Foard 2012: 108-109; Foard & Curry 2013: 167).

Experimental firing conducted by Harkins (2006) notes that using a wad while firing may give the bullet some protection from pitting and melting. The wad would act as a defensive barrier if used between the gunpowder charge and the bullet. Bullets fired with a wad have a lower chance of attaining this type of evidence. This may cause some confusion with the interpretation of bullets found in the archaeological record dating to the 18th century as cartridges became more common; however, it has been noted that the cartridge paper was generally put in after the bullet to keep the bullet from rolling out of the barrel. This type of evidence may also help identify whether a bullet was fired with or without a wad as well, as it is more likely that pitting will be exhibited if the bullet were fired without a wad (Harkins 2006: 42).

Figure 1.19: Pitting from firing, B25 experimentally fired bullet.

1.3.4.3 Smoothbore Barrel Wall Characteristics

Sporadically, a bullet’s surface will contain segments of linear striations that wrap around the circumference of the bullet, but do not cause the bullet to become distorted in the same manner as the banding effect; this is illustrated in figure 1.20. This is caused by the bullet striking or glancing the smoothbore barrel wall as it exists the firearm. This evidence is similar to that seen on rifled bullets although it is not as pronounced.

Figure 1.20: Barrel wall characteristics B13 experimentally fired bullet.

1.3.4.4 Evidence of Rifled Barrels

A rifled barrel wall contains slanted, twisting grooves for the purpose of putting a spin on the bullet to make it more accurate in flight (Babits 1998: 13); these grooves create distinctive evidence on the bullet which can be seen in figure 1.21. Foard (2008, 2012) notes that rifled barrels were only used in very special circumstances during the English Civil War and that this type of evidence is not likely to appear much for that period (Foard 2008b: 161; 2012: 109-110). As firearms technology developed, rifling became more common but it was not until the time of the American War of Independence that rifled muskets were relatively common on the battlefield (Neuman 1967; Babits 1998; Babits & Howard 2009).

Figure 1.21: Bullet showing rifling evidence, courtesy of Glenn Foard.

Sometimes, bullets fired from rifled muskets were fired with a patch. A patch is a round piece of cloth or linen, and the bullet was placed in its centre and loaded into the muzzle mouth. In this manner the windage is reduced and the bullet grips the grooves of the barrel, leaving a fabric impression on the surface of the bullet once it was fired (Homann & Weise 2009: 36; Smith *et al.* 2009: 56; Sivilich 2016: 66).

1.3.5 Evidence of Intentional Modification and Alternate Bullet Types

The conventional spherical lead ball was not the only type of bullet fired in battle. During battlefield archaeological investigations other bullet types have been recovered. These small arms munition types are generally the result of either alternate bullet types or intentional modifications of the standard lead ball and therefore require some explanation so that they are not confused with impact evidence. Most of these bullet types can be found in primary accounts and military treatises dating to the early modern period. Surgical treatises can assist in identifying bullet types as well; Guillemeau (1598) and Lowe (1654) are two such surgical treatises. Both authors state that when considering surgery on the wounded one must consider the variety of bullets before proceeding. The most common types of bullets are made of lead, sometimes bullets are made of tin, copper, brass, iron, or steel. They go on to state that most bullets are round, but some have three corners, some four. One must also consider the number of bullets as some firearms fire more than one bullet. Both authors also mention that some bullets can contain poison, but do not elaborate further (Guillemeau 1598: Fol 6; Lowe 1654: 300-301).

1.3.5.1. Multiple Loads

Multiple loads are classified as an alternate bullet type and can come in many forms, such as the double load, the double headed bullet and multiple categories of buckshot.

The first form of a multiple load is the double load. This happens when a firearm is loaded with two or three bullets before firing. These types of loads could produce bullets that have facets on conjoining end where the bullets were in contact with one another during firing. This can also come in form of fused bullets, where two bullets that have fused at conjoining ends from being fired (Foard 2009: 25; 2012: 111-112); one such example of a double load can be found in figure 1.22.

Figure 1.22: Fused double load, Oudenaarde 552.

Historical evidence for the use of double loads has been noted from the 17th to the 18th centuries in the English Civil war in the United Kingdom and the Seven Years war in America (Blackmore 1990: 49; Harding 2012: 84). Gaya and Harford mention another type of bullet called the double headed shot, which is two bullets fixed by a piece of iron that are then fired from a musket (Gaya 1678: 16; Harford 1680: 19). A bullet recovered in New Jersey by a local metal detectorist in North America contained an iron wire imbedded in it. This could be archaeological evidence of the aforementioned double headed bullet (Sivilich 2009: 97). This type of bullet is similar to a dumb-bell bullet which are two bullets fixed together by a common sprue (Foard 2012: 77; Harding 2012: 110).

Multiload bullets are generally a refence to firing multiple bullets from the same firearm at the same time. Boyle (1677) suggests loading a musket with five or six pistol bullets when firing and fighting in close quarters during a field engagement as this type of multiload would cause far more destruction than one bullet out of many guns (Boyle 1677: 30, 192). Turner (1683) mentions that cavalry soldiers would fire several pistol or carbine bullets or small slugs of iron from a blunderbuss as opposed to using their normal carbine (Turner 1683: 173). The evidence of this type of multiload on a bullet's surface is virtually identical to the next category, buckshot.

The most common form of a multiple load is termed as buckshot, musket grape, swan shot and large and small buckshot. Buckshot was a widely used type of multiple load bullet in North America through the American War of Independence until the American Civil war and is specifically termed 'buck and ball'. Buck and ball is made up of one standard size bullet and several (although usually three) smaller calibre sized bullets packed into the same cartridge.

When fired, the bullets would spread out and cause greater destructive force at close range (Babits *et al.* 2003; Babits *et al.* 2006; Branstner 2008: 169; Sivilich 2016: 33). During the American Revolution, American soldiers would close ranks with the British soldiers and exchange one volley, after the first or second volley the British soldiers would then charge the American ranks with bayonet and scatter the American forces that were not issued a bayonet nor trained in how to use one. To counter this effect the American forces, under the recommendation of General George Washington in 1777, began using a type of multi-load bullet called buck and ball for their second volley which proved highly successful in breaking the British bayonet charge (Peterson 1968: 60-61; Sivilich 2016: 32).

Buck and ball leaves very distinctive surface alterations on the bullet as seen in figure 1.23. These alterations are created on the bullet's surface due to compression from firing, which is related to the load pattern as can be seen in figures 1.24 and 1.25 below.

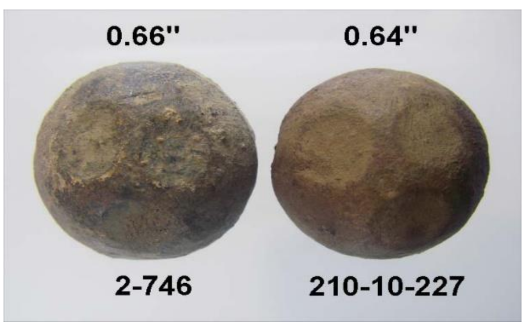

Figure 1.23: Buck and ball impressions, courtesy of Dan Sivilich.

Figure 1.24: Buck and ball load.

Figure 1.25: Load diagram, courtesy of Dan Sivilich (drawing by Raya Lim).

Figure 1.26: Multiload evidence Edgehill 2235.

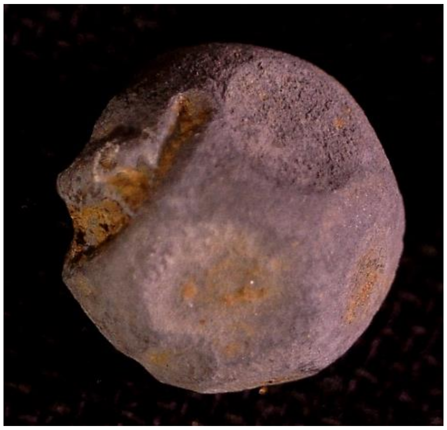

Figure 1.27: Multiload evidence Edgehill 441, note the casting fault in the upper left portion of the bullet.

There is evidence that the English army had also used this munition type. Sometimes it was referred to as ‘musket grape’ or ‘swan shot’, but the diagram of the load pattern is virtually identical to that of buck and ball (Harding 1999b: 12). Musket grape and swan shot are both mentioned in the 1776 English Board of Ordinance records, but the size of the bullets used are not mentioned (Harding 1999b: 12). However, Ezekiel Baker, writing in 1835, does mention the size of both musket grape and swan shot, as he also mentions the usage of and size of both large and small buck shot (Baker 1835: appendices). Figures 1.26 and 1.27 are bullets recovered from the Edgehill battlefield survey, these bullets clearly show multiload evidence.

1.3.5.2 Slugs

Slugs are a relatively common type of munition found during battlefield surveys. A slug can be created in two ways: either by taking a normal spherical bullet and cold hammering it into an elongated rectangular, cylindrical or lozenge shape (Mandzy 2012), or by clay casting the bullet as a slug (Sivilich 2016: 81). Foard states that the most effective way to establish the calibre of a slug is by either taking a linear measurement or by taking the bullet's weight (Foard 2008b: 99; 2012: 51).

Figure 1.28: Slugs of various forms.

Figure 1.28 illustrates various forms of slugs created by the author of this thesis by cold hammering spherical lead bullets. The exact reason for the use of slugs in combat is debateable. One theory is that slugs were normal bullets that did not fit the bore of the individual's firearm, so the bullet was pounded into a shape that would allow the bullet to fit. Another theory states that a slug possessed a tremendous amount of stopping power and could cause extensive damage at close range in comparison to the normal spherical bullet. A third theory states that the first two theories are partly correct. A bullet of a slightly larger calibre was pounded or moulded into a shape that would fit the bore of their firearm thus having a bullet of greater mass that could cause extensive damage at close range (Sivilich 2005: 15; Foard 2008b: 121; 2009: 9; Sivilich 2009: 95; Foard 2012: 77; Mandzy 2012). While slugs are mentioned within the literature from the period, the slug's intended purpose is not described. A surgical treatise dating to the early modern period suggests the removal of a slug from a wounded individual, but state no further details (Wiseman 1676: 382, 412, 421).

1.3.5.3 Quartered Bullets

Quartered bullets are any normal bullet that is cut or divided into four or eight parts. Figure 1.29 below shows a section of a quartered bullet. These are an early fragmentation bullet designed to break apart upon firing or impact creating extensive damage (Smith 1627: 68-69; Sivilich 2005: 15; Foard 2008b: 127; Sivilich 2009: 95-96; Foard 2012: 83; Sivilich 2016: 73-75). Quartered bullets have been found at battlefield archaeological sites such as Oudenaarde, Belgium (1708), Edgehill, United Kingdom (1642), and Monmouth, United States (1778). While these bullet types are found on battlefields, they are not as common as the normal spherical bullet in the overall bullet assemblages. Quartered bullets are mentioned in at least one early modern period military manual written by John Smith (1627); however, Smith only mentions their usage during naval engagements (Smith 1627).

Figure 1.29: Quartered bullet, Oudenaarde 624.

1.3.5.4 The Problem with Case Shot

Case shot is a relatively common find during a battlefield survey although not as prevalent as the normal spherical bullet and can be seen in figure 1.30. The name case shot is synonymous with mentions of canister shot and grape shot, but the construction and firing of these munition types are slightly different (Smith 1627: 66; Blackmore 1976: 195; Sivilich 2005: 17-18; Foard 2009: 15; Sivilich 2009: 98).

Figure 1.30: Fused case shot

This thesis does not intend to investigate case shot or any other form of artillery-based munitions; however, case shot can easily be confused for small arms bullets during a battlefield survey. Extensive experimental firing has already been conducted using case shot and the following information may assist with the firing and impact evidence seen on case shot to help differentiate it from small arms bullet evidence, as the two are quite different. Experimental firing conducted by Harkins (2006), Eyers (2006), Allsop and Foard (2008), and Clarke (2008), have all investigated the spread of case shot upon firing, and the firing and impact evidence seen on the case shot bullets themselves. The construction of the container used to fire the case shot in all experiments was roughly identical, consisting of a wooden case filled with 62, 12-bore bullets (37g) (Eyers 2006; Harkins 2006; Allsop & Foard 2008; Clarke 2008).

All the above studies discuss the same forces acting on the bullets inside the case. The main force being the force of compression from all of the 62 tightly packed bullets being accelerated at a high velocity. This compressive force gives each of the bullets a different characteristic level of compression depending on their location within the case. Harkins determined that the bullets at the top of the case will have less force acting on them, than the bullets from the bottom of the case. What this means is that bullets from the bottom of the case will appear more compressed than the bullets from the top of the case; this may allow one to be able to determine, archaeologically, where case shot bullets was located within the case when found during an archaeological survey (Harkins 2006: 49-56).

1.3.5.5 Chewing Evidence

Teeth mark impressions on a bullet's surface have been noted on several archaeological sites such as Oudenaarde (1708), Edgehill (1642), and Monmouth (1778), and leave very distinctive evidence. The degrees of teeth mark impressions, or chewing evidence varies substantially depending on whether the chewing was related to human or animal activity, or occurred pre-or post-deposition (Sivilich 2005: 13; Foard 2008b: 151-152; 2009: 21-22; Sivilich 2009: 93; Foard 2012: 103-104). Figures 1.31 and 1.32 demonstrate the difference between animal and human chewing evidence.

Figure 1.31: Bullet chewed by animal.

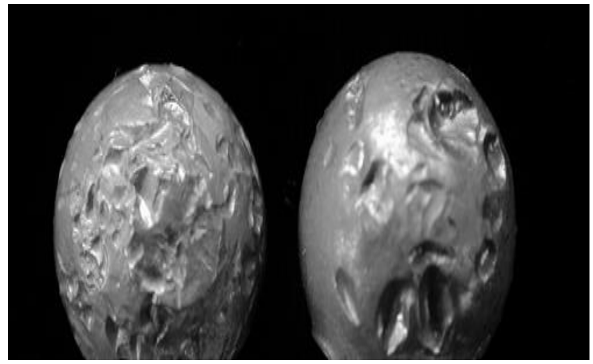

Figure 1.32: human chewing evidence, photo courtesy of Dan Sivilich.

Animal teeth mark impressions are far more destructive to the bullet. Chewing experiments conducted by Dan Sivilich and Dr Henry Miller (2016) have thus far matched teeth mark impressions to swine, large rodents (rats and squirrels) and deer (Sivilich 2016: 102-108,159-169).

There have been multiple explanations for human chewing evidence. Human teeth impressions could signify battle related, or post-battle surgical activities. There are many primary accounts and explanations for humans chewing bullets, such as to endure pain from surgery or from some sort of punishment, and to promote salivation on hot days (Foard 2008b: 151-152; 2009: 21-22; 2012: 103-104; Sivilich 2016: 108-109). Both Foard and Sivilich note accounts of soldiers chewing bullets to roughen up the surface and to add foreign substances to the bullet thereby acting as a poison or to promote infection on the individual who may be struck by it (Foard 2008b: 151-152; 2009: 21-22; 2012: 103-104; Sivilich 2016: 108-109).

1.3.5.6 Surgical Extractions

Another type of non-impact related evidence that can appear on the bullet's surfaces result from surgical extractions from wounded soldiers. The surgical extraction of a bullet from a wounded soldier would leave characteristic evidence on the bullet's surface depending on the device being used. Extraction evidence may be in the form of multiple linear striations that radiate toward the centre of the bullet, suggesting multiple attempts to find and grip the bullet (Sivilich 2005: 12; Foard 2008b: 169-170; 2012: 116; Sivilich 2016: 59-60); an example of this can be seen in figure 1.33.

Figure 1.33: Surgical extraction evidence courtesy of Dan Sivilich

1.3.5.7 Fabric Impressions

Fabric impressions can be transferred to the surface of a bullet in several different ways. An example of a fabric impression on a bullet's surface can be seen in figure 1.34. As discussed earlier, patched bullets fired from rifled muskets can transfer the impression of the cloth or linen used onto the bullet's surface (Homann & Weise 2009: 36; Smith *et al.* 2009: 56; Sivilich 2016: 66). Fabric impressions can also be transferred to a bullet through the use of a canvas bag, such as from the firing of case shot from artillery (Foard 2012: 92). Fabric impressions can also be transferred to the surface of a bullet through impact. If a bullet impacted a soldier's clothing or accessories, the fabric worn by the soldier could transfer to the bullet's surface (Smith *et al.* 2009: 56; Sivilich 2016: 71). Experimental firing has confirmed that firing a bullet into clothing will take on fabric impressions (Roberts *et al.* 2008; Scott *et al.* 2017: 53).

Figure 1.34: Fabric impression from Edgehill 665.

1.3.6 Post Deposition Evidence

It is not the intent of this thesis to fully detail and document the effects of corrosion, erosion, and concretion that can happen to a bullet in the burial environment. But it is worth discussing in passing to create awareness of the post-depositional effects that can work to obfuscate, obscure and erase all forms of evidence on the bullet's surface (Foard 2008b: 172; 2012: 118). The level of corrosion on the bullet can vary from site to site and within sites. For a more in depth investigation and methodology into the effects of corrosion of the bullet's surface, it is advised to consult (Rowe 2018).

1.3.6.1 Corrosion and Erosion

Lead carbonate is a white colouration and the most typical form of corrosion deposit on a bullet recovered during an archaeological excavation (Foard 2008b: 171; 2009: 27; 2012: 117; Sivilich 2016: 17). Foard notes that this form of corrosion can act as a defensive layer protecting the bullet from further corrosion. Both Foard and Sivilich note that the colour of the corrosion layer can give some indication as to the conditions in the burial environment (Foard 2008b: 171;

2009: 27; 2012: 117; Sivilich 2016: 17). Figure 1.35 below illustrates multiple levels of corrosion that can be found on archaeologically recovered bullets.

Figure 1.35: Bullets showing varying levels of corrosion.

Stuart Harkins (2006) conducted accelerated corrosion experiments to investigate the effects of corrosion on linear cut marks on the surface of multiple bullets. Harkins completed this by manufacturing five bullets and engraving six deep lines and six finer lines into each bullet. Next, all five bullets were placed into a hydrochloric acid bath for 61 hours (Harkins 2006: 24). The conclusion was that, with time the corrosive forces acting on a bullet could erase any evidence on the bullet's surface (Harkins 2006: 66).

1.3.6.2. Concretion

A thick concretion covering the surface of the bullet is more likely in waterlogged conditions. A thick concretion would be a complete and total obfuscation of any surface details on the bullet. Foard notes that the evidence can survive underneath the concretion and can be studied if the concretion layer can be broken away (Foard 2008b: 172; 2009: 27; 2012: 118).

1.4 Bullet Impact Evidence and Battlefield Reports

The above sections on non-impacted related evidence served to introduce and examine the types and varieties of evidence that can be found on the bullets' surfaces throughout its lifespan. The evidence found on a bullet's surface from the manufacture, transportation, loading, firing and from post-depositional effects must be clearly understood before investigating impact related evidence. This is due to the potential amalgamation of characteristic traits transferred onto the bullet's surface, and with this knowledge made clear, the extraneous evidence can be discounted and the remaining evidence can be more closely examined as potential impact evidence or evidence from an unknown origin.

To date, there is little consistency and standardization as well as no specific methodology or categorization system within the discipline of conflict archaeology on how impacted bullets are managed and studied (Schürger 2015: 173). This lack of knowledge on impacted bullets is reflected within the literature on how impacted bullets are used and discussed in those studies. For example, Mandzy's (2012) report of the battle of Poltava (1709) mentions that impacted bullets were recovered from the battlefield, but does not go into further detail about the condition or interpretation of any impact evidence (Mandzy 2012: 72). The only mention of a deformed bullet in the report for the battle of Kunersdorf (1759) is that one was found in the right scapula of a Lone Grenadier (Podruczny & Wrzosek 2014: 37). The problem with both studies is that they mention impacted bullets in passing and fail to deliver any further information on the bullets thereby revealing a gap in the overall literature. As the impacted bullets are overlooked in each study, one is unable to gain further insight or information regarding their respective impacted bullet evidence and one cannot use their studies when comparing other impacted bullets.

Most battlefield archaeological reports refer to bullets as fired or unfired with little attempt at further explanation or interpretation. The conventional theory states that if a bullet has suffered any form of impact damage or distortion then the bullet was fired and if the bullet appears to be unaltered then it was dropped or unfired, but almost no attempts have been made to understand the impact evidence or distortion levels on those bullets. Massed groupings of fired bullets (impacted or distorted bullets) in one region of the battlefield suggests the position of soldiers firing, while unfired bullets (spherical in shape) suggest a position in which soldiers were either killed or where a bullet was lost or dropped during the battle (Homann & Weise 2009: 38; Smith *et al.* 2009: 54, 56-86; Butler 2011: 24-29). This type of analysis can be seen in the battlefield reports written by Legg et al (2005) who uses this method for the bullets recovered during the archaeological survey of the battle of Camden (1780), and in Butler's (2011) analysis of the Buford's massacre battlefield (Legg *et al.* 2005; Butler 2011). However, the classic method for using fired and unfired bullets for analysis and interpretation has been called into question by the experimental firing trials conducted by Dave Miller (2009). Experimental firing results from Miller have demonstrated that the conventional theory of using fired and unfired bullet categories for interpretation is incorrect. Miller showed that fired bullets do not always show evidence of firing or impact. Miller's results further revealed that bullets fired from long distances, which then impacted damp grass with soft soil field conditions can show no firing or impact evidence at all. Meaning a bullet fired in those conditions could appear unaltered, and may subsequently be misinterpreted as unfired (Miller 2009; Foard 2012: 158-160). Not only is the fired versus unfired categorisation too broad and generalised in scope and does not analyse the impressions left on a bullet, but also this categorisation itself has been called into question regarding its reliability and validity through Miller's experimental firing. This is a clear example of why experimental firing studies are needed to assist in the understanding and interpretation of the impact or non-impact evidence in general and how such evidence may be seen within the archaeological bullet assemblages.

Another common occurrence in battlefield reports is that impacted bullets are explained or interpreted based on visual observations from within the battlefield landscape. Smith et al (2009) states that 'musket bullets' from the battle of Camden retain impressions from impact surfaces such as wood and soil (Smith *et al.* 2009: 56). This is mentioned in passing as if this is an established fact, while this may or may not be true, there is no indication as to where this knowledge came from, and it reads as conjecture. Some explanations of impacted bullets are questionable and seemingly based on observations and conjecture, such as Bonsal's (2007) statement from the battle of Cheriton (1644) that the heavily impacted bullets found in one region of the battlefield are possibly from 'striking human bone or a field boundary' (Bonsall 2007: 36). Similarly, Harding's (2012) explanations for what bullets impacted at Easton Maudit, are always qualified with the phrase ‘possible impact with’ (Harding 2012: 69-74); however, his rhetoric to describe the bullets’ surfaces is more specific and descriptive than other observational reports and provides a well written visual analysis. Yet, all three reports fail to provide definitive information that furthers our knowledge base on bullet impact evidence despite descriptive language because the conclusions for what the bullets impacted are seemingly rooted in observation and conjecture. Just as with the fired or unfired categorisation, scientific experimental firing trials could call into question these reports’ assumed impact targets and the damage left on the bullets. Without any comparative tool or reference collection of known bullet impact evidence, one cannot be definitive to say one way or another as to what caused these impact impressions. These reports are clear evidence of why the creation of a reference collection of known bullet impact evidence is needed in conflict archaeology so that the bullet impact evidence is based on scientific fact and not conjecture. Such a collection and overall knowledge will ensure that the advancement of battlefield bullet assemblages, bullet impact analysis and their respective battlefield reports will be rooted in factual science alongside already used historical accounts.

Research conducted by Dr Glenn Foard, a foremost expert in the field of bullet analysis, indicates that the level of distortion and the number of impacted bullets will vary between and within sites. Foard’s use of descriptive terminology for unknown bullet impact evidence is exemplary. For example, when describing bullets from a site, he states that the bullets, besides showing large scale deformation contain various degrees of damage in the form of shallow grooves and gouges, and rarely hazards a guess as to what the bullet impacted unless it can be cited to a known example from experimental firing (Foard 2008b: 169; 2012: 116). When investigating bullet impact evidence from archaeological sites with no baseline for comparison, this method initiated by Foard should be followed. This is because the use of descriptive terminology can help convey impact impressions to others without including unverifiable assumptions, as other battlefield reports advised above have done.

Several battlefield reports seem to follow Foard’s approach. These reports address the issue of bullet impact evidence using observations from within the battlefield landscape, and through the deployment of descriptive terminology to convey the bullet impact evidence to the conflict archaeology community without basing their conclusions in conjecture. The reports contain a description of what was recovered and from where within the battlefield landscape. With this information, along with detailed site locations and photographic evidence, experimental firing studies could be designed to recreate the archaeological findings. Homann and Weise discuss the battle of Lauenburg (1813). They state that 66 bullets were recovered and that the bullets show a range of deformation and damage such as deep dents and impressions, hemispherical forms or an almost complete flattening (Homann & Weise 2009: 33). The missing information from this study is the site locations from the recovery of those impacted bullets. Without site location, the study limits the overall battlefield analysis and provides no foundation which subsequent studies may use to create experimental firing trials to potentially recreate the observable, described bullet deformation. Campillo's (2008) report on the battle of Talamanca (1714) states that bullets found from a section of the battlefield that had very rocky soil were mostly flattened (Campillo 2008: 32). Further information from this study could be used such as a better description of the impact surface of the flattened bullets, and a more detailed description of the rocky soil in which the bullets were found. Such information would be useful for further studies when looking to accurately recreate this flattened bullet distortion through experimental firing. Wilson's study of the siege of Basingstoke Common (1643-1644) also appears to use Foard's descriptive terminology. Wilson's study singles out one bullet that had been partially stained red and contained a grainy impact surface. Wilson theorises that the bullet could have hit a nearby brick wall or building, but suggests that the bullet location is too far away from the building to be accurate (Wilson 2015: 17). The finds section in the appendix of Wilson's report contains good use of descriptive terminology, such as multiple areas of impact damage with stone inclusion, and that some bullets show radiating striations (Wilson 2015: 25, Appendix A). Wilson conveys enough information that an experimental design could be created, involving the experimental firing of multiple bullets at varying distances against a brick wall to investigate the transfer of characterises traits, which could confirm or disprove his hypothesis.

Along with Dr Glenn Foard mentioned above, Dan Sivilich is another foremost expert on the analysis of impacted bullets and uses descriptive terminology within his work. The research of Sivilich and the analysis of the bullets from the Monmouth battlefield (1778) is intriguing. Sivilich describes with great detail the bullet's shape and surface characteristics. Then, having completed the research on the reconstructed landscape of the battlefield places the bullet finds within that landscape. Next, Sivilich compares the reconstructed landscape to the other bullets found in the same section of the battlefield and theorises what the bullet impacted. For example, Sivilich states that, hypothetically, when a bullet impacted a tree after the bullet passed its maximum velocity then it would have impacted the tree and bounce off, never embedding in the wood. Sivilich states that due to the high mass of the bullet and its soft lead composition that the bullet would be deformed into a hemispherical shape. He states this theory because many hemispherical shaped bullets were found in an area of the Monmouth battlefield where an orchard existed dating to the battle (Sivilich 2016: 51). Sivilich takes clues from the surrounding landscape from the time of the battle and interprets the impacted bullets based on potential targets that may have been present on the battlefield. The major problem with the research by Sivilich is that there is no baseline for comparison with known impact evidence. Sivilich uses observations and logic to theorise about potential impacts, and states as much within his body of work by using phrases such as ‘possible impact with’ or ‘probable impact with’. The only piece missing from the work of Sivilich is the experimentation phase to test the hypothesises and overall analysis of the Monmouth impacted bullets.

As can be seen in the section above there is no consistency, standardisation or categorisation on how impacted bullets are managed within battlefield archaeological studies. This is due to the absence of a standard methodology used within conflict archaeology to handle and examine bullets for impact evidence. Furthermore, the lack of a standard methodology is due to the rarity of experimental firing trials that aim to reproduce the impact evidence seen on a bullets’ surface from the archaeological assemblages. What is desperately needed is a standard methodology for managing bullet impact evidence that is founded on experimentation before any type of consistency can take root within battlefield archaeology studies. Due to this gap within the conflict archaeology literature, it is the intention of this thesis to create a series of proof of concept experimental firing trials, with the aim of creating a reference collection of known bullet impact evidence to establish a baseline of comparison to the bullet impact evidence within the archaeological assemblages. Due to the vast scope of creating a comprehensive reference collection, a proof of concept will be established within this thesis, that will demonstrate the validity of using experimental firing to create a reference collection of known bullet impact evidence that can be used as a comparative tool against bullets from the archaeological assemblages. Future experimental firing studies will be needed to continue the expansion of the reference collection, which will enable the further development of a standard methodology for how impacted bullets are discussed within the literature.

1.4.1 Bullet Impact Classification Systems

It is clear from examining battlefield reports that there is no standardisation or methodology for how impacted bullets are managed and studied. The lack of consensus when studying impacted bullets can also be attributed to the lack of any type of classification system followed by more than just the author creating it. Thus far, only three attempts have been made to classify impacted bullets, all of which were created for different purposes. These attempts are from Foard (2008 and 2012), Schürger (2015), and Scott et al (2017).

Foard (2008 and 2012) created the first impact classification system that consists of an intensity grade and class given to each bullet which can be seen in table 1.1. Foard created this classification system to compare frequency and degree of impact damage on bullets from different assemblages (Foard 2012: 112).

Intensity grade	Intensity class	Impact evidence	Impact diameter as % of ideal diameter calculated from mass
0	None	No evidence identified	No significant deformation
1	Possible	Embedded grains; shallow groove(s)	No significant deformation
2	Minor	One or more gouges or depressions	No significant deformation
3	Major	Substantial deformation	> 50% of ideal
4	Massive	Loss of bullet form through deformation and melting	< 50% of ideal

Table 1.1: Bullet impact classification system reproduced from Foard 2012: 113.

The intensity grade and class are subjective and based entirely on the observer completing the analysis. The impact evidence and diameter section are less subjective but may not cover enough information as it seems to group different types of impact evidence together as the groups are not specific enough. This means that there is a possibility for two bullets which have impacted two different targets being in the same group. This broad spectrum of categorisation begins to help one understand levels of distortion within impacted bullets. However, it does not address all individual impressions and characteristics to help identify what has happened to a bullet during its lifespan from loading to firing to impact. The impact evidence and intensity class may be too rigid to account for all variations of bullet impact evidence and variations in multiple targets and therefore different impact types.

The second impact classification system was created by Schürger (2015) to investigate the impact damage seen on bullets from the Lützen (1632) battlefield assemblage. Schürger created this system in hopes that patterns would develop in the distribution map of impacted bullets that would allow for an advanced interpretation of the battle (Schürger 2015: 173). Schürger states that his classification system was subjectively based on the degree of bullet deformation in 10% increments. Where 10% to 30% signifies light impact damage, 40% to 60% indicates that the bullet was moderately damaged and 70% to 90% meant that bullets were flattened into an irregular shape (Schürger 2015: 173). This method is too broad and subjective, and leaves no room for descriptive analysis or for a comparative study between sites as it is site specific. Like Foard's classification, Schürger's method does not identify each specific mark on the bullet but rather generally groups bullets together in a scaled categorisation. While both Foard's and Schürger's classifications acknowledge differing distortions, both fail to reduce overall subjectivity of the observer as well as fail to be specific enough to identify what causes such distortions and characteristics on a bullet.

The newest classification method created by Scott et al (2017) is termed the *Lead Ball Deformation Index.* This proposed bullet deformation scaling is intended to give an approximate between the deformation of a bullet and the velocity at impact (terminal velocity) (Scott *et al.* 2017: 59). The index was created in response to plotting the relationship between the bullet's terminal velocity and bullet deformation upon impact and discovering a clear general trend which suggested that terminal velocity and deformation are linked. However, Scott et al does note that it is only a general trend as the variable of target characteristics is an unknown variable in the archaeological record (Scott *et al.* 2017: 58). While this method does not discuss impact evidence, it is the first potential methodology in conflict archaeology that can objectively quantify the distortion level of a bullet after impact. This method was not used on the reference collection of known bullet impacts analysed in this thesis because it was published after the completion of the experimental firing trials.

1.4.2 Objective Bullet Impact Analysis Techniques

The two classification methods detailed above are solely based on visual observations made when examining a bullet and subjective techniques. The final method discussed, created by Scott et al, is the first step towards creating an objective method of analysing impact evidence. However, studying impacted bullets recovered from battlefields in a manner that removes all subjective techniques is problematic as will be seen below. Microscopic techniques have been deployed in previous studies to investigate bullet evidence under magnification; however, whereas these techniques are effective on newly cast or manufactured experimental bullets, when used on archaeologically recovered bullets varying levels of corrosion can act to obfuscate the evidence (Foard 2008b: 159).

The use of microscopic techniques to objectively investigate, map and measure a bullet's surface was the primary goal of the following two studies. Both studies utilised 3D digital laser scanners to map the bullet's surface to objectively examine the level of distortion and evidence on the bullet's surface.

Mackie (2011) used a 3D topographic digital scanner, the Metris MCA II 3D laser scanner to create a digital image of a cannon ball before and after it was fired (Mackie 2011: 16). A software package was used to measure the degree of deformation to 0.01mm (Mackie 2011: 45). Mackie notes that without the expensive software package, the results are limited to 2D reports that offer only limited data (Mackie 2011: 125). Mackie concludes that the scanner's resolution was not good enough to capture small details or evidence that was on the surface of the cannon ball, even with evidence that was easily visible through macroscopic inspection (Mackie 2011: 126).

Wynne (2012) used the NextEngine 3D laser scanner to look at bullets recovered from the Oudenaarde battlefield (1708). Wynne states that the 3D laser scanner was excellent for creating permanent records of the bullet, but that the 3D scanner was too time prohibitive and that the accuracy of the laser scanner was not high enough for detailed analysis (Wynne 2012: 46-49).

To date, there are no completely objective methods with which to examine the surface of a bullet for impact evidence. This study did not pursue the use of 3D laser scanners or more advanced microscopic techniques as those methods have thus far proven ineffective and impractical during the analysis of the bullet's surface as seen by the two mentioned studies. Instead, this study created a new bullet impact analysis methodology influenced by the classification methods and descriptive terminology suggested by Foard in sections 1.4 and 1.4.1.

1.5 Bullet Impact Analysis Methodology

Multiple approaches and methods were explored in this thesis to create an objective method for analysing impacted bullets; however, after repeated failures, all approaches were determined to be ineffective or too open to observer bias. As these methods proved ineffectual, this section will only focus on the successful methodology created for bullet interpretation and analysis. This methodology is used throughout this study to analyse both the bullets from the experimental firing trials as well as the archaeological bullet assemblages.

It was decided that the most effective method to investigate impacted bullets was to create a series of iterative steps involving visual assessment, both macro and microscopic, in which the whole of the bullet's surface could be examined. This method considers the multiple layers of evidence that can be found on a bullet's surface that needs to be understood to fully analyse and interpret bullet impact evidence. The overall aim of this method is to rule out non-impact related evidence, thereby isolating the remaining evidence which can be interpreted as either as evidence from impact or evidence from an unknown origin. The method was also developed so that it could be widely applied to any archaeological bullet assemblage with minimal equipment so that it could be easily reproduced. This method was created by building on the foundation of known bullet evidence experimentally collected by Dr Glenn Foard and Dan Sivilich as seen in the above sections on bullet evidence (section 1.3).

This method is completed by visual macro and microscopic inspection of every bullet in an assemblage, looking for specific diagnostic indicators and documenting what can be seen on the bullet's surface. To do this, a bullet recording form was created, an example of which can be seen below in table 1.2. All evidence noted on the bullet's surface is recorded, and any evidence seen but not fully understood should become subject to the use of further descriptive terminology. All bullets that are positive for impact evidence are specially noted and can be easily separated out in the table for rapid location and identification.

Find Number	Condition	Shape	Weight (g)/ Diameter (mm)	Manufacture Evidence	Transport Evidence	Loading Evidence	Firing Evidence	Impact Evidence

Table 1.2: Bullet recording form.

The first step of this new method is to record the finds number or identification number of the bullet. This is determined by taking the finds number from the finds bag or the bullet's specific numerical identification. Nothing new is created as this is just a way to locate the bullet later if the need arises. The second and third step can happen simultaneously. Step two is to make a condition assessment of the bullet's surface. Notes are made as to the state and degree of erosion, corrosion, and concretion on the bullet's surface, and whether it creates difficulty in identifying diagnostic traits. In this thesis, the degree of that condition is marked as either good or corroded. A good condition means that surface evidence is visible, and a bullet marked as corroded means that the level of corrosion and/or erosion has rendered all surface evidence to be unobservable. The third step is to determine the overall shape of the bullet. This method is based on Foard's bullet impact classification system which can be found in the above section 1.4.1. The overall shape of the bullet is determined by its percentage of distortion from the ideal spherical shape or diameter. This can be seen in table 1.3 and in figures 1.36 and 1.37 below.

Percentage of Distortion from Ideal Shape	Distortion Level
0%	S- Spherical
25%	SD- Slight Distortion
50%	MD- Moderate Distortion
75%	HD- Heavily Distortion
100%	I- Irregular

Table 1.3: Bullet distortion levels.

Determining the shape or distortion level of a bullet is based on visual and subjective methods, as no method established or attempted by the author could quantify the level of distortion without observer error. A bullet that is determined to be spherical in shape is as close to its ideal shape as possible and appears unaltered, although the bullet may still contain various types of evidence, including impact evidence. A bullet that is slightly distorted means that it no longer holds its ideal shape, nor is the bullet's shape significantly altered. Common causes of a slightly distorted bullet can be attributed to an offset mould seam during the manufacture process, the banding effect from firing and various forms of impact damage. A moderately distorted bullet no longer holds its ideal shape and has been altered to some degree. A bullet that is moderately distorted will generally be distorted from impact, although that impact evidence can be obscured by corrosion. A bullet that is heavily distorted can be recognised as a bullet, but its ideal shape and appearance may be difficult to determine. A bullet categorised as irregular in shape has completely lost its ideal spherical shape and is no longer easily recognisable as a bullet. Irregular bullets can be caused by animal activity such as chewing, although this level of distortion is generally caused by the bullet impacting a surface.

Figure 1.36: Bullet distortion levels, from left to right: spherical, slightly distorted, moderately distorted, heavily distorted, irregular.

Figure 1.37: Bullet distortion levels from Edgehill, from left to right: spherical, slightly distorted, moderately distorted, heavily distorted, irregular.

These distortion levels can also be assigned a numerical quantity for future statistical analysis, as seen in table 1.4 below.

Numerical Quantity	Distortion Level
0	S
0.25	SD
0.50	MD
0.75	HD
1.00	I

Table 1.4: Numerical quantity for distortion levels.

The fourth step in this methodology is to take the bullet's weight and diameter measurements if possible. The weight of the bullet is recorded in grams (g) and the bullet's diameter is measured in millimetres (mm). Measuring a bullet's diameter is done at a 90° angle to the mould seam, although sometimes the bullet's diameter cannot be measured if the casting sprue or mould seam is not visible, in this case only the bullet's weight is taken. Both measurements are taken to discern calibre or bore of the bullet.

The fifth step is to record any and all manufacturing evidence seen on the bullet's surface. This includes manufacturing evidence such as the bullet's mould seam, and sprue cut which can assist in orientating the bullet and allowing for the diameter measurement to be recorded. Casting faults should also be recorded, such as turning lines or an offset mould seam so that they are not misinterpreted as impact evidence.

Step six is to examine the bullet for any transportation evidence. Bumping depressions can be seen on the bullet's surface as multiple circular depressions and must be eliminated from the investigation so they are not confused for impact evidence.

Step seven is to examine the surface of the bullet for loading evidence, such as ramrod indentations and impressions made from multiload bullets. As these types of evidence can leave circular depression of various forms on the bullet's surface and it must be ruled out when investigating a bullet for impact evidence.

The eighth step is to rule out firing evidence from the bullet's surface. Firing evidence such as banding, barrel wall characteristics, and powder pitting can be seen on the bullet's surface and this evidence must be noted and discounted from further analysis and discussion.

The final step is to investigate the bullet's surface for impact evidence. With all other forms of evidence accounted for, what remains unidentified should be attributed to the bullet impacting a target or targets, or from an unknown origin. This evidence should be first handled by using descriptive terminology to identify what is observed on what regions of the bullet, as this can assist in identifying the type of impact evidence. Secondly, a comparison of bullet impact evidence will take place using the reference collection of known bullet impact evidence discussed in Chapter Seven. Using this reference collection in conjunction with descriptive terminology will enable the identification of known impact evidence seen on a bullet's surface. However, as previously noted in section 1.4, not all impact evidence is currently known, and further experimental firing needs to be undertaken to further develop the reference collection.

1.6 Experimental Firing

As established in the above sections, multiple forms of evidence can be transferred to a bullet's surface and experimentation has been able to reproduce certain surface characteristics and alterations. In order to fill in the gaps in the impact analysis research while addressing its limitations and inherently subjective nature, the creation of a series of experimental firing trials is paramount to test the hypothesis of impacted bullets from archaeological assemblages.

Foard states that the analysis of impacted bullets may yield important information about a bullet's velocity, angle of incidence and the character and nature of the impact surface with which the bullet has impacted, and that the majority of our knowledge on impacted early modern bullets comes from modern conical bullet studies (Foard 2008b: 167; 2012: 112). Environmental variables such as land use, character of the soil, and ground moisture play a role in the nature of a bullet's impact with the ground (Foard 2008b: 166; 2009: 27; 2012: 113). Foard and Morris (2012) argue that this is an aspect of bullet analysis that has seen very little research, and that to date there is scant data about the nature of impact and of its potential for evidence (Foard 2008a: 165; Foard & Morris 2012: 134). Understanding what a bullet impacted can give a clear indication and a more reliable interpretation of potential landscape features and the events on the battlefield, by creating a more advanced interpretation of the bullet assemblages.

However, experimentation to reproduce specific impact evidence has not been extensively completed. There have been scant experimental firing studies conducted that examine the impact evidence of early modern period spherical lead bullets. The clear majority of experimental firing studies set out to examine the firearm's ballistic capabilities (Krenn 1991; Babits *et al.* 2003; Eyers 2006; Harkins 2006; Roberts *et al.* 2008; Miller 2009; Smith 2009; Lockau 2012; 2016; Scott *et al.* 2017). Several experimental firing trials examined the firing of case shot and other ordnance from artillery (Eyers 2006; Allsop & Foard 2008; Clarke 2008; Kohlisch 2011; Mackie 2011), but very few experimental firing trials have attempted to capture and analyse data from impacted bullets (Linck 2005; Green 2010; Wynne 2012; Scott *et al.* 2017). A much more detailed discussion of previous experimental firing trials can be found in Chapter Three of this thesis, but this section should serve to identify the large gap in the knowledge base of the conflict archaeology literature regarding experimental firing with the overall aim of collecting known bullet impact evidence which can be used to assist in interpreting archaeologically recovered bullet assemblages.

1.7 Conclusion

While the significance of some of the evidence found on a bullet's surface can be definitively stated, such as the evidence from the bullet's manufacture, loading, transport, firing and other actions throughout its lifespan, impact evidence remains largely unaddressed using systematic experimentation. Inferences have been made about bullet impact evidence based solely on the location of the bullet find in an archaeological context, in conjunction with visual observations from the reconstructed historic landscape. These theories about what a bullet may have impacted, have not been rigorously and scientifically tested, instead the theories of bullet impact evidence have been presented as fact. It is the intention of this thesis to demonstrate in Chapters Seven and Eight that experimental firing can provide valuable insight into bullet impact evidence which can be used to further our understanding of archaeological bullet assemblages. As a result, the creation of an experimental firing methodology must first be completed. To create an experimental firing methodology, key variables must be first identified through the discipline of ballistics. These variables influence how a bullet arrives and impacts its target, and is the focus of the following chapter.

Chapter 2: Ballistics

Modern ballistics is well understood and mainly concerned with rifle barrelled weapon systems, streamlined conical bullets, and synthetic propellants. All of these behave differently from the less understood historic smoothbore barrel, spherical lead bullet, and black powder propellant (Hall 1997: 5-6, 134). The firearms of the early modern period were never subjected to meticulous, modern, scientific investigations when they were in use, due in large part to the ballistic instrumentation having not yet been invented. In the time it took to create and develop the ballistic instrumentation to properly study the ballistics of smoothbore firearms, the firearms themselves had undergone significant technological advances. With the next generation of firearms being produced and researched, the firearms of the early modern period were no longer of scientific interest (Krenn et al. 1995: 101-102).

The ballistics of smoothbore firearms have been the central focus of the vast majority of experimental firing trials to date in conflict archaeology (2017), these experimental firing trials will be discussed in further detail in Chapter Three of this thesis. Experimental firing can assist in creating reliable data on the ballistics of early modern period firearms and artillery. They can also assist in creating reliable interpretations of the bullet assemblages found on early modern battlefields by creating comparative experimental data sets, which can then be compared to archaeologically recovered bullet assemblages. The caveat is that the majority of known experimental firing trials are interested in the internal, external, terminal and wound ballistics of the firearms, the prediction and dispersal of fire, the range, accuracy and the effectiveness or lethality of early modern firearms. While these studies have the potential to progress the disciplines of conflict archaeology and the ballistics of smoothbore firearms, they do not tend to focus on the impact evidence or analysis of the bullets that were fired during those experiments, nor are those bullets used to compare impact damage with those of the archaeological assemblages, thus leaving a large gap in our knowledge base.

Previously completed experimental firing trials (Chapter Three) have revealed multiple variables that have a direct effect on the velocity of the bullet and will, therefore, have a direct effect on the nature of the impact of the bullet with a specific target or feature. The way the bullet impacts a target or an unintended surface, such as the ground, will determine the amount and nature of the evidence transferred to the bullet's surface allowing for distinctive traits to be identified and categorised. This avenue of research is within the discipline of ballistics.

Ballistic research is subdivided into internal, intermediate, external, terminal and wound ballistics (Greenwood *et al.* 1987: 1). This chapter will examine the ballistic issues with smoothbore firearms, spherical lead bullets, and black powder propellants, which will assist in identifying key variables for the creation of an experimental firing methodology. These variables will be of further discussed throughout Chapter Four of this thesis. Ballistics information regarding modern weapon systems, munitions and body armour have been intentionally excluded from discussion. This chapter will also serve to introduce the terminology used throughout Chapters Six and Seven which cover the firing experiments conducted in this thesis.

2.1 Internal Ballistics

A firearm is a mechanical device designed to launch a bullet towards a specific target. All smoothbore firearms are essentially a tube, closed at one end and open at the other. This tube imparts both motion and direction on the bullet once the propellant charge is ignited (Greenwood *et al.* 1987: 153; Moss *et al.* 1995: 9). The closed end of the tube is called the chamber, while the open end is called the muzzle, the entire length of the tube is called the barrel (Greenwood *et al.* 1987: 154; Moss *et al.* 1995: 9). In smoothbore firearms, the propellant charge is placed in the chamber by pouring it down the muzzle mouth, from either a bandolier or a cartridge. In both cases, the bullet is then loaded after the propellant charge and rammed down to ensure that the bullet is properly seated on top of the propellant charge.

Once the propellant charge is ignited energetic gases are rapidly released. Since the gases are restricted to the chamber of the firearm, the gas pressure rises causing the propellant to burn at a faster rate. This process begins to put increasing pressure on the base of the bullet, which is called 'shot start pressure' (Greenwood *et al.* 1987: 161; Eyers 2006: 15; Miller 2009: 35). With the bullet now moving down the barrel of the firearm the propellant gases continue to expand,

and will continue to expand until the propellant grains are completely consumed. Once most, or all of the propellant grains are consumed, the stage of 'all burnt' has been reached. This phase in between shot start and all burnt is known as peak pressure (Clarke 2008: 44). After the propellant is 'all burnt', the gases expand adiabatically and the chamber pressure drops (Greenwood *et al.* 1987: 161; Moss *et al.* 1995: 26-27). This production of high temperatures and pressures within the chamber of the firearm which propels the bullet and forces it down the barrel and out of the muzzle is a process known as the 'internal ballistic cycle' (Greenwood *et al.* 1987: 159-162; Clarke 2008: 43-45; Miller 2009: 35).

Internal ballistics, also known as interior ballistics, is concerned with the ignition and burning of the propellant, the in-bore movement of the bullet, and ends when the bullet leaves the muzzle of the firearm (Greenwood *et al.* 1987: 153-154; Moss *et al.* 1995: 9; Kisak 2014: 50). Factors which influence this process are the design and quantity of the propellant, the in-bore motion of the bullet, the amount of windage and the wadding material if any were used, and the length of the barrel of the firearm. These variables have a direct effect on the muzzle velocity and therefore muzzle energy, which in turn will directly influence the way the bullet impacts its target. Muzzle velocity is the speed of the bullet as it leaves the muzzle of the firearm. Muzzle energy is the kinetic energy of the bullet as it exits the muzzle of the firearm (Greenwood *et al.* 1987: 154). The following section on internal ballistics serves to identify several key variables that will lead to the creation of a period accurate and reproducible experimental firing methodology. These key variables will be further explored in Chapter Four of this thesis through the use of military manuals and publications dating to the early modern period.

2.1.1 Propellant

One of the main factors that influence internal ballistics is the propellant. The terms black powder and gunpowder are synonymous, although there are major differences between them. Black powder is less refined, produces a quantity of oily soot in the barrel known as fouling, and produces a lot of smoke when fired. Modern gunpowder is well refined, and produces little to no soot and smoke when fired (Fadala 2006: 200-201; Miller 2009: 37-39).

Gunpowder is a combustible propellant that is used to propel a bullet from a firearm. The characteristics of the propellant have the greatest influence on the internal ballistics of early modern firearms (Eyers 2006: 16). Black powder is one of the earliest forms of gunpowder and was used in all firearms in the early modern period. The most important variables in gunpowder that influence its effectiveness are its composition and grain size (Brown 1998: 21-22). Gunpowder is composed of an intimate mixture of three ingredients; saltpetre (potassium nitrate) charcoal, and sulphur. The way in which these ingredients interact with one another has a direct effect on the burn rate of the powder and therefore the overall strength and effectiveness of the powder as a propellant (McConnell 1988: 273; Cocroft 2000: 2; Kelly 2004: 36; Eyers 2006: 16; Fadala 2006: 192; Kohlisch 2011: 24; Kisak 2014: 51).

Over time, the composition and purity of these three ingredients have changed, leading to a wide variety of gunpowder recipes. The design and recipe of the propellant, including its type, shape and charge size all play a significant role in the efficacy of gunpowder (Greenwood *et al.* 1987: 164). Haag and Patel (2012) demonstrate that the velocity and kinetic energy produced by modern reproduction black powders vary substantially when the firearm and bullet variables are held constant. The results show that supplementary inorganic elements create a substandard charge, while the powders without such additions perform to a higher standard (Haag & Patel 2012).

The variables grain size and shape of gunpowder determines its total surface area. The total surface area significantly affects the burn rate which in turn influences the performance of the powder (Brown 1998: 21; Kisak 2014: 55). Gunpowder burns from the surface, inwards. Therefore, if the composition is fine grained, it would burn more rapidly than coarse or large grained powder due to its larger surface area (Brown 1998: 22; Denny 2011: 31). The additional strength which grained powder had over compacted, fine (serpentine) powder is the free passage of the flame between the grains (War Office Unknown: 38). In terms of ballistic performance, different gunpowder recipes produce different muzzle velocities and muzzle energies, which in turn affects the impact of a bullet (Eyers 2006: 7). The higher a bullet’s velocity and the more energy it has will have a dramatic effect on how a bullet impacts its target.

The choice of gunpowder is one of the key variables when creating an experimental firing methodology. A type of gunpowder must be chosen that reflects the gunpowder used during the early modern period. A larger discussion on gunpowder can be found in Chapter Four (section 4.1) of this thesis that details the creation of an experimental firing methodology.

2.1.2 In-bore motion

Another factor that directly affects internal ballistics and the performance of the bullet inside the barrel of the firearm is the in-bore motion of the bullet. As the bullet moves down the barrel of the firearm it is subject to a resistant force known as in-bore sliding friction (Greenwood *et al.* 1987: 168). In rifled firearms, the gas pressure from ignition forces the bullet towards the barrel wall. The bullet for modern rifled firearms contains rings around the base, such as the two to three rings at the base of a Minié ball. The rings on the base of a modern conical bullet are called ‘driving bands.’ The barrel wall contains grooves and when the ‘driving bands’ engage the grooves, the bullet begins to rotate as it goes down the length of the barrel. This rotation or spin on the bullet is what gives the bullet a more stable flight path (Greenwood *et al.* 1987; Moss *et al.* 1995: 24). Smoothbore firearms do not have this internal grooving of the barrel, nor did the bullet have ‘driving bands.’ However, the bullet is still subject to the same resistant force, wherein the bullet is forced towards the barrel wall (Greenwood *et al.* 1987: 174). Experimental firing has confirmed that this can be a contributing factor and possible explanation for the banding effect seen on bullets fired from smoothbore firearms as discussed in Chapter One (1.3.4.1) on bullet evidence (Miller 2009: 103-105). The issue of bullets, striking or glancing against the barrel wall was known in the early modern period, as D’Antoni (1789) states that a bullet striking against the sides of the barrel upon firing was a result of a warped or ill made gun barrel. He was, of course, talking about artillery and not small arms; however, this force still influences how bullets leave the barrel and the stability of the bullet in flight (D'Antoni 1789: 122-124).

2.1.3 Windage

Along with propellant and in-bore motion of the bullet, windage also directly influences the internal ballistics of a firearm. Windage is the difference between the firearm barrel internal diameter and diameter of the bullet (Sivilich 1996: 107). It has been assumed that this difference can allow some of the gas from the ignition of the propellant charge to escape around the bullet as it moves down and out of the barrel causing a loss of muzzle velocity and muzzle energy (Eyers 2006: 7, 54; Denny 2011: 33).

A brief firing experiment conducted by Miller (2009) demonstrates that windage alone has a direct effect on muzzle velocity. Miller was studying the effects of differing barrel diameters on the same 12-bore (37g), 18.51mm diameter bullet (Miller 2009: 92). Miller first created a nominal 10-bore musket barrel with a 19.49mm bore diameter. Next, Miller created two other musket barrels, one to simulate a tight-fitting bullet (18.7mm internal bore diameter) and one to simulate a loose-fitting bullet (20.4mm internal bore diameter). The same 12-bore bullet with an 18.51mm diameter was fired from each barrel using the same 18g charge size of G12 black powder (Miller 2009: 92). Results are shown in table 2.1 below.

Barrel Diameter (mm)	Windage (mm)	Velocity (m/s)
18.7	0.19	452
18.7	0.19	465
19.49	0.98	410
19.49	0.98	420
20.4	1.89	346
20.4	1.89	351

Table 2.1: Bore diameter and muzzle velocity without a wad from (Miller 2009: 92-93).

The results in table 2.1 show that the mean velocity using a barrel with an 18.7mm internal bore diameter and a windage of 0.19mm is 459m/s. The mean velocity using a barrel with a 19.49mm internal bore diameter and a windage of 0.98mm is 415m/s. The mean velocity using a barrel with a 20.4mm internal bore diameter and a windage of 1.89mm is 349m/s. These results show that windage has a direct effect on muzzle velocity, and a tighter fit of the bullet to the barrel results in a higher muzzle velocity (Miller 2009: 92-94).

Windage is an important variable when creating an experimental firing methodology. The above section shows that windage can have a direct effect of the velocity of the bullet. The experimental firing trials in this thesis have chosen to keep windage as close to a constant throughout the entirety of experimentations to remove or control this variable. This variable cannot be completely controlled for due to fluctuations in bullet diameter during the casting process.

2.1.4 The Use of a Wad

Experimental firing has shown that wadding has an effect on the velocity and accuracy of a bullet (Eyers 2006; Fadala 2006). Historically, the type of wadding was variable, if any wadding was used at all. Foard (2012) notes that an experimental firing study conducted in Leeds in 2007 showed a marked increase in the velocity of a wadded 12-bore bullet close to 30% (Allsop & Foard 2008; Foard 2012: 105). However, there is a disagreement within modern sources over the purpose of wadding. Eyers (2006) states that the use of a wad creates a seal allowing no energy to escape and therefore all energy is transferred to the bullet creating an increase in velocity (Eyers 2006: 7). Fadala (2006) contends that a wad has nothing to do with sealing in gases, simply stating “It’s not a gasket” (Fadala 2006). Fadala elaborates that the wad serves two purposes: to take up the windage in the barrel creating a more accurate flight path and to help clean the fouling out of the barrel between each shot (Fadala 2006: 151-153). Both Eyers and Fadala agree that wadding made of different materials should have an influence on the performance of the bullet. However, it seems in this instance that Fadala has been proven wrong by experimental firing conducted by Eyers and Miller (Eyers 2006: 27-41; Miller 2009). An aim in the experimental firing trials conducted by Eyers (2006) was to fire 100 bullets, 50 bullets with a wad and 50 bullets without a wad, using the same charge size and powder. The collated muzzle velocities would then be averaged to investigate how effective a wad is. The wadding material was made up of nine sheets of balled-up toilet tissue (Eyers 2006: 25-27). The results can be found in table 2.2 below.

Eyers 2006	Mean Velocity (m/s) for all 100 shots
Without a wad	400
With a wad	431

Table 2.2: Mean velocity with and without a wad from (Eyers 2006: 38-41).

The results from Eyers' firing experiment show that a wad influences muzzle velocity; however, no statistical data sets were provided to further demonstrate Eyers' findings. In theory a T-test should have been completed to verify the significance of the test results; however, not enough data was made public for this thesis to complete it.

As discussed in the windage section above, Miller (2009) conducted an experiment that investigated the effects that windage and wadding had on the muzzle velocity of a 12-bore bullet with an 18.51mm diameter using different barrels with different internal bore diameters. The full results can be found in table 2.3 below.

Barrel Diameter (mm)	Wad	Velocity (m/s)
18.7	Yes	472
18.7	Yes	459
18.7	No	465
18.7	No	452
19.49	Yes	431
19.49	Yes	427
19.49	No	420
19.49	No	410
20.4	Yes	410
20.4	Yes	403
20.4	No	351
20.4	No	346

Table 2.3: Muzzle velocity with and without a wad from (Miller 2009: 93-94).

The results show that the mean muzzle velocity with a wad for a 12-bore bullet fired from an 18.7mm internal bore diameter and a windage of 0.19mm is 466m/s and 459m/s without a wad. The mean muzzle velocity with a wad for a 12-bore bullet fired from a 19.49mm internal bore diameter and a windage of 0.98mm is 429m/s and 415m/s without a wad. The mean muzzle velocity with a wad for a 12-bore bullet fired from a 20.4mm internal bore diameter and a windage of 1.89mm is 407m/s and 349m/s without a wad (Miller 2009: 93-94). It is clear from the experiments conducted by both Eyers and Miller that reducing the windage of a musket and using a wad will lead to an increase in muzzle velocity. However, the statistical significance could not be ascertained as not enough data was made public.

The use of a wad is another important variable when creating an experimental firing methodology. The above section demonstrates that the use of a wad can influence the velocity of the bullet, which in turn would influence the impact of the bullet. A larger discussion on the use of a wad can be found in Chapter Four of this thesis (section 4.6).

2.1.5 Barrel Length

The length of the barrel of the firearm is the final influential factor in internal ballistics and the velocity of the bullet. During the 'internal ballistic cycle', as the gas pressure builds behind the base of the bullet, the longer the barrel length means the longer this pressure can act on the bullet, which creates an increase in velocity and distance (Eyers 2006: 7; Kisak 2014: 55). The correlation between velocity, distance and barrel length has been known since the late 16th century. Biringuccio (1590) commented that, after witnessing many experiments, bullets fired from a longer barrelled firearm would travel further than those that were fired from a shorter barrel (Biringuccio 1540: 224). The original understanding was that overcharging the firearm with more gunpowder was what created a higher muzzle velocity and greater travel distance for the bullet. This understanding was also rejected in the 17th century by Hexham (1637, 1642, 1643) who stated that all one would accomplish by overcharging their firearm was the waste of good gunpowder (Hexham 1637: 13-14; 1642; 1643). Both Turner (1683) and Robins (1742) commented that longer barrel lengths were preferable to gain greater velocity and distance using the same propellant charge size (Turner 1683: 260; Robins 1742: 248).

Barrel length is a consideration with the creation of the experimental firing trials, which is discussed in further detail in Chapter Four (section 4.6). The barrel length will be kept constant throughout the experimental firing trials as a means of controlling this variable.

2.2 Intermediate Ballistics

Intermediate ballistics or transitional ballistics is the transition period between internal and external ballistics, and is still not completely understood (Moss *et al.* 1995: 64-65). There are two distinct waves of energy that are released from the muzzle of the firearm, a shock wave and a blast shock wave (Moss *et al.* 1995: 52). Once the 'internal ballistic cycle' has begun and the bullet begins to accelerate, the bullet pushes a column of air inside the gun barrel ahead of the bullet. This air mixes with any propellant gases that escaped past the bullet due to windage and forms a shock wave which exits the muzzle before the bullet. This shock wave is called precursor blast shock (Moss *et al.* 1995: 52-53). As the bullet exits the barrel, the gases from the burning of the remaining propellant exits behind the bullet, expanding in every direction and causing a blast shock wave that creates the blast sound generally associated with firearms (Greenwood *et al.* 1987: 340; Moss *et al.* 1995: 54; Kisak 2014: 62). The muzzle flash associated with the firing of a gun is attributed to the last of the propellant gases exiting the muzzle and combining with the outside oxygen (Moss *et al.* 1995: 54-55; Kisak 2014: 62). While the shock wave produced can impart some motion onto the bullet, it is believed to have a negligible effect (Greenwood *et al.* 1987: 340; Kisak 2014: 62).

2.3 External Ballistics

External ballistics is an important aspect of this thesis. Chapter Six details the creation of an external ballistic trajectory modelling program and, in order to create that program, the forces acting on a bullet during flight must be understood. External ballistics can assist in understanding the accuracy of a firearm and the trajectory of a fired bullet. The type of bullet fired strongly affects its flight path, for example, conical bullets will generally hold a straight path when fired from a rifled weapon, while spherical bullets tend to corkscrew as they are fired from a smoothbore weapon (Miller 2009). Spherical bullets fired from a rifled barrel can hold a straighter flight path than those fired from a smoothbore barrel, but do not have the same accuracy and distance that a conical bullet has due to the bullet's spherical shape and aerodynamic drag.

External ballistics encompasses the in-flight behaviour of the bullet after it leaves the barrel of the firearm and before it strikes its target (Greenwood *et al.* 1987: 153, 443; Kisak 2014: 64). The in-flight behaviour or motion of a bullet is influenced by several forces, such as gravity, air resistance or drag, and wind (Greenwood *et al.* 1987: 445; Moss *et al.* 1995: 67; Kisak 2014: 65). These factors are further influenced by the characteristics of the bullet. Gravity causes a loss of vertical motion of the bullet; air resistance causes the loss in velocity of the bullet, and wind causes the bullet to deviate from its original trajectory. All of these forces act on a bullet during its flight and must be taken into account and understood in order to model the trajectory of a bullet (Kisak 2014: 65). The ‘fluid external medium’ in which the bullet is traveling (Earth’s atmosphere) causes aerodynamic drag (Greenwood *et al.* 1987: 445; Moss *et al.* 1995: 67; Kisak 2014: 65). Aerodynamic drag causes a decay in the velocity of the bullet which will shorten its maximum range (Greenwood *et al.* 1987: 53). The size and magnitude of the forces of drag depend on the characteristics of the bullet such as size, mass, shape, velocity and spin rate. The amount of drag is also dependent on the local atmospheric properties such as temperature, mass air density and viscosity, local area speed of sound, static pressure, wind speed and gravity (Greenwood *et al.* 1987: 53; Moss *et al.* 1995: 67).

2.3.1 Gravity

Gravity acts to accelerate the bullet in a downward motion causing the bullet’s flight path to drop or decay, this is also known as bullet drop (Kisak 2014: 65). Gravity accelerates the bullet downwards at a constant speed of 9.81m/s^2 on Earth and this effect is independent of any and all characteristics of the bullet (Allsop & Foard 2008: 118; Kohlisch 2011: 70). Elevation of the barrel of the firearm comes into play when gravity and bullet drop are considered. There is an imaginary line drawn down the centre of the barrel bore, and this line continues to infinity. The bullet, leaving the barrel can never hit a target above that centre line because of bullet drop (Kisak 2014: 65-66). The barrel of the firearm must be elevated to another degree to hit a target above the previous centre line. While changing the elevation of the barrel, a new centre line is formed. However, this will create a higher trajectory arch causing the bullet to lose distance (Kohlisch 2011: 70; Kisak 2014: 66).

2.3.2 Wind

Wind can cause the bullet to deviate from its original trajectory, this is called wind drift. Wind is not the actual cause of this deviation; the culprit is drag. Wind seems to have more of an effect for long range firing versus short range firing (Kisak 2014: 75). This body of research will conduct all the experimental firing in an indoor facility, so the effects of wind will be negligible to non-existent. Wind is a variable that cannot be controlled for, and most trajectory modelling programs do not account for wind because it is an unpredictable variable.

2.3.3 Aerodynamic Drag or Drag Force

In a total vacuum, the only force acting on the flight behaviour of a bullet is gravity (Greenwood *et al.* 1987: 53; Denny 2011: 80). When air is introduced, air resistance retards the forward momentum of the bullet and the bullet's trajectory decays, this is called drag (Greenwood *et al.* 1987: 53; Moss *et al.* 1995: 71). The amount of drag that affects the bullet during flight is proportional to the square of the speed of the bullet. In other words, the faster the bullet is moving the more drag affects it. When a bullet is fired, gravity and drag act together to decay the forward momentum of the bullet.

The size of the bullet also affects the amount of drag. The larger the bullet, the more surface area there is which means the more drag will affect it (Denny 2011: 84). The shape of the fired bullet also influences the amount of drag applied. For example, a streamlined conical bullet will allow the on-rushing air to slip past the bullet, whereas a spherical bullet will face more drag as it pushes through the air.

There are three main types of drag: skin friction, pressure drag and yaw-dependent drag (Moss *et al.* 1995: 72). Skin friction is caused by fluid viscosity; while the effect that viscosity has is considered small, it does add to the overall drag acting on the bullet (Moss *et al.* 1995: 72; Denny 2011: 90). Pressure drag is the result of the way the fluid flows around the shape of a moving bullet causing the pressure behind the bullet to be less than the fluid pressure in the front of the bullet. As a result, the shape of a bullet directly affects how much pressure drag force is applied to it. A conical bullet is more streamlined and will create a smaller wake behind the bullet, whereas a spherical bullet will create a larger wake due to its shape, which creates more pressure drag (Moss *et al.* 1995: 72-78).

Yaw is term meaning a non-spin stabilized bullet. If a bullet is in yaw than the bullet will strike a target off of the bullet's centre line (Scott & Haag 2009: 113). For example, if a conical bullet leaves the muzzle of the gun and a force causes it to wobble in the air then it is no longer stabilized and is said to be in yaw. While in yaw a bullet's body shape will contribute to its drag instead of just its streamlined nose, this is yaw-dependent drag (Moss *et al.* 1995: 78-79). A spherical bullet fired from a smoothbore barrel will have no spin stabilization and theoretically never be in yaw. A spherical bullet has no single axis of geometric symmetry and therefore cannot be in yaw (Champion 2016 *pers. comm.* 30 September 2016). The total sum of all three types of drag represent the total drag force against the bullet while in flight.

2.3.4 The Atmosphere

It is important to note that a fluid can be either a gas or a liquid and that the motion of a fluid is covered by the study of fluid dynamics (Young *et al.* 2012: 373). Earth's atmosphere, which is a fluid, is comprised of 78% nitrogen, 21% oxygen. Carbon dioxide, water vapour and other gases make up the final 1% of the Earth's atmosphere up to an altitude of around 20km, while at higher altitudes the gases begin to separate (Moss *et al.* 1995: 67). Air temperature, mass air density, viscosity, and air pressure are subject to change as altitude changes (Moss *et al.* 1995: 67). These atmospheric changes have a direct effect on the drag of the bullet and therefore have a direct effect on the range of the bullet. For example, mass air density decreases with the increase of altitude above sea level, which in turn will decrease drag and increase the range of a bullet (Moss *et al.* 1995: 67).

Earth's atmospheric properties change with time and locale, therefore any firing experiments that are conducted must make careful consideration and note of certain atmospheric properties at the time of firing. Temperature must be noted on the day of any firing experiments as it is a measure of the gas molecules kinetic energy and changes the viscosity of the air. Micro-localized temperature differences can cause up or down drafts which can change the vertical motion of the bullet (Moss *et al.* 1995: 68). The local barometric pressure must be noted as this is a measure of the local static pressure. Dew point for the local area must also be recorded during the time of any experimental firing as the dew point is needed to calculate air density.

2.3.5 Drag Coefficient

The drag coefficient varies with the velocity of the bullet. It is dependent on the shape of the bullet and can only be found experimentally. Previous experimental firing trials that use ballistic trajectory modelling programs use the Braun (1973) data set that modelled the trajectory of a perfect sphere, this issue will be discussed further in Chapter Six of this thesis. However, due to the spherical lead bullet's shape and the soft nature of lead, 'musket balls' can be deformed in the barrel during the firing process, causing the bullet to lose its spherical shape. As a result, the drag coefficient will be greater than that of a perfect sphere, and the results from the modelling data presented in Braun will not be as accurate as a modelling program designed specifically for 'musket balls' (Eyers 2006; Allsop & Foard 2008: 120; Clarke 2008: 55).

The drag coefficient is generally expressed in terms of its Mach number, which is the ratio of the bullet's speed to that of the local area speed of sound. When a bullet is supersonic (faster than the speed of sound), there is an increase in the drag coefficient because shock waves have formed around the bullet (Allsop & Foard 2008: 119; Clarke 2008: 53-55). The efficiency of a bullet is measured by the bullet's drag coefficient (Moss *et al.* 1995: 80), and the shape of a bullet plays a large role in its drag coefficient. Compared to a musket ball, a streamlined conical bullet will part the air exerting a smaller force on the on-rushing air, in turn creating a less turbulent wake behind the bullet. This means the bullet will have a lower drag coefficient. A spherical bullet presents a blunt nosed or cube shape that pushes its way through the air. This, in turn, causes a more turbulent wake behind the bullet, creating a larger drag coefficient than a conical bullet. The higher the drag coefficient of a bullet means the more velocity lost during flight (Denny 2011: 86-88).

2.3.6 Supersonic, Transonic and Subsonic

Supersonic, transonic and subsonic is a division in the velocity of a bullet during flight. Supersonic means a bullet is travelling faster than the local area speed of sound. The speed of sound is variable with location because of the variability within Earth's atmospheric properties. Transonic is the transitional period in which a bullet that was travelling at supersonic speeds has then slowed enough to drop below the speed of sound; however, a transonic bullet will experience a mix of both supersonic and subsonic air flow (Moss *et al.* 1995: 69-70). Finally, subsonic means the bullet is travelling slower than the local area speed of sound. A bullet may be supersonic, transonic or subsonic at different times during its flight (Moss *et al.* 1995: 70). When a bullet crosses the threshold of supersonic into transonic the bullet's behaviour can become unpredictable. This is due to a very common issue known as the transonic problem. The transonic problem states that when a bullet shifts from supersonic to transonic to subsonic, the shift in air pressure and the combined mixture of supersonic and subsonic air flow on the bullet causes the bullet's flight to become unstable. The bullet will regain some stability as it passes into the subsonic region, which can account for a short jump in acceleration (Kisak 2014: 73). At this point, the drag coefficient of a bullet depends on the Mach number. (Moss *et al.* 1995: 69-70; Allsop & Foard 2008: 119; Breithaupt 2010: 132; Denny 2011: 88).

2.4 Terminal Ballistics

Terminal ballistics is the study of the effects of the bullet impacting its target, the damage caused to the target and the effect the target has on the bullet (Greenwood *et al.* 1987: 642; Moss *et al.* 1995: 147; Kisak 2014: 197). The conditions in which bullets impact their targets are extremely variable. Variables include terminal velocity (the velocity of the bullet when it strikes its target), impact angle and the characteristics and composition of both the bullet and the target (Greenwood *et al.* 1987: 91; Moss *et al.* 1995: 147). Impact velocity is the most fundamental variable because the velocity in which a bullet impacts its target can supplant almost all other variables (Moss *et al.* 1995: 147).

The elements of terminal ballistics, such as angle of obliquity and angle of incidence, ricochet, bounce and roll and over and under firing are major considerations for the experimental firing designs in Chapter Five of this thesis, as well as the experimental firing trials conducted in Chapter Seven. Terminal ballistics can enable a greater understanding of the impact evidence seen on a bullet's surface both experimentally and archaeologically. This section on terminal ballistics will serve to introduce the terminology and key factors that provide a clear understanding of the bullet impact evidence seen in Chapter Seven of this thesis.

2.4.1 Angle of Obliquity and Angle of Incidence

An important variable that must be understood is the angle in which a bullet impacts its target. A normal bullet impact should theoretically occur at a 90° angle, meaning that the bullet had been fired at a target directly in front of the muzzle of the firearm. Angle of obliquity and angle of incidence are the area of study that is concerned with bullets that impact their target off of that 90° angle. The angle in which a bullet arrives at its target can be affected by the stability of the bullet in flight and the type of bullet being fired, or more simply whether the bullet was fired at an oblique angle on purpose (Greenwood *et al.* 1987: 644; Moss *et al.* 1995: 147). Military manuals in the early modern period make specific mention of firing at the enemy in either direct or oblique angles depending on battlefield tactics and conditions. Direct fire can be any means of firing at the front or rear of the enemy from the shooter's centre, i.e. if the soldier is firing directly in front of himself. Oblique firing is any means of firing either to the left or right of the shooter's centre, this is also known as angular firing. Firing directly or obliquely at an enemy is dependent on enemy position and the situation on the battlefield (Barriffe 1635: 186; 1647: 81; Elton 1650: 51; Smith 1779: 101-102). Ultimately, regardless of the tactical situation, the bullet is being fired either at a direct 90° angle, or an angle of obliquity.

The angle of obliquity is the change in the angle of the target. The angle of incidence is the change in the angle at which the bullet impacts that target. For example, if a target is placed down range in a horizontal position, the angle of obliquity is 0° and the angle of incidence (the angle at which the bullet arrives and impacts the target) will be 90°. Now, if the angle of obliquity changes, the angle of incidence also changes but must always come to equal 90°. For example, if the target down range was moved to a 30° angle of obliquity, that means the bullet will strike the target at a 60° angle of incidence (Champion 2016 *pers. comm.* 30 September 2016).

If soldiers in the early modern period were given orders to fire at an oblique angle, this means that an unknown number of bullets in every archaeological assemblage could be bullets that impacted a target or the ground at an angle. Experimental firing conducted in this study will investigate oblique firing and therefore, the angle of obliquity and the angle of incidence.

2.4.1.1 Ricochet

A bullet striking a target off the normal angle of incidence that does not penetrate the target is called a ricochet. Ricochet can also mean the rebounding of a bullet from the impact surface (Zukas & Gaskill 1996: 601). One of the key factors that influence the ricochet of the bullet is the hardness of the impact surface (Knock *et al.* 2004; Xu *et al.* 2014: 57). The theory that different building materials could resist bullet penetration and hence cause a bullet to ricochet was well known in the early modern period (Greenwood *et al.* 1987: 645). Knock (2004) states that if the hardness of the impact material is known, then it is possible to predict the rebound or ricochet of the bullet (Knock *et al.* 2004: 8). Experimental firing conducted in this thesis will investigate ground surface bullet impacts. In order to complete this, the bullet will be ricocheted off the surface of the ground and into a soft capture system, this will be discussed in further detail in Chapter Seven.

2.4.1.2 Bounce and Roll

When a bullet misses its intended target, or due to over or under firing, the bullet will continue onwards until it either impacts another target or until its trajectory decays and the bullet impacts the ground. Once the bullet impacts the ground, it does not always stay in the ground. The remaining kinetic energy of the bullet will cause the bullet to bounce and roll across the ground surface. The amount of bounce and roll is dependent on the bullet's remaining kinetic energy, the compactness of the soil, angle of impact, and any objects in the ground the bullet might encounter, such as stones. Experimental firing trials with case shot have noted that after the bullet contacts the ground it then skips across the surface of the ground before coming to a rest (Eyers 2006; Allsop & Foard 2008; Clarke 2008; Kohlisch 2011). Clarke remarks that the length of the skid marks from the bullet varied considerably (Clarke 2008: 110).

Long range musket test firing carried out by Miller (2009) also noted skid marks from bounce and roll and discovered that the degree of elevation and velocity of the bullet when fired was the greatest factor governing the distance in which the bullet bounced and rolled. Experimentation shows that the most influential factor in determining the distance a bullet will travel to the point of ground impact is the angle of elevation of the firearm. If the angle of the barrel varies from 0° to 5°, then the distance the bullet travels varies from 169m to 629m. The velocity of a bullet impacting the ground at a 0° elevation is roughly 230m/s and the distance to first ground impact is between 150m to 180m from the muzzle of the firearm (Miller 2009: 145), while the velocity of a bullet impacting the ground at 5° elevation is close to 83.5m/s. Miller notes that the slower the velocity at ground impact, combined with the steeper angle of decent will reduce the overall distance of a bullet's ability to bounce and roll (Miller 2009: 120). Miller also noted that ground conditions played a major role in determining the rate of bounce and roll. Hard ground conditions allowed the bullet to skip a considerable distance, whereas soft soil conditions allowed the bullet to come to a rest at a much shorter distance (Miller 2009).

Miller also demonstrates through long range firing and observance of bounce and roll after the initial ground impact that the bullet could continue onwards for a long distance. All long-distance firing was conducted by Miller to examine the distance travelled by a bullet from muzzle to ground impact. The barrel was mounted on a light weight trailer 1.39m above the ground surface using a level to keep the barrel at 0° elevation. The bullets were fired using an 18g charge of G12 Powder (Miller 2009: 125). The results can be found in table 2.4 below.

Bullet Number	Muzzle Velocity (m/s)	Distance to first ground impact (m)	Final resting point (m)
1	410	213	288
2	298	115	323
3	438	146	310

Table 2.4: Reproduction from Miller’s first long distance firing experiment (Miller 2009: 129).

Millers results show that a bullet, once impacted with the ground even at 0° elevation can continue to bounce and roll for close to twice its original firing distance. Miller concludes that bullets found on battlefields are not in the position where they impacted the ground because of the effect of bounce and roll upon impact. Without knowing the angle of barrel elevation, it would be difficult to determine the original firing location based on where the bullet was archaeologically recovered.

2.4.2 Over and Under Fire

Bullets did not always hit their intended target, often they missed. There are many accounts of soldiers firing either over the heads of their enemy or under firing. Foard states that this may account for most of the bullets found on battlefields during an archaeological survey (Foard 2012).

Smythe (1594) and Elton (1650) both discuss instances of musketeers being packed into the square formation, surrounded by pikemen preparing for a cavalry charge. The musketeers would have to fire over the heads of the pikemen in front of them to hit the oncoming cavalry, which could in some instances result in firing over the heads of the cavalry (Smythe 1594: 32-33; Elton 1650: 77, 117). Military manuals discuss the proper ways for soldiers to exercise and give fire with their firearms. Gaya states that the muzzle of the musket must always be pointed at the enemy at chest height, the recoil from the firearm or the movement of the enemy may cause the shooter to sway and fire either too high or too low (Gaya 1678: 17-18). Boyle adds that when firing above chest height the bullet will pass over the head of the enemy (Boyle 1677: 32). For cavalry soldiers firing carbines, Venn advised to fire at the knees of the enemies horse as the movement of the soldier's own horse may throw the bullet at random (Venn 1672b: 14).

Many accounts from the American Revolution mention over and under shot. A contemporary author claims that English officers complained that the very nature of platoon firing performed by the English line infantry caused them to both under and over fire (Middlekauff 2005: 507-508). Schenck states that during the battle of Charlotte (1780) all English bullets fired passed over their heads (Schenck 1889: 110). Babits, quoting from Draper, states that low American casualties from the battle of Musgrove Mill (1780) were due to the English soldiers firing over the heads of the American soldiers (Draper 1881: 115; Babits 1998: 15). Draper, discussing the battle of King's Mountain (1780) states that the English soldiers who occupied a hill fired at the American who were in the valley, firing over the Americans' heads, which is often the case when firing downhill, even for experienced soldiers (Draper 1881: 279).

2.4.3 Failure Mechanisms

The defeat of a target implies one of two actions, either perforation or penetration. If a bullet passes completely through a target, then the bullet has perforated the target. If the bullet strikes a target and the bullet does not pass completely through the target than the bullet has penetrated the target (Greenwood *et al.* 1987: 644; Moss *et al.* 1995: 149).

When a bullet impacts a target, both the bullet and the target are subject to a variety of forces. This is a result of the characteristics of both the bullet and the target. Some of these forces cause frictional heating, deformation and fracture of both the bullet and the target. This can result in the defeat of the target; where the bullet penetrates or perforates the target, or the shattering, fracturing or distortion of the bullet so that the bullet fails to destroy the target (Greenwood *et al.* 1987: 655; Moss *et al.* 1995: 149).

2.4.4 Bullet Characteristics

The characteristics of the bullet determine its ability to defeat the target. For example, a conical bullet will have a penetrating and piercing effect on the target, whereas blunt bullets such as spherical bullets will have a plugging and perforating effect on the target (Greenwood *et al.* 1987: 91; Moss *et al.* 1995: 147). However, when any bullet type impacts a target it may perforate the target, penetrate the target and/or ricochet or rebound (Moss *et al.* 1995: 149). Deformation on the impact of a bullet increases the bullet's diameter, which decreases its ability to penetrate the target (Moss *et al.* 1995: 148). A spherical bullet would be considered a kinetic energy projectile. It is not designed to penetrate or defeat armour in any specific sense that modern bullets are. A kinetic energy projectile is designed to impart as much energy and momentum as possible onto a target (Moss *et al.* 1995: 153).

2.4.5 Target Characteristics

The characteristics of the target will determine not only how the bullet deforms upon impact, but also what characteristic traits may transfer to the bullet's surface. Target types on an early modern battlefield could include, infantry soldiers, cavalry soldiers, their equipment, horses, cannons, fences, hedges, the ground, and buildings to name a few (Greenwood *et al.* 1987: 642; Moss *et al.* 1995: 148).

The traditional way to classify a target is by its relative thickness. This is an effective way to classify a target because of all the above targets mentioned, it is generally a section or a subsection of the target that the bullet impacts and the target may not have the same dimensions throughout (Greenwood *et al.* 1987: 644; Moss *et al.* 1995: 148). Another way to classify a target is geometrically, referring to its shape: curved, irregular or flat (Moss *et al.* 1995: 149). With all experimental firing trials, the material of the target will also be noted, as the target material will affect how the bullet impacts the target. For example, the bullet will impact differently if it were to impact a soft target, such as soil, or a hard target, such as stone.

Armour plating and ceramic body armour are major topics in modern terminal ballistics. The use of body armour was in transition throughout the early modern period. During the 16th to the late 17th centuries, body armour was still worn by infantry and cavalry soldiers. Throughout this period armourers were capable of making steel armour that was pistol proof, as can be seen in figure 2.1 below (Hall 1997: 147). The indentations on the armour are from pistol proof testing.

Figure 2.1: English breastplate showing pistol proof testing, dating between 1625-1650. Photo courtesy of Dan Sivilich.

Beginning with the Thirty Years War (1618-1648) several cavalry and infantry troop types wore armour covering different regions of their bodies. Cuirassiers; a type of heavy cavalry wore three-quarter to full body armour, while Harquebusiers, a type of light cavalry wore a helmet and breastplate (Wilson 2009: 92-93; Schürger 2015: 90-91). Some infantry soldiers wore armour as well. Some Pikemen wore breast and back plates, along with helmets while some did not wear armour at all (Wilson 2009: 88; Schürger 2015: 96). During the English Civil War Cuirassiers wore three-quarter armour to below the knee (Vernon 1644: 42; Foard 2012: 42). Pikemen began the war wearing armour, but Foard states that by the end of the war, pikemen may have worn no armour other than a helmet (Foard 2012: 43). Soldiers began shedding their armour as it was cumbersome and exhausting to wear, coupled with the growing occurrence of bullets demonstrating their ability to defeat contemporary armour on the battlefield. As a result, by the beginning of the 18th century onwards body armour became rare on the battlefield (Hall 1997).

2.5 Wound Ballistics

Wound ballistics is the study of the wounding capabilities and the motion of a bullet inside the body (Greenwood *et al.* 1987: 781; Moss *et al.* 1995: 167). While the experimental firing trials in this thesis do not fire bullets into bodies of any variety, it is recommended that future studies do to collect impact evidence from what is without argument the main intended target on the battlefield, the human body. While this is not a focus for this thesis, a small section will be provided here on wound ballistics for future studies.

When a bullet enters the body it creates a wound channel. As the bullet passes through the body it causes the body tissue to stretch and expand, this is known as permanent and temporary cavitation (Kneubuehl 2011: 112; Kisak 2014: 208). The wounding effects caused by the bullet are dependent on the tissue that the bullet is passing through, such as muscle tissue or through the elastic organs. The damage caused to the body by the temporary cavity is varied depending on the anatomical location of the wound (Fackler 1996: 199).

The kinetic energy of the bullet is the most important aspect of wound ballistics, this is due to the transfer of energy from the bullet to the body, thereby creating the wound track (Greenwood *et al.* 1987: 781; Moss *et al.* 1995: 167; Kneubuehl 2011: 93). Temporary cavitation is caused by the momentum that is transferred to the human body's surrounding tissues when a bullet enters it. This momentum causes the surrounding tissues to move continuously, but briefly even after the bullet has passed through the area, this action causes a large cavity to form. These violent changes in the surrounding tissues are sufficient enough to rupture blood vessel, break bones and rupture organs (Greenwood *et al.* 1987: 782; Moss *et al.* 1995: 168; Kneubuehl 2011: 112; Kisak 2014: 208).

Permanent and temporary cavitation is dependent on the characteristics of the bullet, such as its size, and shape. The bullet's velocity, mass and its flight stability are important factors to consider as well (Greenwood *et al.* 1987: 781; Moss *et al.* 1995: 167; Fackler 1996: 195; Kisak 2014: 208). Knowledge of the flight behaviour of the bullet is essential for the study of wound ballistics (Greenwood *et al.* 1987: 781; Moss *et al.* 1995: 167). The human body's soft tissues are 800-900 times as dense as air and when a bullet hits human body tissue, the bullet almost always becomes unstable. Any yaw angle that the bullet may have had before impact will greatly increase upon impact as will the damage created by the bullet (Greenwood *et al.* 1987: 781; Moss *et al.* 1995: 167).

Bullets are designed to have different effects upon impact, and it is their design that has the greatest effect on the wounding capabilities. Bullets can fragment, expand, tumble and disintegrate upon impact (Moss *et al.* 1995: 168; Kisak 2014: 208). Quartered bullets from the early modern period are assumed to work like modern hollow points, fragmentation or frangible bullets, where in they are designed to enter the body and fragment creating a massive wounding effect on the body (Kisak 2014: 201).

2.6 Conclusions

This chapter discussed the ballistics of smoothbore firearms and introduced the ballistic principles and terminology that will be used throughout the entirety of this thesis. In order to create an accurate and measurable experimental firing methodology, it is important to understand the science and variables of ballistics that directly affects the bullet and how it arrives and impacts its target. As seen in internal ballistics, variables such as the choice of a propellant, windage, the use of a wad, and barrel length can all be controlled to an extent throughout the experimental firing trials to remain consistent and to collect comparable results. Each of these variables will be explored further in Chapter Four through the usage of military treatises and scientific publication from the early modern period with the aim to create an experimental firing methodology. External ballistics introduces variables that need to be acknowledged, but cannot always be controlled. The principals and variables the define external ballistics are vastly important regarding Chapter Six of this thesis, where an external ballistic modelling program has been created to model the trajectory of spherical lead bullets for the experimental firing trials. Terminal ballistics considers the final sequence of variables that must be considered when designing firing experiments. The characteristics of both the target and the bullet will affect what happens when the bullet impacts its target. While some aspects like target type and how a bullet reaches its target can be controlled, the moment of impact can only be recorded.

Chapter 3: Previous Firing Experiments

This chapter discusses the experimental firing trials known to the author. There is little to no overlap or progression from one experiment to the next as most of the experiments remain unpublished. The exceptions being what has been dubbed as the Cranfield trials, which was an intentional program of study conducted at the behest of Dr Derek Allsop and Dr Glenn Foard at the Defence Academy at Cranfield University, United Kingdom from 2006- 2011. The major source of overlap and progression between these experiments is the pursuit of the creation of an experimental firing methodology in accordance with English Civil War firing standards and the collection of bullet evidence that could be compared to the archaeological bullet assemblage from the Edgehill battlefield. The results from the Cranfield trials have elucidated some of the evidence found on the bullet's surface as seen in Chapter One (section 1.3). However, as will be seen below, experimentation with the aim of understanding bullet impact evidence has been rarely undertaken, instead, the vast majority of experimental firing trials have been undertaken to better understand the ballistic capabilities of smoothbore firearms.

It is the intent of this chapter to not only examine the previous experimental firing trials but to examine their firing methodologies and how they were created, as a basis in which to build an experimental firing methodology for this thesis. As noted in Chapter Two of this thesis on internal ballistics (section 2.1) certain variables must be identified, such as the choice of the propellant, the use of a wad, the barrel length of the firearm in use and windage as well as the composition of the bullet and the ratio of charge weight to bullet weight. These variables must be controlled and kept constant throughout the experimental firing trials to collect comparable results. With the knowledge of these variables, the experimental parameters can be identified and defined. The previous experimental firing trials detailed below are discussed in chronological order. Each section will discuss the aims and methods of each experiment with a brief discussion at the end of the section. The experimental firing trials that involved artillery have been omitted as the study of artillery is outside the research scope of this thesis.

3.1 The Graz Tests 1988-1989

The Graz tests were carried out in the winter of 1988-1989 by Dr Peter Krenn. Fourteen firearms were chosen for test firing and represented a range of types from arquebuses to pistols, rifled and smoothbore, with differing lock mechanisms (matchlock, wheel-lock, and flintlock) and some muskets that had been converted from one lock mechanism to another. Three of the firearms were rifled muskets, while the remaining eleven were smoothbore (Krenn 1991: 34; Krenn *et al.* 1995: 102; Hall 1997: 136). All fourteen firearms were fired a total of 325 times under controlled conditions. The total number of bullets fired from each firearm varied, but generally numbered around 18 bullets per firearm. All firearms were tested for their ballistic capabilities such as their accuracy, range, and ability to penetrate different target types (Krenn 1991: 36; Krenn *et al.* 1995: 103). The muzzle velocity of all Graz firearms was averaged around 454m/s, and 10 out of 13 firearms were recorded between 400m/s to 500m/s (Krenn *et al.* 1995: 107; Hall 1997: 136).

3.1.2 Methods

All bullets were fired with modern gunpowder, and the charge weight was determined to be one-third the weight of the bullet. The choice of powder is known as ‘Köln-Rottweil Nr.O. grain size 0.6 to 0.3mm’ and for priming powder ‘WANO-feuerwerks-pulver 75%, grain size 0.15 to 0.35mm’ (Krenn 1991: 37; Krenn *et al.* 1995: 102; Hall 1997: 136). Krenn states that at times the charge weight varied from firearm to firearm and in each case, the optimal charge was determined experimentally. The firearms were fixed to a frame or gun mount to avoid human error; all firearms were sighted on target and fired electronically. Every bullet fired was measured and tracked electronically and the measurements for the bullets fired were taken at 7.5m or 8.5m and at 24m from the muzzle, and muzzle velocities were calculated from that collected data (Krenn *et al.* 1995: 102; Hall 1997: 136).

The Graz tests mark the beginning of experimental firing with early and modern firearms. The Krenn experimental firing trials focused largely on the ballistic capabilities of the firearms in their collection, but did not focus on the soft capture and analysis of the impacted bullets. However, there are some issues that should be discussed, starting with the charge weight chosen for the firing of the muskets and pistols. Krenn states that one-third the weight of powder to bullet was used to fire the firearms, but never explained where that information came from or why that amount of powder was chosen. Even more concerning is the declaration of an ‘optimal’ charge being found experimentally, which would mean Krenn had an ideal target velocity but never bothered to explain what that was or why it was chosen. Furthermore, Krenn states that the muzzle velocity of all Graz firearms was around 454m/s and that 10 out of 13 firearms were between 400m/s to 500m/s. Krenn is mistaken with the claim that this is to be of importance to the firearms themselves, what this reflects is the gunpowder charge size used and the choice of gunpowder. If the powder and charge size is held constant, the results will also be constant. This is a matter discussed further in Chapters Four and Six of this thesis.

The firing methodology used by Krenn shows that the key variables listed in Chapter Two of this thesis were sought after to create a firing methodology. The choice of powder was a modern gunpowder with a grain size of 0.60mm to 0.30mm, also known as a 3FG powder. The sought-after muzzle velocity for the Krenn experiments was between 400m/s to 500m/s, and the bullet weight to charge weight ratio was chosen as one-third. However, the source material to clarify these choices is not made clear. Furthermore, Krenn’s firing experiments did not seek to collect the fired bullets to investigate impact evidence, but rather to explore the ballistic capabilities of early modern period firearms.

3.2 Babits et al 2003

Babits et al (2003) is an unpublished firing experiment, that investigated the lethality of ‘buck and ball’ fired from smoothbore muskets at various ranges. Babits researched primary accounts from the battles of Camden (1780), Hobkirk’s Hill (1781), and Guilford Courthouse (1781) to identify firing tactics and ranges used by American soldiers against the British during the American Revolution. Using primary accounts, Babits determined that the American Charleville musket was much more effective at a longer range than the Long Land Brown Bess musket used by the British. Babits determined that this meant that the Americans could fire their first volley from close to 91.44m and reload with buck and ball while the British fired their first volley. Then, when the British charged with bayonet the Americans would fire their buck and ball load into the British ranks at close range breaking the momentum of their bayonet charge.

3.2.1 Methods

Babits fired 120 rounds of buck and ball ammunition at various ranges at human targets made of wood in accordance with an American drill manual written by the Baron von Steuben (Von Steuben 1794). Von Steuben's manual was originally developed during the American Revolution at Valley Forge in the winter of 1777-1778. Babits used a cartridge to load the firearms, and each cartridge contained a 3.89g charge of FF (also known as FFG -Grain size is 0.59 to 1.19mm) black powder for both a reproduction 14-bore American Charleville musket, and a 12-bore Long Land pattern British Brown Bess musket. Five shot groups of buck and ball were fired at a target that was 812mm x 660mm. The target had a rough white cross in the centre for aiming the musket, which was shoulder fired. Each cartridge contained one 17-bore bullet (for the Charleville) or one 14-bore bullet (for the Brown Bess) and three 100-bore buckshot bullets. After placing powder in the barrel, the bullet was rammed home, then the buckshot dropped in and wadding rammed down over the load. The conclusions of the experiments revealed that at close range buck and ball had a devastating effect and would have badly wounded or killed soldiers. Thus it was concluded that the use of this type of ammunition would have broken a bayonet charge if fired at the proper range (Babits *et al.* 2003).

The immediate issue with this experiment is that the charge size of 3.89g seems very low and that there is no clear indication as to why it was chosen. The velocities of the bullets were never recorded, and the bullets for this study were not examined for impact analysis. However, the use of military treatises from the period to replicate firing conditions are ideal.

3.3 Linck 2005

Linck (2005) is a brief, unpublished firing experiment where four 14-bore bullets, made of pure lead were fired from a 2nd model Brown Bess musket (12-bore). All bullets were wrapped in a cartridge containing a 6.48g charge using 3F black powder (also known as FFFG, Grain size 0.29 to 0.84mm). The bullets were fired at an 'old' spruce log with a fallen pine tree acting as a backstop. All four bullets were fired from a resting position at a distance of 'about' 18.2m. Two of the bullets were recovered, one bullet was found lodged inside the spruce log and the other bullet was recovered from the pine tree back stop. The bullet recovered from the pine tree showed little distortion but retained a wood grain impression noted as 'grooves.' The bullet found lodged inside the spruce log retained impressions from the wood grain and contained directional distortion patterns from where the bullet penetrated the log (Linck 2005).

The main issues with this study are the lack of an explanation of why those charge sizes and powder were used, nor does Linck record muzzle velocity or the velocity of the bullet. The study does examine the bullets recovered from the wooden targets and demonstrates that experimental firing can collect data on bullet impact analysis, in this case, wood grain impressions.

3.4 Eyers 2006 (Cranfield Trials)

Eyers (2006) is the first of many experimental firing trials conducted at Cranfield University, Shrivenham campus from 2006-2011, and is an unpublished MSc thesis. Eyers investigated the ballistics of both smoothbore muskets and artillery dating to the English Civil War. The overall aim was to use the ballistic data to extrapolate firing positions on the battlefield and to explore the possibility of finding original firing locations on the battlefield in reference to the archaeological bullet finds. The research used primary accounts from the English Civil War to recreate firing conditions as accurate to the time period as possible. Eyers also investigated the ballistics performance of both the smoothbore musket barrel as well as the artillery to establish muzzle velocities, peak pressures, accuracies and to determine the range of both weapon systems. Eyers also investigated if the use of a wad influenced the performance of the firearms. Eyer's sections on artillery have been purposefully omitted as it is considered outside the scope of this thesis.

3.4.1 Methods

The firearm used was a 10-bore barrel, 48 inches in length attached to a breech block. A pressure transducer was attached to the breech block to measure peak pressure and Doppler radar was used to track the bullet down range after it was fired. The musket fired a 12-bore bullet; composed of 99.9% pure lead based on the findings from the Harkins (2006) study. The wad used consisted of nine sheets of balled-up toilet tissue and was placed in the barrel after the powder but before the bullet (Eyers 2006: 25-27). A small amount of powder was poured into the touch hole and ignited via an electric match (Eyers 2006: 26). Test firing was carried out with and without a wad to determine if there were any changes to the velocity and accuracy of the firearm and muzzle velocities were used to predict the maximum range of the musket (Eyers 2006: 24).

The full results from the Eyers experiment on the use of a wad were already discussed in Chapter Two (section 2.1.4) and will not be discussed further here. However, a second experiment was conducted by Eyers which aimed to achieve a muzzle velocity comparable to both the Robins (1742) and Mordecai (1844) studies, which recorded muzzle velocities between 450m/s and 500m/s (Eyers 2006: 26). The averaged results from the firing experiment can be found below in tables 3.1 and 3.2 below.

Powder Charge (g)	Velocity (m/s)
10	295.71
12.01	387
14.016	440
15.015	470

Table 3.1: Velocity obtained without a wad using A3 powder (Eyers 2006: 26).

Powder Charge (g)	Velocity (m/s)
12.513	466
14.05	489

Table 3.2: Velocity obtained with a wad using A3 powder (Eyers 2006: 27).

Eyers determined that an optimal charge size of 12.5g would be used as it matched the target velocity of between 450m/s to 500m/s in accordance with the Robins and Mordecai experiments mentioned above (Eyers 2006: 27).

Eyers used primary accounts and military treatises dating to as close to the English Civil War period as possible to recreate firing conditions, which is an ideal tactic. Eyers also revealed that according to two experimental studies conducted by Robins (1742) and Mordecai (1844) that muzzle velocity for the period should have been between 450m/s and 500m/s, which may have been what Krenn was basing his results from but was left unstated. Eyers determined the charge size of the musket based on experimentally firing the musket with varying charge sizes until the ideal velocity was achieved. Eyers also conducted experiments with and without a wad which revealed a marked increase in the muzzle velocity of the firearm when a wad was used; the results of which were discussed previously in Chapter Two, section 2.1.4. However, as many wads types were documented in the early modern period, this topic warrants a more in-depth discussion, which can be found in Chapter Four (section 4.5).

3.5 Harkins 2006 (Cranfield Trials)

Harkins (2006) is an unpublished MSc Thesis conducted at Cranfield University. The aim of this firing experiment was to attempt to soft capture a musket bullet for examination of loading and firing evidence. Then, those bullets would be compared to bullets recovered from the Edgehill battlefield survey in an attempt to identify similar characteristics within the assemblage (Harkins 2006: 13). The firing methodology used in this study was borrowed from the Eyers (2006) study. A 10-bore musket barrel was used, with a 48-inch barrel length. The musket was loaded with a 12.5g charge of A3 powder, fired using an electric match (Eyers 2006: 25-27; Harkins 2006: 24).

3.5.1 Experiments Collecting Bullet Evidence

Harkins test fired the musket directly into a soft capture mechanism to investigate loading and firing evidence. One bullet was loaded into the muzzle of the firearm and rammed into place with a metal ramrod, but not fired. A circular facet was discovered on the bullet's surface and this was determined to be from the action and force of the use of a metal ramrod, as previously noted in Chapter One (section 1.3.3) (Harkins 2006: 45).

Bullets that were fired directly into the soft capture mechanism exhibited surface characteristics that are also seen on some of the bullets found in the Edgehill assemblage. Harkins determined that powder pitting was caused by the bullet resting on top of the powder when the bullet was fired causing the bullet's surface to melt where it was in contact with the powder. Harkins noted that this may also indicate if a bullet was fired with or without a wad (Harkins 2006: 42). Harkins determined that the banding effect found on the surface of the bullet was from the bullet 'setting up' and expanding to fit the bore of the barrel and that this was caused by the high peak pressure from the ignition of the gunpowder, as previously noted in Chapter One (section 1.3.4.1) (Harkins 2006: 42).

The Harkins study used the results from the Eyers study to create the firing methodology used during the experiments. While Harkins did not investigate the bullet's surface for impact evidence, he did positively identify the cause of the loading and firing evidence seen on the bullet's surface through experimentation.

3.6 Roberts et al 2008

Roberts et al (2008) examined the ballistic performance and lethality of the 18th century British Brown Bess musket at varying ranges. Roberts researched primary accounts from the battle of Culloden (1746) to recreate clothing and armour that would have been worn by the Jacobite soldiers on the day of the battle. Roberts investigated both the effects the bullet would have on the clothing and armour but also on the soldier himself. To complete this, Roberts created a human proxy made of ballistic gel and dressed it in Jacobite clothing, armour and a wooden shield. Roberts sought to achieve the averaged muzzle velocity data mentioned in Eyers (above), as a baseline for experimentation. This averaged baseline was founded on the Robins (1742) and Mordecai (1844) data sets. Roberts determined that the average muzzle velocity between the two data sets was 457.2m/s (Robins 1742; Mordecai 1844; Roberts *et al.* 2008: 4). To achieve this a mixture of 3A and G12 black powder was mixed at a ratio of 1:3, both powders contain a grain size equivalent to 2FG or 3FG (Roberts *et al.* 2008: 13).

Doppler radar and a pressure transducer were used to measure the ballistic performance of the weapon, including the muzzle velocity and peak pressure. The 12-bore musket was placed on a mount and fired using an electronic trigger, firing a 14-bore bullet. The bullet was loaded into the musket using a cartridge containing a charge of 8.89g to 10.66g of black powder based on the charge sizes recommended by Harding (1999) (Harding 1999c: 105; Roberts *et al.* 2008: 3). Eight shots were then fired at the human target to examine deformation of the bullet and the wounding effect the bullet had. To examine the bullet after hitting the targets a soft capture method was used. The results show that the first four shots perforated all armour and clothing and penetrated the ballistic gel with 'deadly effect.' The fifth bullet penetrated two rows of ballistic gel to reveal that the bullet had enough force to pass through one individual and still have a wounding effect on the individual behind him. Unfortunately, the soft capture method failed and no analysis could be performed on the bullets for impact evidence (Roberts *et al.* 2008).

Roberts attempted to capture the bullets from the experimental firing with the aid of a soft capture system, unfortunately, the soft capture system failed, and no analysis could take place. Roberts also used primary accounts from the time of the battle to recreate firing conditions and experimental designs. Roberts used the same firing data from Robins (1742) and Mordecai (1844) that was used in the Eyers study to establish a baseline muzzle velocity, which would be used for comparison when selecting a replica black powder. Roberts choice a 1:3 mixture of 3A to G12 black powders that were found to be in accordance with this standard when the choice of charge size was factored in from the Harding study of the East India Company firing standards.

3.7 Miller 2009 (Cranfield Trials)

Miller is an unpublished MSc thesis conducted at Cranfield University. Building upon the Eyers experiments, Miller set out to fill in the gaps in Eyers' research. The aim was to infer the firing position of a musket given the known location of the archaeologically recovered bullet. Miller created a soft capture system that could safely capture a musket bullet without causing further damage. Miller also investigated the muzzle velocity of multiple powders to discover which one achieved the desired velocity recorded by Robins (1742) and Mordecai (1844). Miller also empirically examined firing with and without the use of a wad, the banding effect from firing, and bullet weight loss from firing. Miller also explored musket elevation in relation to distance and velocity and conducted long distance firing to explore the effects of bounce and roll of the bullet after ground impact.

Remaining as accurate to the English Civil War period as possible and to have a data set comparable to Eyers, Miller used the same 10-bore gun barrel on the same mount for firing using an electric trigger to fire the gun. Miller determined the ratio of charge size to bullet weight as being 2:1 according to Turner (1683). Miller combined this with the findings in Roberts et al (2008) study in regards to a muzzle velocity baseline achieved by averaging the results from Robins (1742) and Mordecai (1844) at 457m/s (Roberts *et al.* 2008: 0; Miller 2009: 26).

3.7.1 Experimental Results

Miller used three different black powders for the experiment: Swiss No1, G12 and 3A. All bullets were fired with the same 12.5g charge. Swiss No1 was excluded because it produced a large amount of banding and melting on the surface of the bullet, and this was determined to be from high peak pressure (Miller 2009: 87). G12 was chosen because it was a slower burning powder and believed to more representative of the powders existing in the time period. Miller's experiments with windage show that a tighter fitting bullet would increase the velocity of the bullet. The experiments with wadding demonstrate that the muzzle velocity is increased when a wad was used, it also proved that using a wad decreases the amount of melting and pitting on the bullet's surface by acting as a barrier (Miller 2009: 92-94). These experiments were discussed in Chapter Two (sections 2.1.3 and 2.1.4) in further detail.

Long distance firing and experiments with angle of elevation show that a bullet can travel between 169m to 629m depending upon barrel elevation and bounce and roll of the bullet after first ground impact (Miller 2009: 120-145). Miller concluded that bullets found on the battlefield are not in the position where they originally impacted the ground, because of the effects of bounce and roll after first ground impact, as previously mentioned in Chapter Two (section 2.4.1.2).

Miller used military treatises to discover that the charge weight to bullet weight ratio was 2:1, and that when combined with the muzzle velocity data sets first recorded by Robins (1742) and Mordecai (1844) achieved the ideal velocity standards. Miller also fired extensively with and without a wad, verifying the conclusions made by Eyers that the use of a wad has a marked increase on the velocity of the bullet, the results from those experiments can be found in Chapter Two, section 2.1.4. Miller also demonstrated the importance of windage on the velocity of the bullet, the results of which can be found in Chapter Two, section 2.1.3.

3.8 Green 2010 (Cranfield Trials)

Green (2010) is an unpublished MSc thesis conducted at Cranfield University. Green set out to determine if there was a clear relationship between the velocity of a bullet and the resultant deformation of the bullet after impact. This marks the first study to examine terminal impact and impact analysis of the bullet, albeit that this study is only concerned with steel plate and stone wall impacts. The aim was to examine impacted bullets from known impact surfaces and to attempt to interpret the characteristics of the impact surface from the evidence recorded on the bullet's surface (Green 2010: 8, 39) The study questioned whether there was a way to infer the velocity of a bullet recovered in an archaeological context based on the bullet's deformation. The firing trials were conducted using a 12-bore and a 20-bore shotgun barrel fired from a mount using an electric trigger. The powder charges varied with each cartridge to simulate different firing distances. Some of the bullets were cast using pure lead, while others were cast using lead with an added hardening agent known as antinomy. Bullets were fired at various velocities and at a variety of stone and metal targets. Bullets were also fired at differing angles to investigate how the angle of incidence would affect bullet deformation upon impact.

The results show that at low velocities, the impacted pure lead bullets revealed noticeable deformation whereas, at high velocities, the pure lead bullets would all but disintegrate on impact. Bullets with the added antinomy hardening agent were found to fracture or shatter instead of 'squashing', as the pure lead bullets did. This study concluded that as velocity increased so too did the level of impact damage recorded on the surface of the bullet. However, the most notable deformations occurred at the extreme ends of the bullet's velocity. The intermediate velocities were harder to tell apart meaning that any bullet in the intermediate range of velocity would have the finer details removed from the bullet surface due to corrosion after being in the ground, thus at the intermediate velocities, it would be impossible to tell the difference (Green 2010).

Green proved the importance of using pure lead bullets as opposed to bullets containing the antimony hardening agent. Green also proved the concept that adjusting charge size of the firearm can simulate distance; however, the problem with this study is that no specific distance was mentioned. Green also proved that a musket bullet could be fired from a shotgun cartridge using black powder instead of modern gunpowder. This was also the first study to attempt to examine the impacted bullets for evidence, although no attempt was made to juxtapose these experimental bullets with those from the archaeological record.

3.9 Scott et al 2017

The experimental firing conducted by Scott et al (2017) and the experimental firing trials in this thesis were parallel studies with no previous knowledge of one another's existence. With that established, Scott's firing methodology will not be reviewed as it had no bearing on the development of the firing trials in this thesis.

Scott marks the first, extensive experimental firing trial where the collection and analysis of impacted bullets was the focal point. Scott aimed to investigate how bullet impacts can be linked to velocity, range and the characteristics of the target. This was completed by firing multiple bullets into ballistics gelatine, with cloth attached to one end to simulate clothing. All bullets were either fired into or through the gelatine into a sand back stop. Scott also fired bullets into a wooden palisade made of different species of wood to obtain a variety of bullet impact evidence on wood (Scott *et al.* 2017: 2-4). The experiment used a variety of firearms that were common in North America during the Seven Years War and American Revolutionary War (Scott *et al.* 2017: 6).

The gunpowder used in the study was Swiss (FFg) black powder that was used for both the priming powder and main charge, and were loaded into the weapon via a cartridge. The charge weight for firing was varied for the experiments using ballistics gelatine (Scott *et al.* 2017: 6). The muskets were fired from a bench rest, for high speed video recording and to record the velocity of the bullet (Scott *et al.* 2017: 13). After each bullet was fired, team members used metal detectors to find and recover the bullet, and recovered bullets were then bagged and labelled (Scott *et al.* 2017: 14). 74 bullets were fired, as well as 63 buckshot bullets (Scott *et al.* 2017: 19-20).

Results from the experiment show that bullets that impacted the ballistics gelatine, the dry soft woods, the wet pine and the loose sand showed the least deformation from impact and that bullets of a smaller calibre showed less distortion from impact than larger calibre bullets (Scott *et al.* 2017: 52). The results also demonstrate a correlation between bullet deformation and velocity on impact (Scott *et al.* 2017: 76). Scott confirmed the transfer of cloth impression from the bullets impacting the clothing, as well as several wood impact impressions. As a result of this firing experiment, Scott created the bullet deformation index, discussed in Chapter One (section 1.4.1).

3.10 Conclusion

The previous experimental firing trials detailed above tend to focus on the ballistic capabilities of the musket, such as its range, accuracy, 'lethality' and its ability to penetrate or perforate specific targets. Experimentation has also been conducted to collect different types of evidence found on the bullet's surface, such as the accomplishments of the Cranfield trials which definitively proved the ability to reproduce bullet evidence from loading and firing.

Only three of the previous experimental firing trials sought to collect impact evidence from the surface of the bullet. Those trials demonstrate the parallel between the nature of the impact surface and the characteristic traits transferred to the bullet's surface. The vast majority of firing trials remain unpublished, rendering their information inaccessible and unknown to the majority of the conflict archaeology community. Therefore, due to a gap in the literature and research on experimental firing for impact evidence, a proof of concept established through experimental firing will provide insight into the relatively unaddressed issue of impacted bullets and advance our ability to interpret battlefield archaeology bullet assemblages. To accomplish this a rigorous experimental firing methodology must be created that is in accordance with early modern period firing standards to reproduce the impact evidence seen on the bullets' surfaces.

The firing methodologies discussed in the above experiments have created a foundation in which to build by identifying source materials and variables that need to be further expanded upon and better understood. Such variables as propellant choice, the ratio of bullet weight to powder weight, the use of a wad, bullet composition and windage, which are also key variables identified in the previous Chapter (Two) of this thesis. An ideal muzzle velocity has been stated by many of the above authors which needs further expansion as this ideal will be the corner stone for the building of an experimental firing methodology as it provides a scientific baseline in which comparisons can be made that link directly to early modern period firing standards.

The experimentation to find a black powder that replicates the firing data presented by the Robins (1742) and Mordecai (1844) studies is an innovative start to the creation of a firing methodology. However, the use of the muzzle velocity data from Mordecai (1844) as a baseline for any experiment that aims to be period accurate for any period before the Napoleonic Wars is spurious and anachronistic. There was a well-documented revolution in the strength of gunpowder in England, directly after the American War of Independence (1775-1783), when William Congreve was given control of the Royal Powder Mills in England (Cocroft 2000: 30-48), there will be a more general clarification on this issue in Chapter Four (section 4.2.8, and section 4.2.9) of this thesis, as many of the experiments sought this standard. The use of a wad had been explored in the experiments by Eyers and Miller which demonstrated the marked increase in the muzzle velocity of the firearm. This idea needs further exploration as many wad types have been noted for use in the early modern period. There is also a disagreement in the above studies over the ratio of charge weight to bullet weight that must be clarified. Krenn used a powder charge size one third the weight of the bullet but failed to state why. Miller cited a source from the early modern period that stated that the ratio was one half, and Roberts simply stated they used a charge size suggested by Harding (1999), which was a study of the East India Company practices.

Before the experimental firing trials can begin, certain variables and experimental parameters had to be identified and defined, which was completed not only in this chapter but in the previous chapter as well (Chapter Two). While the previous firing experiments above have identified a number of locations in which to begin defining these variables and parameters, providing a foundation on which to build the experimental firing methodology for this thesis. The disagreements amongst the above studies have led to the conclusion that an expansion and re-examination of the source material must be first undertaken. This expansion and re-examination of the source material for the creation of an experimental firing methodology will be the subject of Chapter Four.

Chapter 4: The Creation of an Experimental Firing Methodology

The purpose of this chapter is to detail the creation of an experimental firing methodology that will be used for the experimental firing trials found in Chapters Six and Seven of this thesis. The experimental firing methodology will be deployed in conjunction with the experimental designs created in Chapter Five to create the proof of concept reference collection of known bullet impacts against which the archaeological bullet assemblages from two case study battlefields can be compared in Chapter Eight. Using experimentation to recreate bullet evidence seen on the archaeological bullet assemblages has been thus far successful as seen in the previous experimental firing studies in Chapter Three; however, as previously noted, experimentation to recreate and analyse impact evidence has been largely unexplored. Investigating impact evidence on the bullet's surface and experimentation with known impact surfaces will enable a better understanding and interpretation of archaeological bullet assemblages, leading to a better interpretations of conflict archaeology sites.

Before any firing experiments could be conducted key variables had to be identified through internal ballistics (Chapter Two), and previous firing experiments (Chapter Three). This chapter will define those variables within early modern period firing standards using military treatises and scientific publications. This thesis deemed it essential to re-examine and expand upon the previous firing trials source material to clarify the disagreements within the modern literature as noted in the conclusion of Chapter Three (section 3.10).

To achieve scientifically comparable data, not only to the desired time period but also to previous firing experiments, the advised variables, found below, must be carefully selected and controlled. To understand the impact evidence seen on bullets in the archaeological assemblages, one must first understand the variables that influence the impact of the bullet and to determine the parameters of the experiment. Variables such as choice of gunpowder, muzzle velocity, bullet composition, the ratio of bullet weight and gunpowder charge weight, and whether to use a wad and if so of what material, all influence the outcome of any experimental firing trail and therefore determine the parameters of this thesis. The variables of firearm choice, barrel length and windage will also be discussed below. The method for soft capturing a bullet is also discussed in this chapter as the ability to soft capture a bullet after it impacts a target is the only way to collect bullet impact evidence without adding further damage to the surface of the bullet, which would complicate post firing analysis.

Finally, a preliminary experiment can be found in sections 4.8 below. This experiment pulls together the discussed variables to create the parameters of the experimental firing methodology, and future experiments conducted in Chapters Six and Seven. A brief discussion found in section 4.9 below will discuss a sudden and unforeseen legal change in the usage of black powder on Ministry of Defence firing ranges that occurred as the last of firing experiments were to be conducted. Rather than abandon the last of the firing trials, another firing methodology was created using modern nitro gunpowder.

4.1 Gunpowder

As seen in the previous experimental firing methodologies (Chapter Three), the choice of gunpowder can seem inconsequential or random and most studies never fully explain why their specific powder was chosen. Almost all firing experiments use a reproduction modern black powder to stand in place of an early modern period powder. This is because the exact recipes for those powders remain in large part unknown, as will be seen in detail below. This begs the question, can an early modern period powder be reproduced by examining contemporaneous sources as Eyers (2006) attempted to do? Or must a reproduction powder be used? If a reproduction powder is used, how should it be selected?

Gunpowder is an intimate mixture of three ingredients, saltpetre, charcoal, and sulphur. The composition and grain size of gunpowder are the most important variables that influence its effectiveness (Brown 1998: 21-22). The composition of gunpowder relates not only to the three ingredients used to make it but also to their purity and amount used to make it. Changing the purity or the amount of one ingredient used can alter the recipe significantly. How these ingredients interact with one another correlates to its effectiveness and strength (McConnell

1988: 273; Cocroft 2000: 2; Kelly 2004: 36; Eyers 2006: 16; Fadala 2006: 192; Kohlisch 2011: 24; Kisak 2014: 51). Throughout time, the manufacturing process of gunpowder changed and, as a result, the composition and purity of these three ingredients changed as well leading to a near infinite amount of recipes of varying strength (Hime 1904: 177-198; Cocroft 2000: 2). In the early days of gunpowder, the published mixtures of the ingredients seem quite arbitrary, although it may be more of an indication of experimentation than randomness. This can be seen below in table 4.1. However, as time went on the composition progressed in a distinctive way, the percentage of saltpetre increased as the percentages of charcoal and sulphur decreased. The composition of gunpowder remained unchanged at the 1781 standard until the smoothbore firearm had been eclipsed by the rifled firearm (McConnell 1988: 273).

English Powder- Year	Percentage of Saltpetre	Percentage of Charcoal	Percentage of Sulphur
Roger Bacon 1250	41.2	29.4	29.4
Dr Arderne's Laboratory Powder 1350	66.6	22.2	11.1
Whitehorne's ordinary common powder 1560	50	33.3	16.6
Nye 1647	66.6	16.6	16.6
Turner 1670	71.4	14.3	14.3
Robins 1742	75	12.5	12.5
Bishop Watson 1781	75	15	10

Table 4.1. A breakdown of the composition of the three ingredients and how they changed over time in England. All of these writers give the proportion of gunpowder in their own time (Hime 1904: 197; McConnell 1988: 273).

These changing mixtures lead to numerous existing recipes. If the added variable of the purity of each ingredient was questioned, then a nearly infinite number of recipes could exist. As a result, recreating a specific powder for experimental purposes would be an almost impossible task, as the exact composition and purity of the ingredients would need to be known. Norton (1628a) states that there were "infinite recipes for making of powder, but most states enjoyed a certain proportion (sic) (Norton 1628a: 145)." See table 4.2 below for known National mixture percentages according to Hime (1904).

Nation and Year	Percentage of Saltpetre	Percentage of Charcoal	Percentage of Sulphur
French Powder 1338	50	25	25
French large gun powder 1540	80.7	11.5	7.8
Sweden 1560	66.6	16.6	16.6
Germany 1595	52.2	26.1	21.7
Denmark 1608	68.3	23.2	8.5
France 1650	75.6	13.6	10.8
Sweden 1697	73	17	10
Germany 1882	78	19	3

Table 4.2: A reproduction of the table on the composition of powder by Nation (Hime 1904: 177-198).

Of course the reasoning behind a near infinite amount of recipes could also have been attributed to human enterprise, as Sprat states that authors have a tendency to write up as many recipes as possible as a means to make money, or to save money by reducing the saltpetre and adding more charcoal to the recipe (Sprat 1667: 278). This thesis will not detail the exact manufacturing processes of gunpowder, but rather where the three ingredients were collected for the creation of English gunpowder, and why the origin of the ingredients plays an important role in gunpowder. The type of gunpowder used in small arms and cannons varied as well, and careful attention must be paid to terminology when consulting historic sources and military treatises. How gunpowder was loaded into small arms changed with time, whether by a bandolier or by a cartridge and the priming of the musket to ignite the main gunpowder charge is a topic of scant discussion, which will be addressed further below.

4.1.1 Saltpetre

Saltpetre is the oxidizer for the gunpowder within the chemical reaction during ignition. The burning of saltpetre releases oxygen while the charcoal and sulphur act as a fuel and begin to burn rapidly thereby creating a self-sustaining reaction. This reaction produces a large mixture of hot gases very quickly which raises the pressure in the chamber of the firearm. This pressure pushes on the base of the bullet, rapidly accelerating it out of the firearm. This reaction is termed deflagration, not an explosion (Fadala 2006: 193; Kohlisch 2011: 24-26; Kisak 2014: 50; War Office Unknown 41). Saltpetre or potassium nitrate is a crystalline substance that is a naturally found bacterial waste by-product created from the breakdown of organic matter into nitrates (Cocroft 2000: 2; Kohlisch 2011: 25). Saltpetre could be collected from two sources, either from naturally occurring pockets on the surface of the ground or from special saltpetre plantations (Cocroft 2000: 4; Kelly 2004: 34-35). Saltpetre can be found as a white crust on the surface of the ground in warm and humid climates like India and China. The soil is collected and brought to a refinery for purification, which is done by boiling the soil to separate the soil from the saltpetre (Congreve 1818: 107; Kohlisch 2011: 25; War Office Unknown 40). England, like most European countries, had no naturally occurring pockets of saltpetre, so attempts were made to manufacture it on English soil through the use of saltpetre plantations that resembled giant compost heaps of animal and human excrement (Hall 1996: 90; Kelly 2004: 35). Unfortunately, the saltpetre industry never produced enough to become self-reliant in England and the vast majority of saltpetre had to be imported from Antwerp and the Low Countries and later from India, China and the Barbary Coast (Congreve 1818: 107; Brown 1998: 12-14; Harding 1999c: 32-33; Cocroft 2000: 6; Davies 2002: 4).

4.1.2 Charcoal

Charcoal is created by burning wood in an environment low in oxygen (Davies 2002: 3). Charcoal was available in large quantities in England since the Middle Ages due to its use as a fuel in the metal working industry to extract ore (Brown 1998: 16; Cocroft 2000: 2). It is important to note that the charcoal produced from a single tree can vary in chemical composition and density, which can be exacerbated by high temperatures during the charring process (Congreve 1818: 110). The nature and quality of the charcoal used in the making of gunpowder influence its burn rate because different types of charcoal burn at different rates (Brown 1998: 17; Fadala 2006: 193; Kohlisch 2011: 25). Congreve (1818) states that the only woods used for charcoal production by the English Government were Dogwood, Willow and Alder. Those woods could be found in England; however, the bulk of the government contracts had them imported from Belgium and Holland (Congreve 1818: 110; War Office Unknown 41). Dogwood produced the best charcoal of all the powders because it produced rapid burning, fine grained powders for small arms. Whereas Willow and Alder produced a slow burning, coarse grained powder, which was typically used for cannon powders (Congreve 1818: 110; Brown 1998: 17; War Office Unknown 41).

4.1.3 Sulphur

Sulphur, sometimes called Brimstone, is naturally found in volcanic regions (Brown 1998: 14; Kohlisch 2011: 25). England relied heavily on merchants to acquire sulphur from volcanic regions in the Mediterranean, chiefly Sicily, where it was said that sulphur could be found in great abundance in an almost pure state (Congreve 1818: 109; War Office Unknown 42). Sulphur is considered the binding agent or the catalyst for the three ingredients. It burns at a low temperature and once ignited it produces a great deal of heat, which ignites the charcoal and breaks down the saltpetre (Cocroft 2000: 2; Fadala 2006: 193; Kohlisch 2011: 25).

4.1.4 Serpentine Powder

The earliest form of gunpowder used in Europe is known as serpentine. Serpentine was not a specific recipe, but a term used to describe the pre-corning mixture of gunpowder. Serpentine was a very fine, loose, and dry mixture of the three ingredients, saltpetre, charcoal and sulphur.

(Hime 1904: 181; McConnell 1988: 273; Brown 1998: 19). Serpentine was created by grinding the three ingredients separately and then incorporating them together to create a very fine powder. Bourne (1587) claims that serpentine powder should be ‘as fine as sand, as soft as flour ‘ (Bourne 1587), Smith (1627) says that serpentine powder was ‘like dust and weak’ (Smith 1627: 68), and Robins (1742) refers to serpentine powder as meal-powder and fine meal (Robins 1742: 35). During the era of Serpentine powder, the mixture of the ingredients could only differ in composition; if it assumed that all of the ingredients were equally pure. If the purity of one ingredient differed, then the recipe would be different as a result. As there were multiple locations where each ingredient could be or was collected, it is assumed that the levels of purity varied.

While serpentine powder was widely used there were major problems with it due to its nature as a very fine, loose, dry mixture. The first issue was that it was susceptible to moisture. If the powder became damp it was effectively inert and rendered useless. For it to work properly again, it would have to be dried and remixed. The second issue was that it became separated very easily due to its fine powder consistency and differing specific gravities of each of the ingredients. This was an issue during transportation because as each ingredient has a different specific weight, the different ingredients would subsequently separate out of the mixture into its original components. This means that if the powder was sent to the battlefield via a wagon over a long distance, it would have to be remixed to be used as it would have separated in transit (Hime 1904: 181; McConnell 1988: 273; Brown 1998: 19; Cocroft 2000: 14). Finally, serpentine powder was so finely mixed that it became easily compacted when loaded into the firearm. If the powder was compacted too tightly in the chamber of the firearm, it would not burn properly, or it would burn irregularly if it burned at all. This is because if the powder was too compacted then there would be little area for oxygen to freely move within the chamber of the firearm meaning less opportunity to promote deflagration. If the powder did not burn properly in order to fire the bullet, the firearm would misfire or not fire at all thereby leaving the bullet in the barrel and effectively stranding the soldier in the heat of battle (McConnell 1988: 273; Brown 1998: 19; Kelly 2004: 60-61).

Serpentine powder can cause confusion due to the lack of knowledge of a specific recipe of the powder in use. Not a single serpentine gunpowder recipe was written down, only the composition of the ingredients as seen in table 4.1 above. The only known variables for gunpowder at the time were the composition and the purity of the ingredients (which vary depending on origin location of each ingredient) which caused many different recipes to develop. The ability to recreate any form of serpentine powder is almost scientifically impossible due to the lack of known serpentine gunpowder recipes or samples that have survived, which leaves no basis in which to scientifically compare results or to create a modern replica.

4.1.5 Corned Powder

To solve the issues of serpentine powder, a new technique called corning was developed. Corning; however, only seemed to have introduced a third variable, grain size, into the quagmire of numerous recipes already in existence without a standard (Hime 1904: 191; McConnell 1988: 273). Despite the further complication in understanding the specific recipes of gunpowder; corned powder resolved most of the issues that serpentine powder had. Corned powder was not as susceptible to moisture, it did not separate into component parts while in transit and it burned so effectively that it only required two pounds of corned powder to do the same work as three pounds of serpentine powder (Bourne 1587; Smith 1600: 39; Eldred 1646: 26; Robins 1742: 35; Hime 1904: 182). The process of corning consists of moistening the gunpowder after the three ingredients have been mixed together and then pushing it through a parchment sieve (McConnell 1988: 273; Cocroft 2000: 14). Sieving the moistened gunpowder would break the ingredients down into cornes or grains of a chosen size.

By the 15th century gunpowder makers were making corned powder, and by 1550 the corning process was creating grains of relatively consistent sizes in Europe (Hall 1996: 95; Kelly 2004: 62). Davies (2002) claims that corned powder did not become standard in England until 1588 (Davies 2002: 16). However, according to the inventory records for the Tower of London, corned powder was in storage by 1547. The inventory of 1547 lists the three types of powder in storage as serpentine, gross corn powder and fine corn powder (Blackmore 1976: 261-262). By

1635 the tower records show that they contained only two powders, fine and cannon, both of which indicate grain sizes (Blackmore 1976: 287-306). Military manuals written between 1600-1646, claim that corned powder was the most common powder in daily use by 1600 (Smith 1600: 38; Smith 1627: 68; Eldred 1646: 25-26). Further military manuals which discuss musket loading procedures, explicitly instruct the soldier to 'blow off' the excess cornes (grains) from the priming pan after priming the firearm (Barriffe 1635: 4; 1647: 2; Elton 1650: 4; Anonymous 1691: 14). From this evidence, by the time of the English Civil War, corned powder was standard throughout England.

At the beginning of the corning practise, there was no standard for the size of the parchment sieve, therefore the grain sizes could change from recipe to recipe. Machiavelli (1562), Nye (1647) and Venn (1672) all state that the parchment sieve was made full of little round holes, but make no mention as to specific sizes (Machiavelli 1562: Fol.28; Nye 1647: 20-21; Venn 1672a: 18). Norton (1628a) states that "a syve…made of full of holes of the bigness you desire your cornes (sic)(Norton 1628a)". At some point, an ideal grain size was standardised, although the sources never make it clear as to what that size was. Norton (1628b) gives different recipes for ordnance, pistol and musket powder (Norton 1628b: 3-4), which seems to trend with Du Praissac (1639) who lists grain sizes as great, medium and small (Du Praissac 1639: 92). By 1667, Sprat makes mention of a machine that used a two-sieve graining system that separated large grains from small grains. Large grains (course grained powder) were used for cannons and small grains (fine grained powder) was used for small arms (Sprat 1667: 281-283). This; however, still gives no indication for the size of the grains in a way that would allow for a reliable reproduction to be created.

4.1.6 Priming Powder

Priming powder is the gunpowder added to the priming pan of the firearm and used to ignite the main gunpowder charge in the chamber through a small touch hole. Some modern authors claim that different types of powder were used for priming than for the main charge (Krenn 1991: 37; Krenn *et al.* 1995: 102; Hall 1997: 136; Foard 2012: 47). Military manuals from the period have surprisingly little to say about priming powder. De Gehyn (1608) and Hexham (1637) instruct the reader to prime their firearm from the touch-box, as the bandolier and priming flask was used to deliver the firearm its full charge, and priming from either of these would take away the potency from the firearms main charge (De Gehyn 1608: 7, 51; Hexham 1637: 14-16). Neither source makes mention to any type of difference in powder, they clearly state that the reason for priming from the touch-box is to keep the full charge of the firearm from being tampered with.

A French military manual written by Gaya was translated into English by Harford in 1678 and shows that priming powder was different than the powder used for the main charge (Gaya 1678: 16). However, two years later Harford (1680) published an amended version of the same manual in England under his own name. In the amended version, Harford removed certain details from the French manual, chiefly being the mention of priming powder and any other seemingly French specific practices, such as their weights and measurements and bore sizes of their firearms. This could indicate that either Harford disagreed with Gaya or that the French and English practices were different, and Harford's amendments were tailored to an English audience (Harford 1680). In the 18th century with the widespread use of cartridges, the priming powder and the powder used for the main charge of the firearm came from the same source, the cartridge (Stevens 1797: 30-31).

4.1.7 Gunpowder Discussion

Due to the variations of gunpowder, it is scientifically impossible to replicate or recreate a specific black powder recipe from the early modern period without knowing its exact composition, grain size and purity. To date, there is no evidence or data in which to scientifically compare gunpowder recipes from the early modern period as they have only survived as a written record. Even if an attempt to create a black powder recipe based on an arbitrary mixture of ingredients were completed, there would still be no results in which to create a baseline to compare results for verification. To further the point, Robins in 1742 stated that in his time at least 23 different recipes for gunpowder existed (Robins 1742: 32). This anarchy was due in large part to the lack of any reliable scientific instrumentation that could measure and compare the strength of different gunpowder's thus enabling the ability to establish a standard for the proportions of the ingredients and the size of the grain (Hime 1904: 192). If the reproduction of a black powder is out of the question, what can be done? The quantification of the strength of gunpowder through muzzle velocity is a means to verify and reproduce an early modern period gunpowder replica. If the strength of a gunpowder could be scientifically measured, then a baseline for comparison could be established, this can be done with a device called an eprouvette.

4.2 Eprouvettes, Muzzle Velocity and Powder Proofing

An eprouvette is also known as a powder tester and a powder trier. An eprouvette is any mechanical device used to measure and quantify the strength of gunpowder. In the early days of gunpowder, the only way to test its strength and ability was by means of visual inspection. During the early modern period, eprouvettes progressed and became more reliable and by the 17th century were eventually adopted by most governments as a means of proofing gunpowder for military use (Cocroft 2000: 46). The invention of the ballistics pendulum by Benjamin Robins in 1742 was not realised for its true potential until the 19th century, once accepted, Robins' invention of the ballistic pendulum created a scientific revolution which was later termed the ballistics revolution (Steele 1994; Buchanan 1996: 248).

4.2.1 Visual Inspection

The visual inspection of gunpowder was conducted in several ways. First, by burning it on a flat surface and examining the residue left behind. Whitehorne (1573) and Eldred (1646) explain how to visually inspect gunpowder to determine its strength and purity. They advise that the powder must be black in colour, it must leave no sign of moisture when rubbed against a sheet of paper and that when one runs one's fingers through it, one cannot discern one ingredient from another since it has been so finely beaten (Whitehorne 1573; Eldred 1646: 25; Kempers 1998: 16-17). This method of visual inspection leaves much to be desired and is scientifically baseless as it cannot be used to test the strength of one powder over another.

4.2.2 Bourne 1578

The earliest description of a device used for testing gunpowder strength was William Bourne's (1578) "engine or little boxe (sic)", which Hime (1904) claims the engine was "a wretched one". The powder that was tested was ignited through a touch hole at the bottom of a metal cylinder with a very heavy hinged lid. When the lid was lifted upwards a series of iron teeth would catch the lid and lock it into place. The number of teeth that the lid jumped to were counted and this would determine the strength of the powder in relation to other powders (Bourne 1587; Hime 1904: 192; Kempers 1998: 19).

4.2.3 Furtenbach 1627

Joseph Furtenbach (1627) created a slightly better version of Bourne's "little box" by improving the design of the lid. The lid was no longer attached to the cylinder but only rested on the top of it. The powder was placed in the cylinder and ignited via a touch hole. When the powder ignited, the lid was sent upwards guided by two long wires with a weight attached to the opposite end where its final resting place was held by iron teeth. The weight on the opposite end was another improvement over Bourne's method as it allowed a measurable way to determine the strength of one powder over another (Hime 1904: 193; Kempers 1998: 23-24). This method for measuring the strength of gunpowder was also mentioned by Ward in 1639 as the only true way to determine the strength of gunpowder (Ward 1639: 391-392).

4.2.4 Eldred 1646

William Eldred (1646) stated in his work *The Gunners Glasse* that the only way to know a good powder was by its taste, colour and how it burned. He stated that if the colouring was blue to red if one could pick it up without it turning one's hands black and if there was a sharp biting taste than it was a good powder (Eldred 1646: 26). Eldred also stated that the only true way to test the strength of the powder was to fire it. When fired, if it burned with a sudden flash and left behind little to no trace, then the powder was good. However, if burned with sparks, then it was no good (Eldred 1646: 26-27). Finally, Eldred described an eprouvette used to proof the strength of gunpowder, the drawing of this eprouvette looks remarkably similar to Joseph Furtenbach's (Eldred 1646: 91); however, he never describes it, or what it did in further detail.

4.2.5 Nye 1647

Nathaniel Nye (1647) listed four methods for assessing the strength of gunpowder. The first two consists of a visual inspection technique and a rocket test which will be left out as they were ultimate failures; however, Nye did create two reasonable ideas. First, Nye suggested that the comparative strength of gunpowder should be tested by firing pistol bullets into clay and measuring their depth of penetration. This could be done with multiple powders and the one that penetrated the deepest was the best. The second method Nye created is known as the mortar eprouvette. A cast iron mortar piece that is "three quarter inch diameter: and two inches and one third part of an inch deep (sic)" is to be loaded with an ounce of gunpowder without a wad. The mortar was loaded with one lead bullet weighing close to five pounds. Then set the mortar at a certain unchangeable elevation and fire it. The range in which the bullet was fired is directly comparable to bullets fired using other powders. (Nye 1647: 29-34; Hime 1904: 193; Kempers 1998: 24-25). The mortar eprouvette was favoured as an extremely accurate device until the 19th century when it was discovered that finer powders launched the bullet further (Kempers 1998: 25).

4.2.6 Hooke 1663 and Surirey de Saint-Remy 1697

Robert Hooke (1663) and Surirey de Saint-Remy (1697) created five eprouvettes between them, but all of which were so inaccurate they were never considered for use (Kempers 1998: 28-32).

4.2.7 Robins 1742

Benjamin Robins (1742) created the ballistic pendulum, which was the first device that could accurately measure the velocity of a bullet thereby putting the art of gunnery into the scientific field for the first time. As Robins himself stated that the measuring of the velocity of a bullet had been previously impossible to record (Robins 1742: 83). Robins' ballistic pendulum was only viable for small arms, using small amounts of gunpowder.

Robins' ballistic pendulum was composed of three wooden poles spreading at the bottom and joining together at the top. An iron pendulum of a known weight was hung by means of a cross piece attached to the two poles in the front of the device, which becomes its axis of suspension. The lower bit of the pendulum was covered in a thick wood. Robins stated that "If the pendulum is at rest before the moment of impact, it will be known what vibration it ought to make in consequence to a determined blow, and on the contrary if the pendulum being at rest is struck by a body of a known weight and the vibration which the pendulum makes after the blow is known, then the velocity of the striking body may from hence be determined (sic)" (Robins 1742: 84-85). The bullet would be aimed at the thick plate of wood that was mounted on an iron pendulum. A narrow ribbon was attached to the bottom of the pendulum which was then passed through two steel edges (Kempers 1998: 35). The tension on the ribbon could be altered by a set of screws. The striking of the pendulum drew the ribbon out and could thus be recorded (Kempers 1998: 35).

Robins' test results showed muzzle velocities ranged between 434m/s and 518m/s using government standard powder. The average muzzle velocity from Robins' work is 457m/s (Robins 1742). Not only did Robins' invention record muzzle velocity for the first time, but he was also the first person to quantify air resistance (Steele 1994). Robins' pioneering of the ballistic pendulum drew harsh criticism in the early years following its publication but spurred other scientists to create experiments based off of his initial findings (Hutton 1778; Ingenhousz 1779; Thompson 1781). This experimentation lead to a greater understanding of both ballistics and the nature of gunpowder, and in time Robin's was eventually proven correct (Cocroft 2000: 32, 46).

4.2.8 Powder Proofing

After the war of American Independence (1775-1783), the quality and purification of the three ingredients of gunpowder underwent drastic changes when William Congreve was appointed as the Comptroller of the Royal Laboratories and was given control of the English powder mills bought by the English Board of Ordnance in 1759 to force gunpowder production to adhere to state controls and guidelines (McConnell 1988: 275- 281; Everson & Cocroft 1996: 382; Cocroft 2000: 30; Cole 2011: 296). Congreve introduced new standards and machines to assist in the manufacturing and purification process of gunpowder. He also added a system for the government proofing of gunpowder (Congreve 1783; Cocroft 2000: 46-47). Independent powder makers who wished to sell their powder to the English military had to meet this standard before the powder would be accepted for use (Cole 2011: 300).

The English government standard for gunpowder strength was recorded in *An Universal Military Dictionary* written by George Smith in 1779, and stated that '2 drams of powder must lift a weight of 24 pounds, 31/2 inches into the air to be taken into the King's magazine (sic)' (Smith 1779: 135). There was a nearly infinite number of recipes for gunpowder at the time because the exact mixture did not matter, but only the meeting of this standard. The Board of Ordnance changed proofing standards again by the Napoleonic Wars (1803-1815) to the mortar eprouvette mentioned above that was created by Nathanial Nye (Congreve 1783; Baddock 1832: 80-81, 114-116; Baddeley 1857: 20; Buchanan 1996: 248; Cole 2011: 300). By the time of the Napoleonic Wars (1803-1815), English gunpowder was transformed from the worst powder in Europe to the powder that set the world standard (Cocroft 2000: 65). English powder had become so much stronger that charge sizes given to small arms and artillery were being reduced to compensate for the added strength (McConnell 1988: 281-283).

4.2.9 Eprouvette Discussion

As the dilemma of an almost infinite number of gunpowder recipes existed in the early modern period as addressed above, there is no definitive method to determine what type of gunpowder recipe was used at specific battles if the specific powder recipe was not recorded at the time. Robins' study claims to have used government standard powder in his experiments, and it is known what that government standard was from George Smith's description of the methods used by the English Board of Ordnance to proof powder for the King's magazine.

The methods for testing the strength and 'goodness' of gunpowder did not change much in the 201 years between William Bourne's (1578) description of his 'little box' eprouvette, to Eldred's (1646) description of the modified 'little box' created by Joseph Furtenbach in 1627, to George Smith's (1779) description of the methods used by the English Board of Ordnance to proof powder for the King's magazine (Bourne 1587; Eldred 1646: 26-27; Smith 1779: 135; Hime 1904: 193; Kempers 1998: 23-24). However, the creation of a baseline which can be used for scientific comparison forming a direct link to the early modern period can be found due to Robins' creation of the ballistics pendulum.

The overall increase in the strength of gunpowder and reduction in charge size is why using the experiments conducted by Mordecai (1844) as a baseline for experimentation for battles and assemblage predating the Napoleonic Wars is anachronistic as referred to in the conclusion of Chapter Three of this thesis. Robins' ballistics pendulum was adopted by the Board of Ordnance for proofing gunpowder by 1864, but not until the experiments conducted by Mordecai (1844) claimed that Robin's ballistics pendulum was perfectly adapted for proofing gunpowder (Mordecai 1844; Harding 1999c: 36).

To design the experimental firing trials in this thesis to potential period accuracy without the knowledge of a specific gunpowder recipe, this thesis chose the gunpowder based on achieving known, recorded velocities that could be reproduced with modern powders. Benjamin Robins' creation of the ballistic pendulum was the first device that could accurately measure the velocity of a bullet and that velocity data is the baseline for the experiments in this thesis (Kempers 1998: 35; Cocroft 2000: 46; Kelly 2004: 142). Robins' test results showed that muzzle velocities ranged from 434m/s to 518m/s and the average muzzle velocity for an 18th century firearm was 457m/s. For this thesis to be period accurate a reproduction black powder must be chosen that can reproduce a muzzle velocity between 434m/s and 518m/s, with an average as close to 457m/s as possible. Previous firing experiments (Chapter Three) used several different powders to achieve similar muzzle velocities; however, their ratio of bullet weight to charge size weight varied from one study to another and this issue must be made clear before a powder can be selected and will be discussed further below in section 4.4.

There is; however, a paradoxical issue that warrants a brief discussion. Robin's 18th century data set which will be used for comparison postdates at least half of the early modern period. To date, there is no evidence of a recorded, reliable method in which to create a baseline of comparison with gunpowder dating to the 16th and 17th centuries and Robin's data is the earliest and most reliable point from which to begin. There is no possible way in which to be confident that this baseline of comparison equals or reflects those of the 16th and 17th century firing standards. This could cause complications when investigating impact evidence with bullet assemblages predating the 18th century. However, since this is the earliest known measurable link it will have to suffice for experimental purposes until something more firmly dated in 16th and 17th century practises can be located.

4.3 Bullet Composition

The composition of the bullet is an important variable that influences how the bullet behaves when impacting a target. Modern sources state that bullets from the 17th to 18th centuries were comprised of 99.7% pure lead (Sivilich 2005; Eyers 2006: 12; Sivilich 2009; Green 2010: 10). Pure lead bullets are malleable and easily retains the slightest impressions. Harkins (2006) investigated the composition of one bullet from the Marston Moor battlefield (1644) and determined it to be of pure lead. Harkins also found trace amounts of tin, sodium, silicon and sulphur and concluded that they could not rule out that the trace amounts came from contaminating sources (Harkins 2006: 32-33, 64).

There is a current bullet composition study on going at the University of Huddersfield by PhD candidate Sam Rowe that is investigating the composition of bullets from multiple battlefields dating to the English Civil War. Preliminary results show that from a sample size of 79 bullets, that the bullets lead composition is averaged at over 90% pure lead (Rowe 2018).

It was decided that to remain compliant with early modern period standards regarding bullet composition, that this thesis would manufacture and cast its own bullets. Unfortunately most modern lead contains antimony, a hardening agent (Sivilich 2009; Green 2010: 9). This hardening agent influences impact damage as seen in the firing trials conducted by Graham Green at Cranfield University in 2010, found in Chapter Three (Green 2010: 9). However, lead used in modern roofing flashing is claimed to be free of antimony and 100% pure recycled lead. Roofing flashing was acquired and subjected to XRF testing by Sam Rowe at the University of Huddersfield. The test results reveal that modern roofing flashing was compliant with early modern period standards and found to be made of at least 90% pure lead, with traces of other elements (Rowe 2018). The experimental firing trials, located in Chapter Seven of this thesis uses roofing flashing, melted down and recast into bullets.

4.4 Bullet Weight and Gunpowder Charge Weight

As noted in in Chapter Three, section 3.10, modern experimental firing studies used different ratios of bullet weights to gunpowder charge weights. This is a fundamental issue that needs clarification when choosing a gunpowder for this thesis, this issue is also dependent on the time period, as noted above in section 4.2.9, with the changes in the strength of gunpowder, came changes in the ratio of bullet weight to charge weight.

The bullet weight and diameter, the gunpowder charge weight and the firearm are interdependent, meaning that the gunpowder charge weight is dependent on the weight of the bullet and the weight and diameter of the bullet is dependent on the firearm being used. So, how much gunpowder is put into the musket to fire the bullet to be period accurate? Five military manuals answer this question. These five manuals span 148 years and agree on the amount of gunpowder used, henceforth termed charge weight. Cruso (1632), Ward (1639), Venn (1672), Turner (1683) and Muller (1780) all state that the charge weight for a bullet, is half the weight of the bullet (Cruso 1632: 41; Ward 1639: 301; Venn 1672b: 15; Turner 1683: 260; Muller 1780: 178). Table 4.3 below shows the relationship between the bullet and charge weight for a variety of bullets.

Bullet Bore Size	Bullet Weight (g)	Half Weight/ Charge Weight (g)
12-bore	37.9	18.95
17-bore	26.68	13.34
18-bore	25.19	12.59
19-bore	23.87	11.93

Table 4.3: Bullet weight and charge weight.

Robin’s (1742) experiments indirectly confirm that the charge weight is half the weight of the bullet. In his experiments, he used a bullet of 1/12 of a pound avoirdupois lead that was ¾ inch diameter. This equates to twelve bullets from one pound of lead, better known as 12-bore, and a 3/4-inch diameter bullet is 19.05mm in diameter which is roughly the same diameter as a 12-bore bullet. The powder charges Robins used was 12dwt (a pennyweight) this converts into 18.66g.

18.66g is roughly half the weight of a 12-bore bullet that would typically weigh around 37g. Therefore, Robins was using a 12-bore bullet with half charge weight (Robins 1742: 92).

The experimental firing trials conducted in this thesis will use a 17-bore 'bastard musket', which takes a 19-bore, or roughly a 24g bullet. A full charge weight issued to the firearm would then be 12g of powder. Further details about the firearm choice can be found below in section 4.6.

4.5 Bandoliers, Cartridges and the Use of a Wad

The use of a wad is a consideration in this study as it has been noted that wadding affects the velocity and accuracy of the bullet and therefore directly influences the impact of a bullet on a target, as seen in Chapter Two, section 2.1.4. The type of wadding was and currently is variable if any wadding was used. However, the use of a wad in the early modern period is not straight forward. John Smith (1627) declares that a wad was to be made of 'Okum, old clouts, or straw'(sic) and put into the firearm after the powder and bullet (Smith 1627: 66). Hexham (1643) claims that a wad could be made of hay, straw or any other thing (Hexham 1643: 13). Eldred (1646) states that when firing artillery one were to use two wads of 'ocam, hay or straw' (sic) (Eldred 1646: 41). Blackmore (1976) states that a wad was a plug of tow or hay to keep the bullet in position (Blackmore 1976). The use of a wad is also somewhat dependent on how the firearm was loaded, whether the wad was placed between the bullet and powder or after the bullet and powder. The difference this could have on muzzle velocity when fired is currently unknown. As no experimental firing has been completed with various types of wadding material or position of the wad when fired this thesis has decided to control this variable by not using a wad during firing.

From the 16th century until the middle of the 17th century, infantry soldiers carried bandoliers (Humphrey 1594; Foard 2008b: 88; 2012: 47). A bandolier was comprised of twelve powder boxes which hung from a belt and were made of a wood or horn tube that carried one charge of gunpowder. During the battle a soldier would load the powder into his firearm directly from the powder box. Next, the bullet was either rolled into place or rammed into place, depending on the amount of windage or fouling in the barrel, this would generally be done without a wad (Markham 1622: 34; Markham 1625: 3; Foard 2008b: 153; 2012: 104). De Gehyn and Boyle make mention that if care is not taken once the firearm is loaded, the bullet may roll out of the barrel (De Gehyn 1608: 7; Boyle 1677: 32).

In the early 17th century cartridges came into use for cavalry soldiers, while bandoliers were still in use by infantry soldiers. Smith (1627), Cruso (1632) and Ward (1639) state that the fastest way to load a pistol, carbine or musket, especially for cavalry, was to use a cartouche. A cartouche is made of white paper cut into convenient pieces and fit according to the barrel. It is then loaded with a charge of gunpowder and the bullet, in this case, the paper acts as a wad to keep the bullet from rolling out of the muzzle (Council 1623: 9; Smith 1627: 67; Cruso 1632: 41; Ward 1639: 301). Howes (1992) states that while under siege during the English Civil War, the parliamentary garrison of Gloucester paid a local bookseller for white paper which was used for making cartridges (Howes 1992: 38). Foard (2008 and 2012) remarks that loading primarily from the cartridge was not in general use until the 1730's for the military forces in Britain (Foard 2008b: 88; 2012: 47). By the time of the American Revolution (1775- 1783) loading directly from a cartridge was standard practise (Stevens 1797: 30-31; Neuman 1967: 14; Sivilich 2016).

4.5.1 Discussion

The experimental firing trials conducted by Harkins (2006), Eyers (2006), Allsop and Foard (2008) and, Miller (2009) have all demonstrated that using a wad increases the muzzle velocity of the firearm (Eyers 2006; Harkins 2006; Allsop & Foard 2008; Miller 2009). Foard (2012) notes that an experimental firing study conducted in Leeds in 2007 showed a marked increase in the velocity of a wadded 12-bore bullet close to 30% over that of an unwadded bullet. Foard also notes that the use of a wad has both beneficial and detrimental effects on the bullet itself. For example, a wadded bullet will reduce the amount of melting on the bullet's surface from the powder burning, but increases the compression of the bullet from firing (Foard 2012: 105).

Using a wad can be problematic, because the material in which the wad is made of also has an effect on the velocity of the bullet as was demonstrated in Eyers (2006) cannon test firing, where the use of a wad made of hay was discarded in exchange for cotton rags because the hay was allowing too much gas to escape past the bullet which had an effect on the velocity of the bullet (Eyers 2006: 35).

As the early modern literature makes note of a variety of wadding material being used and that experimental firing has proven that different wadding materials have differing effects on the velocity of the bullet, it was decided in this thesis to reduce the number of variables already present. This study will not use any wadding material. It is not the intent of this thesis to determine or decide which material makes the best wad. It is therefore recommended by this thesis that experimental research is undertaken to fire firearms with differing wad types to record the effects differing wad types have on both accuracy and velocity. It is also advised during those experiments to change the location of the wad during firing, as manuals report that sometimes wads were used between powder and bullet and sometimes used after the powder and bullet.

4.6 Firearms, Barrel Length and Windage

The firearms of the early modern period are an extremely complex topic. The type of firearms used in battle varies with chronology and locale. A substantial amount of research would be needed to trace the evolution and introduction of firearms alone. Small arms during the early modern period can be classified by their nature and sub-nature, with each nature and sub-nature having specific patterns and variants of those patterns. These classifications can be made by the firearms appearance, by its role in the military, by its bore size or by the size of the bullet it fired (Harding 1999b: 151; Urban 2011: XII-XIV).

For an effective study on firearms development from the late 16th to mid-17th centuries in Europe, it is advised to see (Schürger 2015: 77-86). Detailed examinations of English Firearms from the mid-16th to the late 17th centuries can be found in (Foard 2008b; Foard 2009a; Foard 2012; Foard & Morris 2012). For a thorough investigation of firearms from the 18th to 19th

centuries in England see (Bailey 1987; 1988; 1997). For a comprehensive investigation of the English and East India Company firearms trade in the Pacific and India see (Harding 1999a; b; c; Chew 2012), and studies examining both English and American firearms in North America reference (Neuman 1967; Ahearn 2005).

This study is primarily concerned with English firearms during the mid-17th century to the late 18th century. During this period, there were three principal bore sizes in use by the English Military, defined as pistol, carbine and musket (Harding 1999a: 156; Foard 2008b: 79-80; 2012: 41). Pistols were typically used by cavalry and had a barrel length close to '18 inches' and fired a bullet between 20-24 bore (Cruso 1632: 29-30; Ward 1639: 293; Harding 1999a: 156; Foard 2008b: 80; 2012: 41-42). Carbines were also used predominately by cavalry and fired a bullet between 17-20 bore and the length of the barrel varies from author to author but is between '2.24 feet and 3 feet, 3 inches' (Markham 1625: 42; Cruso 1632: 31; Ward 1639: 293; Raynsford 1645: 3; Harding 1999a: 156; Foard 2008b: 80; 2012: 42). Muskets used by infantry soldiers, fired a bullet between 12-14 bore and had a barrel length around '4 feet 6 inches' (Markham 1622: 34; Raynsford 1645: 8; Harding 1999a: 156; Foard 2008b: 80; 2012: 42). It is obvious from the above, that barrel length was not wholly standardised for firearms, but varied. Further evidence on firearms dating to the English Civil War can be found in Blackmore (1990) and Foard (2012).

The Littlecote collection of 17th century firearms which can be found in the Royal Armouries in Leeds, United Kingdom, was investigated to measure the degree of standardisation. The Littlecote collection is comprised of the largest surviving collection of English Civil War firearms containing muskets, carbines and pistols (Blackmore 1990: 70; Foard 2012: 67). The aim of the investigation was to find the most common internal bore diameter of the muskets in the collection. The conclusions from the study showed that the musket's internal bore diameters varied from 10-12 bore (Blackmore 1990: 70; Foard 2012: 67) and that the barrel length, that was supposed to be standard at '48 inches' by the Council of War, was in fact not standardised. The Littlecote musket barrel lengths ranged from '41 ¾ to 47 inches' (Blackmore 1990: 70-71). Another example of the lack of standardisation is from a desperate plea from Boyle in 1677, wherein he discusses a few changes that should be made to the English military. One major change is that all muskets be of one bore. He later states that bullets are made of one size and musket bores of various sizes and that many times in battle men would have to chew excess lead off of the bullet to fit it to the musket's bore (Boyle 1677: 29).

Windage is difficult to determine with firearms from the 17th century. There were many variations in bullet sizes and from the above discussion, there were also many variations in firearm bore size. Knowing this, windage is a subject hardly mentioned in the military manuals and sources from the early modern period. It is not possible to determine what the typical or ideal windage should have been with early modern firearms. In this thesis, the windage of the firearm will be as controlled as possible, although variations in the size of the bullet used will fluctuate from one cast bullet to another. The fouling of the barrel during experimentation will also cause fluctuations with the windage of the firearm that cannot be fully controlled. How much these fluctuations will influence the velocity and accuracy of the bullet are unknown and is certainly deserving of its own series of experiments. Due to the lack of knowledge over an ideal windage for firearms of the early modern period and due to variations in bullet sizes and firearm bore sizes, this variable was kept as a constant throughout the experimental firing trials.

4.6.1 Discussion and rationale of firearm choice

Attempts were made at the beginning of this study to locate the 10-bore barrel used during the experimental firing trials known as the Cranfield trials (Chapter Three). The desire was to collect data that would remain consistent and comparable with the research and data already collected by these studies. Unfortunately, due to the passage of time that specific barrel had either been destroyed or lost. Next, two additional 17th century replica firearms were located for use, a 17-bore 'bastard musket' and a 12-bore musket. Consistent access to the 12-bore musket proved problematic and was eventually abandoned. Consistent access to the 17-bore 'bastard musket' was indefinite and this thesis chose to use that firearm for the duration of the experimental firing trials for consistency.

4.7 Soft Capture Systems

Experimentation to create an effective soft capture system began with Harkins (2006). The soft capture system created by Harkins consisted of ballistic gelatine in front of a bullet trap. The bullet trap was made of multiple layers of dense foam rubber. The ballistic gelatine was used to slow the bullet down enough that the layers of dense foam rubber could capture it without imparting additional damage or distortion (Harkins 2006: 25). The soft capture system created by Harkins needed refinement, as his system left the bullets with too much damage (Harkins 2006: 67).

Foard (2008) undertook experimental firing in collaboration with Graeme Rimer at the Royal Armouries in Leeds to confirm loading and firing evidence discovered in the Eyers and Harkins studies. Part of this experiment involved testing the soft capture system used by LGC forensics, who operated the firing range. No exact measurements are given for the soft capture system, but the system consisted of two long metal rectangular boxes that are approximately 2m long x 50cm wide. Each of the boxes contained approximately 28 alternating layers of soft foam and cotton, which would act to slow and eventually stop the bullet. The bullet would then have to be located and extracted from within the system. The bullets recovered from the soft capture system were found to be in good condition (Foard 2008b: 118-119).

Roberts (2008) attempted the creation of a soft capture system using ballistics gelatine and a metal bullet trap, but the system was an ultimate failure as it left the bullets too damaged for further study (Roberts *et al.* 2008).

Miller (2009) experimented extensively on soft capture systems, using shredded rubber, foam and rags, a water tank, a Kevlar vest, and Plastzoate lure foam (Miller 2009: 58-79). Sheets of Plastzoate foam were found to capture the bullet without damaging it, allowing for post firing bullet analysis. The successful soft capture system was created from Plastzoate lure foam consisting of 84 pieces of Plastzoate foam 330x200x30mm followed by 600mm of boat buoyancy foam and Linotex laminate and was noted to be able to consistently soft capture a pure lead musket bullet without damaging the bullet or imparting any kind of surface alterations to the bullet. The Plastzoate foam worked well enough on its own that the Linotex laminate was removed from the system (Miller 2009: 74).

4.7.1 Discussion

The soft capture system that will be used in this study is a combination of materials used from both the Foard and Rimer experiment and the Miller experiment. The soft capture system that was created and used for the experimental firing trials conducted in this thesis, consisted of multiple layers of Plastzoate foam, placed in front of two large boxes (57cm in length and width) filled with soft cotton toy stuffing, with a Kevlar vest loosely draped over the last box in case the bullet went through the entire soft capture system. The system devised by Miller in 2009 was no longer in existence.

4.8 Preliminary Experimental Trials with TS2 Black Powder

The first experiment conducted in this thesis was to verify the results from the above discussions through the defined variables to create experimental parameters and the experimental firing methodology. The experimental parameters are the use of a 17-bore musket that fires a 24g bullet. The ratio of bullet weight to charge weight states that the charge weight for a full charge of a 24g bullet is 12g or half the weight of the bullet. No wad of any type was used during this experiment, and barrel length was noted at 41 inches.

The previous experimental firing trials found in Chapter Three of this thesis discuss the usage of differing reproduction black powders. What has been noted by this thesis is that all those reproduction black powders were listed as 2FG or 3FG, which is a designation of the grain size of each powder. 2FG powder contains a grain size of 1.19 to 0.59mm, and 3FG powder contains a grain size of 0.84 to 0.29mm. These powders were selected by previous studies to maintain a muzzle velocity like those recorded by the Robins (1742) and Mordecai (1844) studies. However as noted above this thesis will not use the Mordecai data as it is anachronistic, and the Robins muzzle velocity baseline is the target data being used in this thesis. In order to gather data that would remain scientifically comparable to previous experimental firing trials conducted at Cranfield University (Chapter Three), a recipe of powder known as G12 was sought after as this was the powder used mainly in those experiments. G12 is a British designation used by the Ministry of Defence (MOD) and defines the grain size of the powder. When manufactured it is corned to incorporate it into grains of different sizes. It is then passed through sieves to produce a powder with grains of a similar size. G12 must pass through a No. 8 sieve (0.081") but must be retained by a No. 16 sieve (0.0305"). However, this powder is not commercially available and is only made in very small quantities by the MOD for ceremonial purposes and could not be attained for use in this study (Derek Allsop 2015, pers. comm, 5 June 2015). This thesis decided to test a type of reproduction black powder known as Henry Krank, TS2 that is a 3FG powder and is similar in grain size to G12, and therefore comparable to G12’s burn rate.

4.8.1 Experimental Materials, Loading and Firing Procedure

The experimental firing was conducted at the Defence Academy at Shrivenham, Cranfield University. Firing took place in the Enfield Small Arms Experimental Range (No 3 Range), under the guidance of Mr Steve Champion and Mr Dave Miller.

A reproduction 17-bore musket with a 41inch barrel was loaded with the full 12g charge of TS2 black powder and fired 10, 19-bore bullets (24g) down range. The musket was fixed to a universal gun mount at a horizontal firing height of 1.39m at 0° elevation parallel to the ground. The musket was remotely fired using an ISFE 9-volt electric match to prevent human error. Doppler radar was used to measure the muzzle velocity of the firearm, the results can be found in table 4.4 below.

Bullet Number - Weight (g)/ Diameter (mm)	Charge Size	Muzzle velocity
Bullet 1 - 24.18g/ 16.26mm	12g	457m/s
Bullet 2 - 24.13g/ 16.20mm	12g	446m/s
Bullet 3 - 24.10g/ 16.20mm	12g	472m/s
Bullet 4 - 24.03g/ 16.25mm	12g	463m/s
Bullet 5 - 24.14g/ 16.24mm	12g	464m/s
Bullet 6 - 24.27g/16.23mm	12g	492m/s
Bullet 7 - 24.09g/ 16.23mm	12g	494m/s
Bullet 8 - 24.27g/16.25mm	12g	476m/s
Bullet 9 - 24.41/16.28mm	12g	420m/s
Bullet 10 - 24.13g/16.28mm	12g	487m/s

Table 4.4: TS2 reproduction black powder trial.

TS2 powder has a muzzle velocity between 420m/s and 492m/s with a full 12g charge size. The average muzzle velocity of the TS2 powder was 467m/s. TS2 powder was chosen for the experimental firing trials as it fits both of the following parameters: the gunpowder charge weight that was determined to be half the weight of the bullet (section 4.4), while maintaining the baseline muzzle velocity of between 434m/s and 518m/s, averaging around 457m/s. This experiment demonstrates that when all variables discussed above are used in conjunction with one another, that a viable experimental firing methodology can be created that is firmly rooted within early modern period practises.

4.8.2 Soft Capture Mechanism Test Firing

The aim of the second experiment was to test the soft capture system to ensure that it would not leave any distinctive characteristics on the bullet's surface while safely and effectively capturing the bullet. Previous soft capture systems had been created and tested extensively by experimental firing as seen in section 4.7 above. The soft capture system that was created and used for this study's experimental firing consisted of 20 layers of Plastzoate foam that were placed in front of two large boxes (57cm in length and width) filled with soft cotton toy stuffing, with a Kevlar vest loosely draped over the back end of the last box. If the bullet went through the entire soft capture system, it would then impact the Kevlar vest completely wrapped in cotton from the boxes. The vest acts as a last resort safety cushion to help reduce any residual kinetic energy as opposed to an actual sudden stop for the bullet. Extensive test firing had already been completed by Miller using a similar soft capture system as discussed above. After the two bullets were successfully fired into and secured by the soft capture system, it was verified that their surfaces were unaffected by the soft capture system and therefore deemed sufficient evidence to continue with this soft capture mechanism throughout further experiments which can be found in Chapter Seven.

4.8.1.1 Results

Two bullets were fired into the soft capture system for analysis. In both cases the bullets contained no impact evidence and appeared unaltered except for firing evidence, i.e. melting, pitting and banding were noted on the bullets' surfaces. Both bullets have an increase in diameter due to the banding effect. The increase of the bullets' diameter seems to be directly related to how each bullet was seated in the chamber when fired. The soft capture system worked successfully to not only capture and safely secure the fired bullets but also to not impart any distinctive post-firing impressions on the bullets' surfaces. As a result, the soft capture system proved ideal for successfully and safely securing all further experimentally fired bullets after impacting their designated targets. Weight loss from firing varied between the two bullets from 0.10g to 0.13g, results can be seen in table 4.5 below.

Bullet Number	Bullet Impact Velocity (m/s)	Bullet weight pre-firing (g)	Bullet weight post-firing (g)	Bullet diameter pre-firing (mm)	Bullet diameter post-firing (mm)	Charge weight (g)	Target type	Angle of incidence
B2	232m/s	24.39g	24.26g	16.19mm	16.22mm	4g	Soft Capture	90°
B13	235m/s	24.41g	24.31g	16.21mm	16.29mm	4g	Soft Capture	90°

Table 4.5: Bullets fired directly into the soft capture mechanism.

B2 contains a barrel band that runs around the circumference of the bullet, fine tight linear striations appearing in clustered groups, consistent with the musket's barrel wall as can be seen in figure 4.1 below. Powder pitting and melting from firing were present as well. B13 contains the same markings as described in B2; however, B13 also has some remaining flashing around the mould seem which can be seen in figure 4.2 below.

Figure 4.1: B2 Musket barrel wall characteristics.

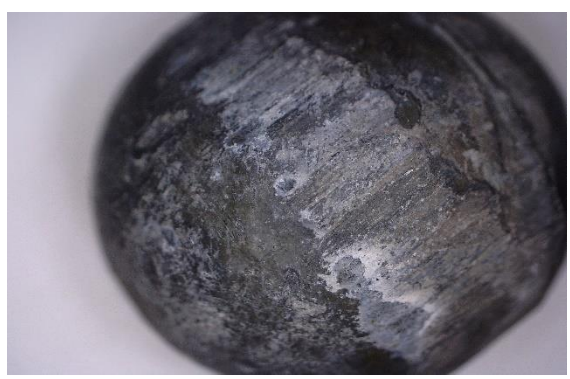

Figure 4.2: B13 Musket barrel wall characteristics

4.9 Experimental Firing Methodology Using Nitro Gunpowder

Due to sudden and drastic legal changes in the United Kingdom, a moratorium on the handling and usage of black powder was put in place on all Ministry of Defence firing ranges. This was a decision made and placed on MOD firing ranges by the MOD and the author was not fully explained the rationale of their decision. This along with other limitation to the experimental firing trials will be discussed further in Chapter Five. This occurred as the last of the experimental firing trials were to begin. Due to these unforeseen circumstances, it was decided to implement another new experimental firing methodology using the same baseline established by Robins and the experiments using TS2 black powder in this thesis. The full experiment demonstrating the viability of this new methodology can be found in Chapter Seven of this thesis.

4.10 Conclusion: Defining the Experimental Parameters

The purpose of this chapter was to investigate specific variables and to establish a set of parameters for the creation of an experimental firing methodology based on the information collected from early modern period military treatises and scientific publications. The experimental variables were identified in Chapter Two of this thesis and the experimental parameters were set by the above sections and will be reviewed here.

The decision was made to use a modern reproduction black powder over attempting to replicate one based on limited information. A reproduction black powder known as TS2 was chosen as it fits both of the following parameters: the gunpowder charge weight that was determined to be half the weight of the bullet, while maintaining the baseline muzzle velocity between 434m/s and 518m/s, averaging around 457m/s, discovered by Robins in 1742. TS2 was chosen for use as it complies with both parameters. TS2 will also be used as the priming powder for this study, as no definitive evidence could prove if a separate powder was used in the early modern period for priming. The composition of bullets from multiple English Civil War sites was experimentally discovered by Harkins and Rowe who both concluded that the bullets are comprised of 99% to 90% pure lead. As mentioned above, this study chose to cast its own bullets from modern roofing flashing that was tested and found to be of at least 90% pure lead and believed to be in compliance of this standard (Rowe 2018).

The ratio of gunpowder charge weight to bullet weight was found to be 2:1. According to military treatises dating to the early modern period, the gunpowder charge weight is half the weight of the bullet. This thesis decided not to use a wad during the experimental firing trials to reduce the effects of an unknown variable.

The firearm chosen for the experimental firing trials is a 17-bore ‘bastard musket’, with a 41-inch barrel. The windage will be held as constant as the variation of the bullet sizes and fouling allows. All bullets will be weighed, and their diameters will be measured before every firing experiment and all results will be tabled pre-and post-firing. In accordance with the above parameters, the 17-bore ‘bastard musket’ will be firing a 19-bore, 24g bullet, with a full charge weight issued to the firearm weighing 12g of black powder.

With the experimental parameters set by this chapter, the next aspect to be identified is the potential targets, field obstructions and landscape features that a bullet fired during battle may have impacted. This will assist in creating and informing a series of experimental firing designs that will aid in the creation of a reference collection of known bullet impacts, which is the subject of Chapter Five.

Chapter 5: Using the Tactical Landscape to Create Experimental Firing Designs: Case Studies of the Edgehill and Oudenaarde Battlefields

To create a reference collection of known bullet impact evidence, which can be used as a comparative tool against bullets from the archaeological assemblages, experimental firing designs must be created that reflect potential targets within the battlefield landscape. As experimental firing to collect known bullet impact evidence has been largely neglected in conflict archaeology, as noted throughout Chapters One and Three, this thesis will begin by collecting the most basic of bullet impact evidence, beginning with key terrain features common to both case study battlefields.

This will be completed by briefly reviewing the tactics and tactical terrain used in the early modern period. Then, an examination of both the Edgehill and Oudenaarde battlefields will be completed by examining the events of the battle within the reconstructed historic terrain, this will enable the identification of the tactical terrain present in the battles which bullets may have impacted. With the tactical terrain features identified from both battlefields, experimental designs will be created for the proof of concept experimental firing trials in Chapter Seven. This chapter also contains a brief discussion on the two most common terrain features from both battlefield landscapes, primarily the ground surface and enclosures.

Finally, this chapter will discuss the vast scope and limitations of firing live ammunition during experimental research, such as the vast scope of needed research, and the legal and costing issues that have prevented a more comprehensive research agenda. This section is aimed at future researchers, so that the obstacles found in this thesis may be better overcome by future researchers.

5.1 Tactics and the Tactical Terrain

By the 16th century, the most important weapons used on the battlefield were fired with gunpowder. With the introduction of gunpowder and gunpowder weapons to Europe, a fundamental change began and by the end of the 16th century, the most advanced armies in Europe were equipped in very similar manners (Van Creveld 1989: 81-84; Urban 2011: 48). The firearm was not the sole occupier of the battlefield at the beginning of the early modern period, as the pike was revived during the 14th and 15th centuries by the Swiss and German armies, along with the classic phalanx formation. However, the combination of pikemen, arquebusiers, cavalry and artillery became the new standard and source of variation within armies from nation to nation. This issue of combined arms demanded the development of new tactics (Van Creveld 1989: 89-90; Urban 2011: XV-XVI).

During this era of ‘pike and shot’, battlefield success came from the effective mixture of pikemen and arquebusiers in a way that allowed for mutual protection. Pikemen could be slow and cumbersome over broken and uneven terrain and since they relied on a tight, dense formations, this made them an excellent target for opposing arquebusiers and artillery. Arquebusiers were more mobile, but slow to reload their muskets and inaccurate firing made them easy targets for other groups of pikemen and cavalry. The combination of ‘pike and shot’ allowed the pikemen and arquebusiers to work in tandem. The pikemen would provide screens in which to protect the arquebusiers while they were reloading and the arquebusiers could protect the pikemen from enemy columns of arquebusiers (Hughes 1974: 11; Van Creveld 1989: 90-91; Urban 2011: 38-39).

The mixture of pikemen and arquebusiers changed with time due to the technological advances and the growing reliability in firearms, with the number of pikemen growing fewer while the number of arquebusiers grew larger. This enabled the development of better tactics starting with Prince Maurice of Nassau and later by Gustavus Adolphus. The increase in infantry carrying firearms allowed them to spread out over the battlefield which brought more guns to bear on the enemy, this idea is also known as frontage (Van Creveld 1989: 90-95; Parker 2007: 342- 346; Newark 2009: 170-175). The Spanish, Dutch and Swedish armies are known as the creators and refiners of early modern combined arms tactics, that is the combined usage of cavalry, artillery, pikemen and arquebusiers or musketeers. The general view is that Spanish dominance was eclipsed by the Dutch under the Prince Maurice of Nassau, who created a more flexible system of fighting and the concept of volley fire (Parker 1995: 154-155). The Dutch system was later improved upon by the Swedish military under Gustavus Adolphus with the concept of the linear formation (Hughes 1974: 80; Wilson 2009: 84; Roberts 2010).

The English military during the battle of Edgehill (1642), during the English Civil Wars, still used blocks of pikemen and musketeers. After the English Civil Wars, the pikemen gave way to the invention of the bayonet, the switch from matchlock to flintlock muskets and further refinements in linear tactics. The invention of the bayonet created a dual role for the musket, part pike and part musket, and this dual role ended the use of pikemen on the battlefield (Hughes 1974: 11, 80; Van Creveld 1989: 90-91; Parker 1995: 152).

By the time of the battle of Oudenaarde (1708), long lines of musket bearing infantry firing volleys at one another from 50m to 100m became the new standard. These long lines of tightly packed soldiers stood shoulder to shoulder and volley fired by rank or platoon on command. Combined arms tactics were still in use, as cavalry and artillery maintained their roles. However, the key to fighting was now to bring as many firearms to bear against the enemy as possible and either continue firing until the enemy had had enough or to charge the enemy with bayonets. This fighting style continued until the Napoleonic Wars (Neuman 1967: 15; Harrington 2005: 96; Middlekauff 2005: 507-508). Tactics, of course, were not always textbook, and the terrain would influence the tactical decisions and flow of the battle.

Generals and commanders throughout history have always sought to use the terrain to their advantage. *The Art of War*, written over 2,500 years ago by Sun Tzu describes how to use the terrain to one’s advantage, specifically identifying nine different types of terrain (Sun-Tzu 1993: 147-171). The famous Spartan King Leonidas took 300 Spartans and around 7,000 allied soldiers to a narrow pass at Thermopylae to hold off between 100,000-150,000 Persian soldiers 2,497 years ago (Sage 1996: 85; Fox 2006: 98-100). The victories of Hannibal Barca and the Carthaginian forces over separate Roman armies at the battles of the Trebia and Lake Trasimene over 2,200 years ago, resulted from using the terrain to his advantage to surprise the Roman armies and defeat them (Livy 1965: 80-83, 98-100; Polybius 1979: 236-244, 249-252). One of the most comprehensive publications from the early modern period on warfare is Carl von Clausewitz's, *On War* originally published after his death in 1831. *On War* describes in great detail the attack and defence of strategic positions such as mountains, rivers, streams, forests and enclosures (Von Clausewitz 2004: 371- 665).

Early modern period military treatises discuss using specific terrain types for gaining a tactical advantage against the enemy, or for taking the tactical advantage away from the enemy, and for laying ambushes. Mentions of terrain types are hints at features within the landscape that bullets may have impacted.

Terrain that can be used for a tactical advantage includes hills, banks, walls, ditches, trenches, woods, shrubs, moorland, marshes, rivers, bridges and enclosures (Smythe 1594: 142; Monck 1671: 85; Boyle 1677: 152; Turner 1683: 236; Von Clausewitz 2004: 764). These terrain types act as obstacles of approach which can prevent or slow the movement of the enemy. They are places of natural or synthetic fortification, which can be used to entrench one's soldiers, conceal their presence or movement, and to dictate the flow of battle (Von Clausewitz 2004: 764). Alternatively, when used against the enemy it can hinder their movement by creating impassable obstacles, or obstacles which slow their movement and exhaust them (Von Clausewitz 2004: 765). The use of terrain can also create situations wherein soldiers must fight through exposed and open terrain to reach a more entrenched and protected enemy.

The enclosed landscape could include hedges, fences, stone walls, ditches, arable and pasture fields, as well as woods. Hedges have a long history of providing a tactical advantage in battle, not only in England but throughout Europe. Julius Caesar wrote in 58 BC in the *Gallic War,* that the Nervii (a tribe from modern day Belgium), would cut into trees and bend them down. The branches from the tress would be tangled with thorns which ensured that it acted as a fortification that could not be penetrated or seen through (Caesar 1996: 44; Wright 2016: 235). During the 1525 Battle of Pavia, Spanish arquebusiers took position behind the hedges and gave relentless fire on the French. The French cavalry could not clear the Spanish infantry from the hedges as their lances could not reach them (Showalter & Astore 2007: XXX).

Military treatises from the early modern period are quite clear on the usage of hedgerows during warfare. Hedges were used as places for laying an ambush (Smythe 1594: 142; Elton 1650: 33; Venn 1672b: 8-9, 39; Boyle 1677: 69; Turner 1683: 236, 329), or as a places of fortification against cavalry or flanking attacks, as hedges hinder movement (Smythe 1594: 142; Monck 1671: 92, 96; Boyle 1677: 152). Using hedges during a battle gave a tactical advantage to either lay an ambush or create an entrenched position wherein the enemy could not be easily removed. The usage of the hedgerow in combat was a common enough tactic in English warfare that the *Universal Military Dictionary* described the intricacies of hedge firing. Hedge firing is only applicable when soldiers are drawn up opposite to each other and are prevented from approaching closer to one another from behind parallel fences, such as hedges, banks, and walls. In this case, the soldiers are brought up two ranks deep and both give fire while standing (Smith 1779: 101). It is unclear as to how old or often the technique of hedge firing was applied throughout the history of England, as this is the only instance thus far discovered by this thesis.

The composition of the army can also dictate the usage of terrain. Monck (1671) and Boyle (1677) both state that if the enemy army comprises more cavalry than yours, to fight in enclosed land which hinders their movement, thereby taking away their army's advantage by using the landscape to your advantage. However, if your army contains more cavalry than the enemy, to fight them in the open landscape (Monck 1671: 92, 96; Boyle 1677: 152). Most of these landscape features are straightforward (hills, rivers, ditches, marshes); however, enclosure is a broad term that encompasses a variety of field boundaries and will be discussed in further detail below in section 5.5.

Foard states that most battles fought in the English Civil War were predominantly fought in the open landscape, such as at Edgehill. The open landscape lacked key aspects of the tactical terrain, such as hedgerows, and that this open landscape was ideal for the set piece battles of the 17th century (Foard 1995: 21). However, even open fields could provide tactical significance. Within open fields, one can find hills, ditches, streams, moorland, local vegetation, pasture fields, trees and a variety of crops in arable land (Foard 2008b: 50). Not only could all of these landscape features provide tactical significance, but they could all provide differing evidence for impacted bullets depending on what surface or material a bullet impacted. Not all battles in the early modern period were set piece, as the battle of Oudenaarde started as an extremely fluid, somewhat impromptu battle as will be seen in section 5.3 below.

As discussed above, the terrain of the battlefield can have a tactical significance during the battle. However, due to the passage of time and actions of human beings, the landscape of the battlefield can change significantly and the tactical terrain that was once present on the battlefield may now be lost or drastically altered (Foard & Morris 2012: 143-144). The reconstruction of the historic terrain of the battlefield is completed using documentary sources and primary accounts from as close to the time of battle as possible and is completed in order to identify any landscape features that may have had a tactical significance during the battle (Foard 2012: 22). The primary accounts from the battle can enable the placing of deployments and the events of the action into the reconstructed landscape by using topographical references (Foard 2012: 127).

5.2 Case Study: The Battle of Edgehill 1642

The reconstruction of the historic terrain for the Edgehill battlefield was completed by Dr Glenn Foard and can be seen in figure 5.1 below.

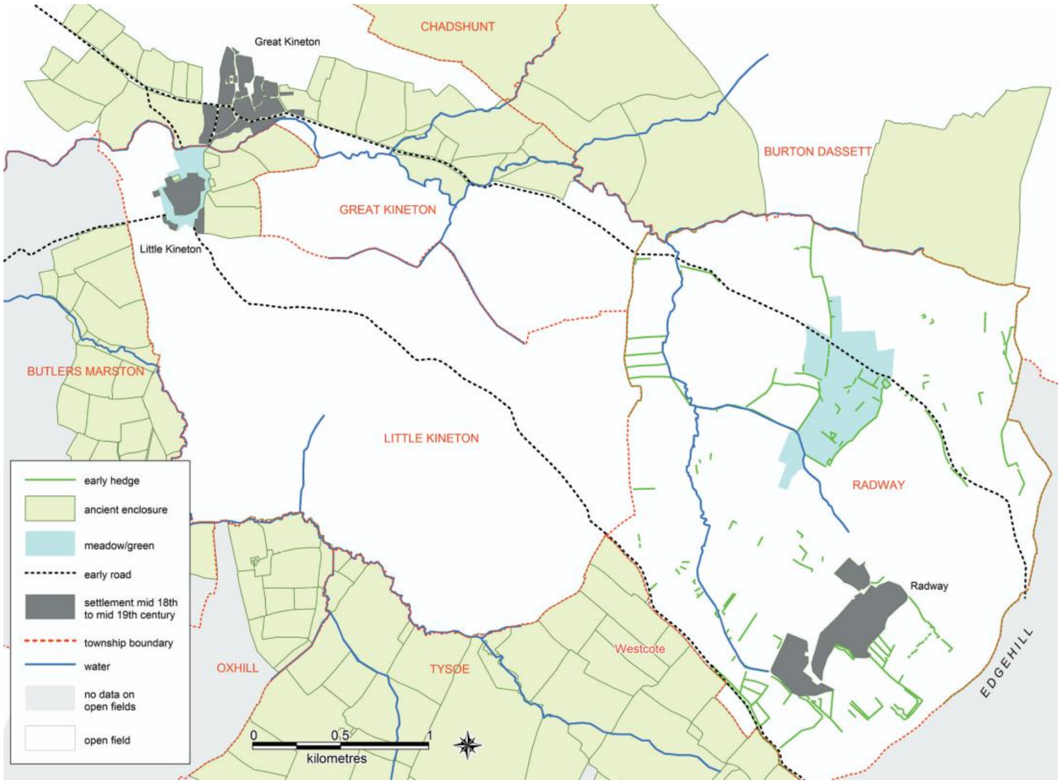

Figure 5.1: The reconstructed landscape of the battlefield created by Foard 2012: 129, courtesy of Glenn Foard.

On 23 October 1642, the battle of Edgehill was fought in the open fields between the villages of Kineton and Radway in Warwickshire, England. Foard states that the land in the townships that border Radway and Kineton was already enclosed by hedged fields and converted to pasture fields long before the time of the battle and that ridge and furrow extended across most of the landscape, with the exception for the slopes of Edgehill. However, the lack of documentary evidence could not enable the identification of which fields were still under cultivation during the time of the battle (Foard 2012: 133). The hedges within the open field landscape, as seen in the boundary between Kineton and Radway, existed at the time of the battle (Foard 2012: 133). The royalist forces under the command of King Charles I and Prince Rupert took position on the steep 300-foot inclined hill known as Edgehill. The battle of Edgehill was the first major engagement of the English Civil War (Harrington 2004: 86; Foard 2012: 121). According to Foard, the open field stretched from the slopes of Edgehill to the village of Kineton, a distance of almost 3 miles. The width of the open field was 1.5 miles across in the widest point. The width of the open field narrowed near Kineton to less than 1 mile across. At this narrow point, a series of enclosures established in 1567 connected together with the enclosed land that continued to Burton Dassett in the northern periphery of the battlefield (Foard 2012: 133, 175). On the southern periphery of the battlefield, Tysoe, south of Little Kineton and Westcote, located to the East of Tysoe were enclosed around the 15th century (Foard 2012: 133).

The parliamentarian army, under the command of the Earl of Essex, received news of the royalist position and marched from their quarters to deploy in the open fields near Kineton, about two miles from beneath Edgehill (Foard 2012: 176). The royalists; with the commanding height of Edgehill, could see the parliamentarian army deployed in the open field, but not advancing. In response, the royalist forces descended the hill into the open field to force battle (English Heritage 1995; Foard 2012: 122, 176). The opposing armies were now drawn up for battle in the open fields between Radway and Kineton, roughly one mile from one another (English Heritage 1995).

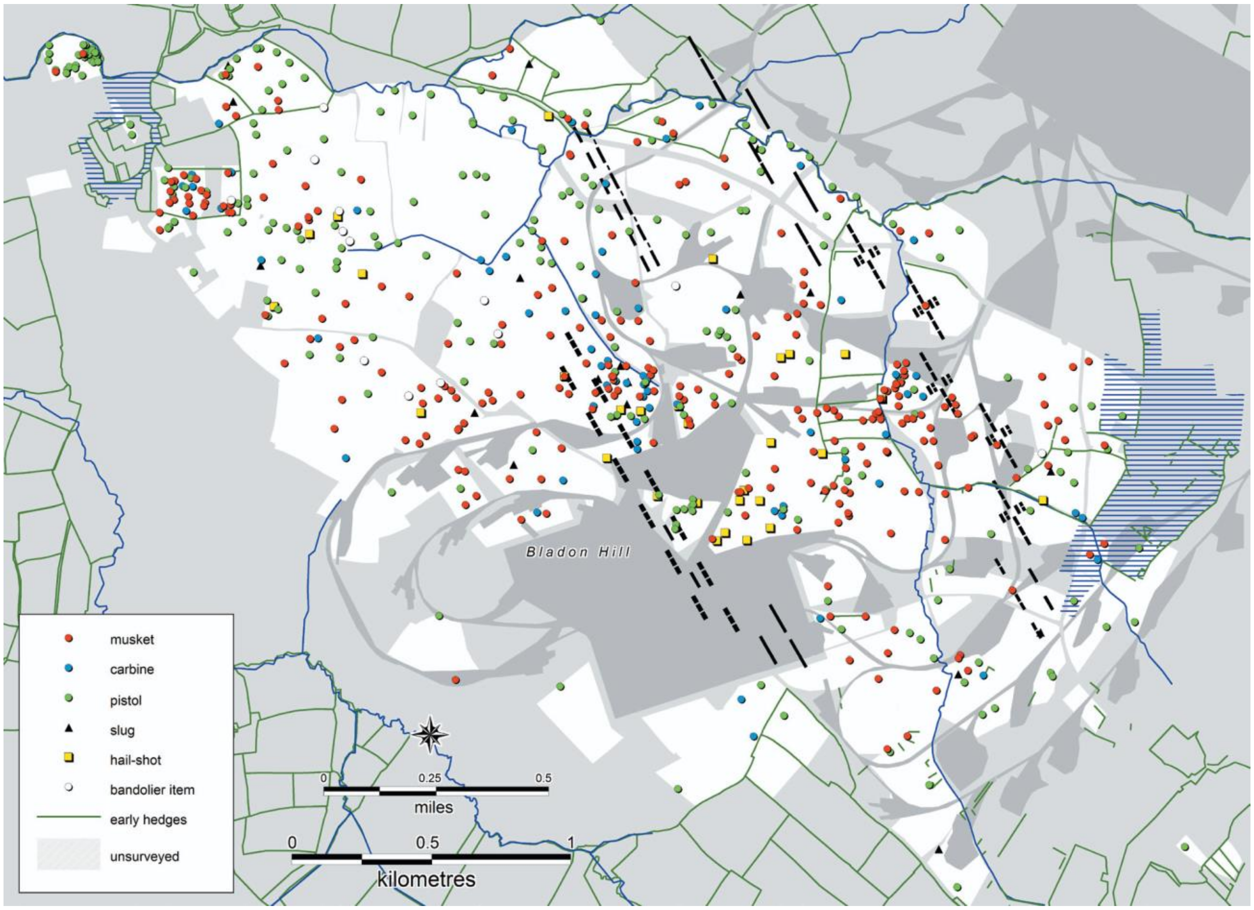

Figure 5.2: The new interpretation of the battle array from Foard 2012: 179, courtesy of Glenn Foard. The parliamentary army is on the left, the royalist on the right.

The deployment for the parliamentarian army had their infantry lines in the centre, eight ranks deep in accordance with Dutch Tactics. Artillery was intermixed between each infantry regiment and their cavalry was deployed on both the right and left wings, as can be seen in figure 5.2 (Foard 2012: 125). On both the right and left flanks of the army were hedges and enclosures. Musketeers and dismounted dragoons were deployed ahead of the cavalry at right angles within these ‘hedges, briars and bushes’ to provide enfilading fire on the royalist cavalry when they charged (Foard 2012: 175-176). Sir James Ramsey, a commander of a parliamentarian cavalry brigade commented that the whole left wing of the army was flanked by a hedgerow and that musketeers and dragoons were deployed forward and to the left of his cavalry in a series of hedged enclosures. Foard states that Ramsey’s location was near Kineton, where the open field narrowed (Foard 2012: 176).

The royalist deployment had their infantry drawn up in the centre, six ranks deep in accordance with Swedish tactics (Foard 2012: 125). Artillery was intermixed between the infantry regiments, also with the cavalry deployed on both wings (English Heritage 1995; Foard 2012: 176).

Before the royalist army attacked, the battle began with an artillery duel. The royalist artillery fire was ineffective due to its placement in a valley. Primary accounts state that the royalist fire fell short, grazing the ploughed land, but that parliamentarian artillery fire could not miss its mark and was effective (Young 1995: 105; Foard 2012: 184). Foard states that this reference to ploughed land could indicate the ridge aspect of the ridge and furrow, although it is not clear (Foard 2012: 184).

After the artillery duel, royalist dragoons were deployed to clear the parliamentarian musketeers and dragoons from the hedgerows on both the right and left flanks (English Heritage 1995; Young 1995: 106; Foard 2012: 127, 176). Foard mentions that the royalist dragoons clearing of the hedges happened on the left flank of the royalist army near Westcote and that this field also contained ridge and furrow (Foard 2012: 176). The royalist cavalry charge on the left wing, had to charge through tough ground which contained hedges and ditches, engaging the enemy musketeers with his dragoons through gaps in hedges (Foard 2012: 176).

After the hedges had been cleared, Prince Rupert advanced his cavalry on the right wing to attack the parliamentarian cavalry. The parliamentarian cavalry stood still to receive the royalist charge and then fired too early. The royalist cavalry attacked them in the flank and rear, routing the parliamentarian cavalry (Foard 2012: 177). The majority of the remaining reserve cavalry on the right wing joined Rupert’s cavalry in routing the parliamentarian cavalry from the field and pursued them to and through the village of Kineton for as far as 4 miles (English Heritage 1995; Young 1995: 107-108; Foard 2012: 178). During this pursuit, Rupert’s cavalry attacked the parliamentarian baggage train and burned the wagons (Foard 2012: 178).

The royalist cavalry on the left wing did the same exact thing as the cavalry on the right wing, including the reserve forces joining in on the rout of the parliamentarian cavalry. While, sources state that the royalist cavalry on the right wing had to charge uphill, leaping through five or six hedges, and ditches which were formerly lined with parliamentarian dragoons (Young 1995: 109; Foard 2012: 177).

With the majority of both armies' cavalry in retreat and/or pursuit, the royalist infantry began to advance. The parliamentarian infantry occupied a round hill known then as Bladon Hill (Foard 2012: 180). Once the infantry lines closed to within range, the musketeers began to fire. 'Push of pike' came when the musketeers from both sides seemingly spent their ammunition (Foard 2012: 184). Once the infantry lines were locked in combat, the parliamentarian reserve cavalry emerged from behind a hedgerow and attacked the flank of a royalist infantry regiment and routed them, pursing them back to their cannon and killing the gun crews (Foard 2012: 184). Rather than continue the pursuit for too long, the parliamentarian reserve cavalry returned to assist in the main battle. On their return to the main battle, the parliamentarians mistook them for the enemy and fired upon them with case-shot, although only one man was wounded. The parliamentarian reserve cavalry then attacked the royalist infantry where the King's standard was located where they were meet with stiff resistance, and not being able to break them retired back to their former position. They attacked again on the flanks when that regiment was engaged in push of pike and finally broke them (Foard 2012: 185). The royalist army began to collapse and was forced from their ground. The retreating royalist infantry was saved from pursuit and destruction by three regiments of foot under the command of Gerard, with the assistance of a ditch and some artillery. Gerald and his three regiments held their ground until nightfall (Foard 2012: 185). Exhaustion and lack of ammunition ended the battle in a stalemate. Both forces withdrew from the battle with the royalist forces returning to Edgehill and the parliamentarian forces returning to Kineton (English Heritage 1995; Young 1995: 112, 124).

5.2.1 Discussion

The reconstruction of the historic landscape for the Edgehill battlefield demonstrates that the battlefield was located within the open landscape, with both flanks of the parliamentarian army extended into hedges and enclosures. This open landscape was once under open field agriculture indicated by the presence of ridge and furrow, which extended across most of the battlefield landscape. It is believed that the plain in which the battle was fought was then common pasture field (English Heritage 1995), although without documentary evidence it is impossible to say which fields were still under cultivation and which were pasture or grass (Foard 2012: 134). The presence of ditches on the battlefield is another common feature and is sometimes associated with hedges depending on region and style of the hedge. There is no mention in the accounts of the style, species, depth or height of the hedges.

The opening of the battle with an artillery duel is a good parallel on which to draw for small arms fire within the open landscape. The artillery fire was impacting the ploughed land; whether this indicates actual ploughed land or the ridge aspect of the ridge and furrow as Foard suggested is unclear. However, the infantry action in the core of the battlefield occurred within the open landscape and the bullets recovered could represent the over and under fire of the infantry. This being the case, the bullets could contain evidence of impact with the ground surface which could assist in further detailed analysis of ground conditions at the time of the battle. Experimental firing designs of bullets fired into differing ground conditions, such as a ploughed field, grass field and pasture field could answer this question, provided the bullet did not impact another target before impacting the ground. Potential targets from this section of the battlefield, whether primary or incidental could include soldiers, soldier's equipment such as firearms, pikes and armour.

Both flanks of the parliamentarian army extended into the hedges and enclosures by deploying musketeers and dragoons into the hedge at right angles. The subsequent purging of those forces before the royalist cavalry charge implies that the impacted bullets from these regions of the battlefield could show evidence of bullets impacting a wooden surface, the hedge. However, other potential targets could be the ground, soldiers, soldier's equipment and even the horses.

5.3 Case Study: The Battle of Oudenaarde 1708

"We drove the enemy from ditch to ditch, from hedge to hedge and from out of one scrub to another in great hurry, confusion and disorder" -Sgt. Millner-

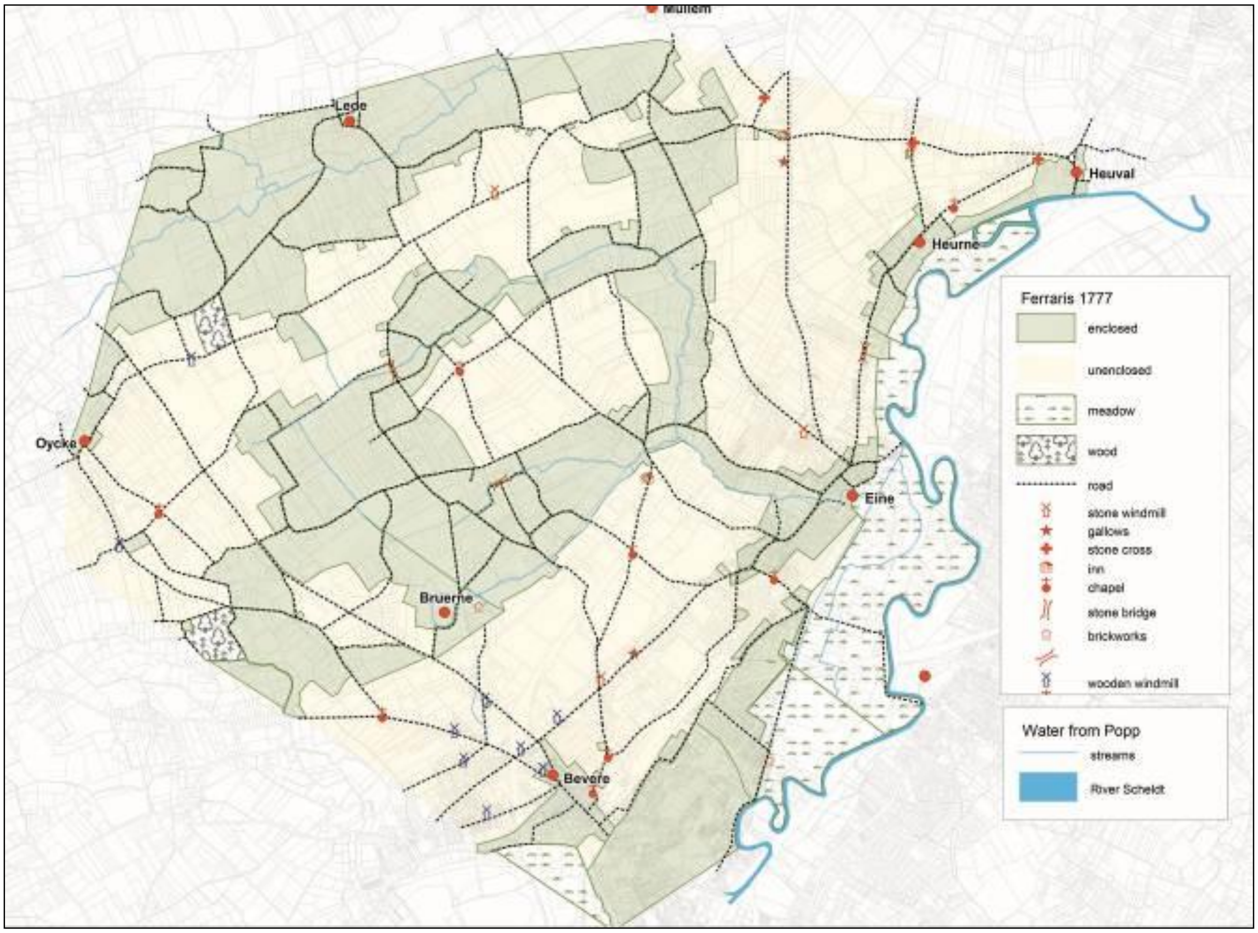

Figure 5.3: The reconstructed landscape of the Oudenaarde battlefield from Foard et al 2012: 20, completed by Tracey Partida, courtesy of Glenn Foard.

The battle of Oudenaarde, fought 11 July 1708 in Oudenaarde, Belgium was a key battle during the War of Spanish Succession (1701-1714). The battle was fought between a coalition army, commanded by the Duke of Marlborough and Prince Eugene of Savoy, comprised of some 80,000 soldiers and the French army, commanded by the Marshal Vendome and the Duke of Burgundy, comprised of some 85,000 soldiers (Vandenburie 2009: 19).

The reconstruction of the historic terrain was completed by Dr Tracey Partida and can be seen in figure 5.3 above. Some issues arise in this battle where the primary accounts that describe the events and the terrain do not always match with the documentary evidence and the other way around. Sometimes the documentary evidence does not map things in great detail and certain aspects of the terrain are left out or the specific locations of buildings are placed in differing locations on the battlefield (Foard *et al.* 2012: 41-47). Some of the names provided in the accounts do not appear on the historic maps at all (Foard *et al.* 2012: 46).

The Ferraris map is the most reliable source for the reconstruction of the historic terrain, despite the fact that it was created in 1777 and that by the time Ferraris created the map the landscape had changed very little (Foard *et al.* 2012: 22). The battlefield landscape contained open fields and enclosures, with the majority of the open fields as arable. No hedges or physical field boundaries were present within the open fields, and determining the exact location of the ditches and hedges in the enclosed landscape was difficult to determine (Foard *et al.* 2012: 22). Ferraris is the only documentary map of the battle that indicated the extent of the enclosed land, and the reconstructed map is based on this source, as seen in figures 5.3 and 5.4 (Foard *et al.* 2012: 20).

Figure 5.4: Ferraris map extract 1777 from Foard et al 2012: 29, courtesy of Glenn Foard.

The extensive network of roads across much of the battlefield landscape remains mostly intact, although there has been some additions and removal of roads since the time of the battle. Major roads were lined with trees at the time of the battle, but very few trees were found outside of the enclosed landscape (Foard *et al.* 2012: 23). The presence of arable and pasture fields, as well as orchards, were identified within the battlefield landscape.

On the morning of 11 July 1708, Marlborough’s second in command, William Cadogan arrived in Oudenaarde with sixteen battalions of infantry and eight squadrons of cavalry under the command of Rantzau. The primary purpose of their arrival was to build five pontoon bridges to supplement the existing bridges in Oudenaarde, so the coalition army could cross the Scheldt River. The commanders of the French army did not believe that the coalition army was approaching as rapidly as they were, and remained far away in the village of Gavere (North, along the road to Ghent, not pictured) and began advancing slowly towards the heights of Huise to gain a position in which they could observe the city of Oudenaarde (Vandenburie 2009: 20). Figure 5.5 below, shows the later phases of the battle but is used here to provide clarity to place names.

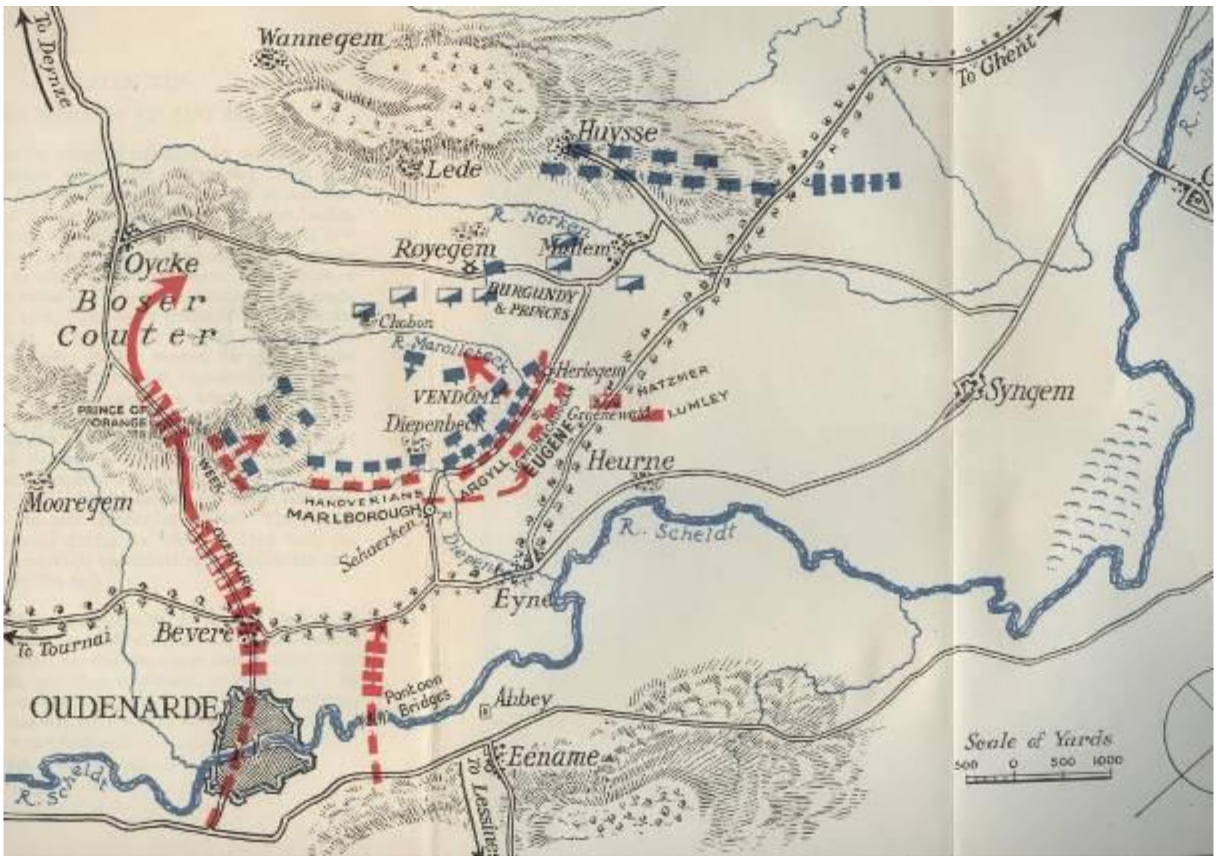

Figure 5.5: Churchill’s map. The French are detailed in blue, while the allied army in red from Foard 2012:17, courtesy of Glenn Foard.

French commander Marquis of Biron observed Cadogan’s forces crossing the Scheldt River. The French commander Louis-Joseph de Bourbon, Duke of Vendome did not take action, because they did not know the strength of the allied army crossing the river and did not want to give up the heights of Huise (Vandenburie 2009: 21). Biron eventually received orders to push the allied forces back over the Scheldt river. Biron occupied the villages of Eine and Heurne, where the French command then decided not to send the cavalry reinforcements because they thought the situation was under control and that the ground was to marshy. Biron along with his infantry and cavalry took up position in the hedges and gardens in the centre of Eine (Vandenburie 2009: 21; 2010: 18; Foard *et al.* 2012: 7).

With the bridges built, Cadogan started marching his 12 battalions of infantry in line with the Hanoverian cavalry at his flank towards Eine (Vandenburie 2009: 21; 2010: 18; Foard *et al.* 2012: 8, 43). On the march, the Hanoverian cavalry encountered a force of French cavalry foraging for supplies and the French cavalry was put to flight. Learning of this, Biron immediately advanced with his infantry and cavalry and the Hanoverian cavalry were forced to retire back to Cadogan's flank. After this skirmish, Biron informed Vendome that the entire allied army was crossing the Scheldt River. Meanwhile, the allied infantry continued to cross the river and was deploying in the enclosures and hedgerows along the Diepenbeek brook as soon as they arrived, while the arriving allied cavalry begins forming on the slopes North of Oudenaarde (Vandenburie 2009: 22; Foard *et al.* 2012: 9).

Vendome began marching his troops off of the heights at Huise into the valley below to a position north of the Marollebeek brook where the allied army was deploying (Vandenburie 2009: 22). Meanwhile, Burgundy kept the main body of the French army at Gavere, never to engage in the battle. Cadogan crossed the Marollebeek brook and then stormed Eine, dislodging the French forces from the hedgerows and capturing three Swiss infantry battalions during the fight (Vandenburie 2010: 20; Foard *et al.* 2012: 9, 43).

Once Eine was captured, Cadogan's forces marched north across the plains of Heurne to Herlegem, his infantry engaged the remaining forces belonging to Biron in an open field and defeated them capturing Biron (Foard *et al.* 2012: 10-11). With Biron's force defeated, Cadogan's forces deployed in the enclosures at Herlegem, providing a right flank to the main body of the allied infantry already deployed within the enclosures (Foard *et al.* 2012: 44).
The French infantry under Vendome, now deployed in the enclosed landscape along the Marollebeek and the Grotebeek with the French cavalry deployed in the plains to support the

infantry (Foard *et al.* 2012: 11-12). At this time Cadogan, engaged in a fierce fight in the hedges forcing a French infantry battalion to retreat (Foard *et al.* 2012: 12). Vendome, who was fighting along with the infantry himself, rallied the retreating infantry and ordered them to renew the fight. However, Cadogan provided enfilading fire on the French infantry and after another fierce fight, the French were forced to withdraw again. After that, Vendome ordered Burgundy to send the entire French army under his command to assist in the battle, but Burgundy ignored the order because he thought the terrain was too disadvantageous for his cavalry (Foard *et al.* 2012: 13). Twenty more allied infantry battalions arrived on Cadogan's left flank and took up position within the hedgerows. At this point in the battle, 36 allied infantry battalions were fiercely fighting close to 50 French infantry battalions with each side giving and losing ground several times over (Vandenburie 2010: 21; Foard *et al.* 2012: 13-15).

It took a combined flanking attack by late arriving Dutch and Danish forces to finally break the French infantry on their right flank, which effectively cut-off the French infantry in the centre of the battlefield (Vandenburie 2009: 25; 2010: 22; Foard *et al.* 2012: 15-16). Vendome attempted to counter attack, but as night fell it became impossible to differentiate friendly from enemy troops. Marlborough ordered a cease fire amongst his troops after night fall, and the allied army held its position until daybreak. The French army retreated north towards Ghent, while the allied army pursued them (Vandenburie 2009: 26; Foard *et al.* 2012: 16-18).

5.3.1 Discussion

The reconstruction of the historic landscape for the battle of Oudenaarde shows that the battlefield landscape was mostly arable land, with areas of enclosed land and open fields. No hedges or any other physical boundaries were located in the unenclosed landscape as mentioned above (Foard *et al.* 2012: 22). The landscape contained very few trees outside the enclosures, although major roads were lined with trees (Foard *et al.* 2012: 23). Fighting from hedgerow to hedgerow was a common theme in the battle, and it is well documented that infantry lines were firing at one another through the enclosures, especially alongside both the Marollebeek and Diepenbeek brooks (Foard *et al.* 2012: 43).

Besides the soldiers, soldier’s equipment and horses it seems that the most common incidental targets would have either been made of wood, such as the hedges or various trees along the road networks or the ground surface from over or under fire. The ground in this case, much like Edgehill was a mixture of arable and pasture fields. The hedge styles, species, height and depth were not mentioned in either the primary accounts or the documentary evidence.

5.4 The Open Landscape

As the open landscape is a theme in both case study battlefields, a brief discussion is needed. Both battlefields mention the open landscape, primarily in the form of arable land. At Edgehill, this comes in the form of the aforementioned ridge and furrow, which extended across much of the battlefield landscape, although it was unclear if this ridge in furrow indicated current or past cultivation. If current, then the presence of soil and stones could influence the characteristics transferred to the surface of the bullet. If the ridge and furrow denoted past land use, then that part of the battlefield may have been covered in grass or other local vegetation. From an experimental standpoint, ground firing experiments conducted against loose sterile soil and stony soil could collect evidence that signifies agricultural land use, whereas experimental firing across grass or pasture fields could collect evidence that signifies past land use. These experiments would be conducted using the concepts from Chapter Two (sections 2.4.1.1, 2.4.1.2 and 2.4.2), of over and under firing leading to the bullet ricocheting and bouncing and rolling after the initial ground impact.

5.5 Enclosures and Hedgerows

As hedges and enclosures are common themes in both case study battlefields, and since the primary accounts and documentary evidence never speak of the hedges outside of their reference, a further detailed discussion into enclosures is needed to gain insight for proper reproduction for experimental purposes.

An enclosure is an area of land of a few acres up to as many as a hundred acres enclosed by a physical boundary such as stone walls, hedges, fences, and ditches (Blith 1649: 102; Gentlemen 1756; Slater 1907: 4; Wright 2016: 54). This seems straightforward until the investigation into hedges and fences is expanded using husbandry treatises from the early modern period. The terminology can be vague; sometimes hedges are called fences, fences as hedges. For example, Leybourn states that a hedge is a field boundary, commonly called a fence (Leybourn 1653: 226). Hedges are also referred to as quicks or quick-sets (Fitzherbert 1534: 78; Norden 1607: 238; Gentlemen 1756). The term hedge and fence can be interchangeable in the literature. Fences are made up of many materials, according to the situation and circumstances under which they are needed such as hedges, ditches, walls, palings, whether made of stone, brick, wood or earth (Smith 1670: 25; Dickson 1805: 110).

Hedges or hedgerows are the landscape feature generally associated with the term enclosure across large parts of England (Partida 2014: 159). Hedges were used as field boundaries to control livestock, to protect the crops on the field, and to secure property lines (Silvanus 1652: 28; Nourse 1700: 27; Baudry *et al.* 2000: 10; Partida 2014: 159; Wright 2016: 11). Hedgerows are made up of rows of trees or shrubs managed in various ways (Hale 1757: 210, 248-250; Oreszczyn & Lane 1999; Baudry *et al.* 2000: 8), although usually to create a stock proof barrier (Barnes & Williamson 2006: 1-2). Hedgerows can also be rows of bushes, intermixed with trees (Orwin 1935; Wright 2016: 50).

Hedges can be either living or dead. Quicks or quick-sets refer to trees or shrubs that are raised in a nursery for sale; a living thing (Gentlemen 1756; Partida 2014: 190). Hawthorn, blackthorn, hazel and holly were the most commonly used trees or shrubs for making quick-set hedges, especially when mixed with oak or ash. Within 8-12 years a hedge made of hawthorn makes the best fence for both height and strength and is completely stock proof (Fitzherbert 1534: 78; Norden 1607: 240; Blasgrave 1669: 38; Smith 1670: 25-26, 194; Nourse 1700: 62-63; Gentlemen 1756; Hale 1757: 244; Partida 2014: 162; Wright 2016: 118-119). At 20-30 years growth, the hedge could reach a height of five feet (Fitzherbert 1534: 80; Blasgrave 1669: 41-42). Hazel grows into a tall, straight hedge very quickly, but is only moderately stock-proof

(Wright 2016: 130-131). Holly was said to be one of the best shrubs for making hedges, as it will grow in any soil condition, is very strong, and stock proof. Hale says it will look more like a wall then a hedge (Hale 1757: 248-250).

A dead hedge is a temporary hedge, made up of dead wood tossed and woven together. Commonly used to keep the land enclosed from cattle while either crops grew or while a living hedge grew to maturity behind it (Norden 1607: 239; Smith 1670: 22; Ellis 1744; Hale 1757: 241). A dead hedge could also be a temporary field boundary, such as a paling fence, or a post and rail fence (Ellis 1744; Dickson 1805: 116; Wright 2016: 233). A paling fence was a timber fence constructed much like a palisade. This fence was a simple nailed fence that consisted of upright posts driven into the ground at predetermined distances, crossed horizontally with 3-4 planks of coarse wood (Gentlemen 1756). Paling fences, post and rails fences and guard fences, which were made of posts with double or triple coarse wood rails, were sometimes used on both sides of a living hedge to protect it while it grew to maturity (Gentlemen 1756; Blaikie 1821: 25; Partida 2014: 190). A variety of examples of paling fences can be found in figure 5.6 below.

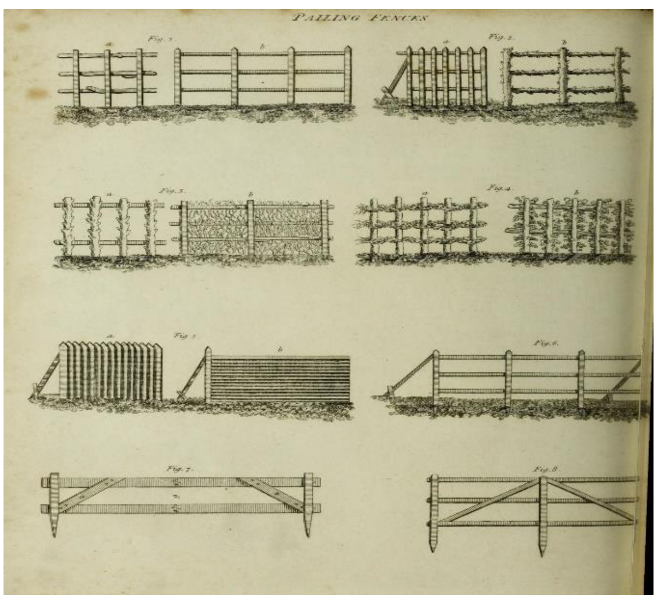

Figure 5.6: Paling fences from Dickson 1805:110.

Many species of trees were planted in hedgerows in England and it was common to find hedgerows made up of multiple species of tree or shrub intermixed (Plattes 1639: 79; Smith 1670: 28; Wright 2016: 10). The main timber trees in England were oak, ash, beech, elm, and willow. These timber trees were planted in hedgerows and used for firewood, shipping and building (Norden 1607: 29, 211; Blith 1649: 115; Smith 1670: 24-25; Partida 2014: 226). Of the timber trees, oak was seen as the best of all wood species and was used mainly for shipping and building houses. Oak was used for so much that Norden wrote in 1607 his concerns that the supply in England would be extinguished for future generations (Norden 1607: 211; Blith 1649: 170; Smith 1670: 8, 195; Cook 1676: 43; Meager 1679: 110).

Hedgerows were traditionally and historically managed by laying or plashing to create a stock-proof barrier, which could last for decades with the occasional repairs. Without the repairs, the hedgerow will form gaps (Barnes & Williamson 2006: 3; Partida 2014: 288; Wright 2016: 235-237). The plashing of a hedge was not completed until 8-12 years growth and must be repeated again at different periods of time. The plashing of the hedge will make the hedge grow back stronger and thicker (Fitzherbert 1534: 80; Norden 1607: 239; Blasgrave 1669: 41-42; Smith 1670: 29; Hale 1757: 239). The stems of the trees or shrubs are cut three quarters of a way through at an angle, the stems are then plashed or pleached (meaning bent or laid) downwards and overlapped or woven with the other stems around it (Fitzherbert 1534: 80; Norden 1607: 239; Blith 1649: 156; Blasgrave 1669: 41-42; Smith 1670: 27; Barnes & Williamson 2006: 6; Wright 2016: 236-237). When plashing the hedge, upright stakes are added every 2 ½ feet to the give the laid branches structure. The plashed or laid branches can be woven around or bound to the stakes. The stakes are to be made of alder or oak to add strength (Fitzherbert 1534: 78-80; Blasgrave 1669: 38-39; Brooks & Agate 1975: 76-77). Hedges could be constructed in regional or personal styles as well, such as the Midland style, the Devon-Somerset style and the Cornish hedge to name a few (Dickson 1805: 110; Brooks & Agate 1975: 101-106; Wright 2016: 238-239).

Hedges were not always pristine, well-manicured, impenetrable walls of wood. Norden explains how he commonly witnessed hedges that have not been taken care of (Norden 1607: 240). Nourse explains that hedges have to be constantly repaired because cattle break them apart and that ‘lazy workman’ kill hedges by either staking them down or by cutting the branches incorrectly (Nourse 1700: 27, 121). Hale states that a hedge of 25 years growth will contain a lot of gaps due to the number of old stumps and shoots of young growth (Hale 1757: 239). Husbandry treatises detail techniques on mending hedges that have gaps in them by either filling them with shrubs or with earth (Fitzherbert 1534: 81; Blasgrave 1669: 43).

From an experimental standpoint, experimental firing against wooden targets to collect impact evidence could be completed by examining living wood and dead wood, as well as test firing against a variety of different species of wood. This would enable a greater understanding of wood impact evidence, and whether different species of wood, living or dead would leave different impressions on a bullet’s surface.

5.6 The Scope of Bullet Impact Evidence and the Limitations of Creating a Comprehensive Study

To complete a comprehensive series of experimental firing trials to create a reference collection of known bullets impacts with the aim of investigating bullet impact evidence is a realm of research that cannot be encompassed within one single study, but rather would constitute the dedication of a life’s work. The answer to what a bullet impacted on the battlefield could be almost limitless. Objects in the battlefield that a bullet may have impacted could include a human being, including their clothing and any gear or section of that gear that the person wore on the day of battle. This could also include, the firearm, pike, or sword that person carried, as well as armour, shoes, belts, and buckles. If the bullet missed its human target it would have impacted something else within the battlefield landscape such as a house, wall, hedge, fence, or tree, and if the bullet’s trajectory decayed and the bullet impacted the ground, there is no limit to what the bullet could have encountered. Ground conditions could include a ploughed field, with any multitude of stones, and any variety of crop types at differing stages of growth. Ground conditions could also include pasture fields and overgrown fields with unknown quantities of local vegetation. The hardness of the ground could influence the impact evidence attributed to the bullet as well. Furthermore, of all the potential target types listed above, this does not even begin to include investigating impact evidence from these same targets from varying distances and angles of impact. At this point within the research, it is not possible to be able to tell what could have an influence on the characteristics transferred to the surface of a bullet and what could not. Experimental firing to collect bullet impact evidence from ‘musket balls’ is a new realm of study that has not even reached its infancy. Filling in the gaps to our knowledgebase regarding bullet impact evidence is certainly vast in scope. Understanding the vastness and unknown potential within this realm of research is why it was decided to create a proof of concept reference collection of known bullet impacts which could be compared to bullets from the archaeological assemblages, by investigating impact surfaces that were likely either the intended or unintended targets. However, limitations arose throughout the duration of this thesis, which further hampered the experimental firing trials.

At the beginning of the experimental firing trials, two main objectives were sought, to fire outdoors in a ‘real world’ scenario and to conduct firing against human proxies, as humans were the main target on the battlefield. Outdoor firing was to include firing at long ranges to recover impact evidence of bounce and roll after ground impact on a variety of different ground conditions, as well as firing bullets through hedges and other target types and to collect the bullets in a mobile soft capture system. Ashdown house was a Ministry of Defence outdoor firing facility and used in the experiments conducted by Dave Miller in 2009. However, since then Ashdown house has been closed to commercial firing. The reasoning behind this is unknown as the author of this thesis is not privileged enough to be given the rationale behind Ministry of Defence decisions. After this, attempts were made to gain permission to fire at alternate sites outdoors but due to ‘right to roam’ one could not guarantee that someone would not wander in a field when firing was taking place and be injured or killed by a stray or errant bullet. This was the rationale behind the Ministry of Defence denying outdoor firing permission, and why all firing experiments conducted in this thesis were conducted indoors. Experimental firing with human proxies such as pigs was also sought after. However, due to the Human Tissue Act, and the resultant red tape the Ministry of Defence would not grant permission for the use of pigs on their range for this study. Ballistic gelatine and a product known as Synbone were the next steps in the attempt to create a human proxy on the firing range. However, due to the staggering cost of those materials and the recent research by Martin Smith (2015) that called into question the validity of Synbone as a human proxy (Smith *et al.* 2015), that avenue of research was abandoned.

At the outset of this thesis, two firing ranges were contacted to conduct the experimental firing trials. The first was the Ministry of Defence firing range located at the Defence Academy at Shrivenham, Cranfield University. This firing range is an ideal location, as they have access to advanced scientific equipment, a wide choice of different gunpowder's (although one can supply their own), and a very knowledgeable staff. However, the range costing can become problematic for a self-funded researcher, as commercial range time costing was £1700 a day.

The second firing range was located at the Royal Armouries in Leeds and was managed by LGC forensics, and commercial range time costing was £1200 a day. This range, while great for modern firearms is not well suited to the constant firing of black powder weapons, due to their ventilation system. The ventilation system could only handle 3 to 5 firings before a break was needed for the system to dispel the smoke. The second major issue was the space available in the range itself. To measure muzzle velocity a chronograph was present, although it could not be used in conjunction with a soft capture system that could safely capture a 'musket ball.' Consequently, firing at that location meant that either measuring muzzle velocity or soft capturing the bullet had to be sacrificed. This thesis was not willing to sacrifice either, and all firing was moved to the Ministry of Defence firing range.

The biggest question at the beginning of any experimental research agenda is what constitutes an appropriate sample size? Modern ballisticians conducting experimental firing studies state that firing 50 bullets per variable is statistically significant. From a costing standpoint, as a self-funded student, this was a major hurdle. On a normal day (9am-5pm) in the Ministry of Defence firing range only between 15 and 20 bullets could be fired and recovered using a musket and black powder. This time frame includes experimental set up, firing and loading of the musket, the recording of results, recovery of the bullet, and dismantling of the experimental set up. The recovery of each bullet from the soft capture system could take anywhere from 30 seconds, up to 30 minutes to locate. The use of handheld metal detectors was used on the range to speed up the recovery time; however, due to all the metal and lead shrapnel from years of range firing made the metal detectors useless in locating the bullet.

With that in mind, the costing issue can be better described. If one wanted to collect bullet impact evidence from two variables (X, and Y), and retain a statistically significant sample size of 50 bullets per variable, that would require 100 bullets. With the knowledge that one could fire 20 bullets per day at best, would mean one would need 5 days of range time to a total cost of £8,500, and that cost does not factor in travel cost, and other supply costs to the researcher. To a self-funded researcher, one can see how this can quickly become an issue. This costing issue was the third largest factor that turned this thesis into a proof of concept, next only to the vast scope of the research and a very serious personal health issue that befell the Ministry of Defence firing advisor for this thesis. The problems that arose because of that health issue included the non-availability of the firing range for the first year and a half of this thesis which severely limited the early stages of the experimental firing trials. During that time, other firing ranges were investigated, such as the one in Leeds, but none fit the needs of this thesis.

As mentioned in Chapter Four, a moratorium on the handling and firing of black powder on Ministry of Defence firing ranges was enacted toward the end of the experimental firing trials and a decision was made to not abandon the last of the experiments, but to create a new firing methodology that used modern nitro powder to work around this issue. The decision was made by the Ministry of Defence and applied only to Ministry of Defence firing ranges, and as stated above the reasoning behind this is unknown as the author of this thesis is not privileged enough to be given the rationale behind Ministry of Defence decisions. After the creation of the new firing methodology, and the carrying out of the first two ground firing experiments, a final moratorium was issued by the Ministry of Defence which cancelled all commercial experimental firing until further notice. This moratorium effectively ended the experimental firing trials for this thesis, and the remaining two experiments that were to explore ground surface firing on a simulated pasture field were cancelled.

5.7 Conclusion: Defining the Experimental Designs

The investigation into the tactical terrain across the battlefield landscape is a complex subject. Mentions of terrain types are hints at landscape features that a bullet may have impacted during battle but what characteristic traits were transferred onto a bullet's surface from impacting these landscape features are virtually unknown in an experimental context. Common mentions of terrain types from the Edgehill and Oudenaarde battlefields include the open landscape and enclosures.

A common mention between the Edgehill and Oudenaarde battlefield landscapes, is the most fundamental aspect, the ground. Arable and pasture fields were present on both battlefields, but the topic is more complex than it appears. Arable land could include any number of crop types in various stages of growth that should be tested for impact evidence, as well as varying levels of the stoniness of the plough soil. The experimental firing trials in this thesis will begin by examining sterile soil conditions within a simulated ploughed field. Then stones will be added to the sterile soil to begin the investigation of stone impacts on a bullet's surface. This will be completed by ricocheting the bullet from the ground surface, directly into the soft capture system that was described in Chapter Four, section 4.7. This type of experiment has never been completed using smoothbore firearms, black powder propellants and 'musket balls.' Experimental firing into pasture fields could include differing lengths of grass and associated plant material in a natural state of growth, as well as testing varying levels of ground hardness, and whether the ground conditions were dry or wet. All these variables and conditions could leave differing impact evidence on a bullet's surface. The examination of pasture fields was originally part of this thesis but was dropped from the firing trials as mentioned in section 5.6.

As seen above the term enclosure can be vague and varied which include a variety of types and species of trees, shrubs and bushes as seen in section 5.5 above. It simply is not feasible to fire at every type of hedgerow considering every year's growth. Because there is so much variation in hedgerows such as the materials, species, styles of build, thickness from one species to another based on weather, elevation, and soil conditions. The most effective method to begin experimentation is to create a baseline for future comparison. As a result, this research chose to examine general wood impacts using the most common types of species used in the construction of a hedge for a broad generalised approach for wood impact evidence.

As with any reference collection, it is important to first be able to differentiate between general overall impact evidence such as the difference between soil, stone and wood impacts before then looking to specifics. A few different species of wood, such as Oak, Hazel and Hawthorn along with coarse versus barked wood are used in the experimental trials to begin specific analysis of differing wood impacts. Along with creating a wood impact baseline for the reference collection, this research will also begin to address the question as to whether different species of wood leave differing evidence from one another. This research will also examine if there is a difference between the impact impressions from living wood or dead wood.

The experimental firing trials in Chapter Seven will be investigating not only the bullet impact evidence from the ground surface and various wooden targets but will also examine the impact of bullets at varying angles of incidence and varying velocities against the target material, this will enable a greater understanding of the bullet impact evidence. However, further investigation is needed into how to accomplish experimental firing at varying velocities within a short-range firing facility. This is the subject of Chapter Six, along with the creation of an external ballistic trajectory modelling program.

Chapter 6: Range, Accuracy and Modelling External Ballistic Trajectory

The aim of this chapter is to discuss the creation on an external ballistic trajectory modelling program that was created by this thesis to model the trajectory of a 19-bore bullet fired from a 17-bore 'bastard musket'. This was completed to enhance the experimental firing designs created in Chapter Five by allowing for an understanding of the bullet's velocity at predetermined distances. As all the firing experiments conducted in this thesis must be completed in an indoor firing range, it is otherwise not possible to fire a bullet at ranges beyond 20m. Advanced knowledge of the bullet's velocity at predetermined distances, will enable the manipulation of the gunpowder charge size given to the bullet to simulate the distance the bullet would have travelled before impacting its target, thus enabling one to investigate bullet impact evidence at all ranges within the maximum range of the musket. The proof of concept for simulating distance by manipulating the gunpowder charge size was noted in Chapter Three, section 3.8.

To complete this aim, the examination of the maximum range of a smoothbore musket must be first completed, as this will enable an understanding of the total distance in which the bullet could travel during its trajectory, which will define the total distance in which experimental firing would take place. With the maximum range of the musket established, the experimental firing designs discussed in Chapter Five can be further regimented into incremental distances, to investigate bullet impact evidence and bullet distortion levels at varying distances. In creating a reference collection of known bullet impacts, it is important to not only to collect evidence from multiple target types but to collect evidence of impact from varying distances from the same target type as this will lead to a better understanding of the impact evidence, and a greater understanding of the impact evidence noted on bullets within the archaeological assemblages.

Muskets have acquired a reputation for being inaccurate, and the second aim of this chapter is to investigate that inaccuracy by examining previously completed research. If experimental firing is to be conducted to create bullet impact evidence from all ranges within the maximum range of the musket, then the inaccuracy of the musket must be overcome. The third goal of this chapter is to conduct a firing experiment using the experimental firing methodology created in Chapter

Four to generate a data set that can be used in the creation of an external ballistic trajectory modelling program. As previously noted in Chapter Two, section 2.3, to create the modelling program, one must understand the forces acting on the bullet during flight, and this modelling data set will be created by experimentally discovering the drag coefficient of a 19-bore bullet. This modelling program can be used to reconcile the inaccuracy of smoothbore muskets by modelling the trajectory of its bullet. Finally, this chapter will discuss the limitations of the external ballistic trajectory modelling program.

6.1 Smoothbore Musket Range and Accuracy

To explore the impact of bullets, the investigation of the accuracy and range of muskets must be examined. The range in which a bullet was fired is directly proportional to the velocity of the bullet on impact. The accuracy of a musket must also be explored to ensure that the bullet impacts the target every time during the experimental firing trials, regardless of the range in which the bullet is fired.

The inaccuracy of smoothbore muskets, firing a spherical lead bullet at medium to long ranges; that is any range beyond 75m is well established (Hanger 1816: 205; Neuman 1967: 2, 5, 14; Hughes 1974: 26; Krenn *et al.* 1995: 105; Nafziger 1996: 32; Babits 1998: 13; Muir 1998: 71; Mandzy 2012: 71; Greener 2013: 624). Beyond 137m, smoothbore muskets become almost ineffective due to poor accuracy and bullet drop (Hanger 1816: 205; Neuman 1967: 14; Babits 1998: 13; Willegal 1999). As Neuman (1967) states, that almost no smoothbore muskets were equipped with rear sights, which should be a good indication of what they expected in terms of accurate fire (Neuman 1967: 14). However, this distance could change from nation to nation and varied with battlefield conditions, such as terrain and weather. The typical engagement distance for battle remained relatively constant throughout the early modern period.

In the late 16th to the early 17th centuries, Roberts (2010) states that infantry lines would begin to fire upon their enemy at 91m to 183m, but says nothing in regards to the accuracy of that fire (Roberts 2010: 39). William Roger (1590) also explains that firing would take place between

46m and no further than 183m (Roger 1590: 37). By the time of the American War of Independence (1775-1783), the typical engagement distance in linear battlefield tactics remained around 46m to 91m.

This was due to the accuracy of the firearms in use. The average musket was accurate beyond 73m and was relatively ineffective against massed soldiers past 137m (Neuman 1967: 14). Greener (1881) states that muskets of the 18th and 19th centuries could hit a target the size of a man at 91m, a volley of bullets had a chance to hit a massed infantry formation at 183m, and that a bullet was no longer lethal at 274m (Hughes 1974: 26; Greener 2013: 624). Experimental firing work done by Picard (1800) demonstrates this inaccuracy at ranges over 75m (Hughes 1974: 27). See table 6.1 below.

Range (m)	Percentage of shots hitting the target
75m	60%
150m	40%
225m	25%
300m	20%

Table 6.1 Range and percentage of shots hitting the target, reproduced from Hughes (1974:27).

Hanger (1816) states that the British Brown Bess smoothbore musket could hit a man-sized target at 73m, but it may have only been able to hit the same target at 91m. A man had to be unfortunate to be hit by a bullet at 137m, and that past 183m, no man had ever been killed with a bullet (Hanger 1816: 205). A series of experiments conducted by the Prussian army using a British made musket during the Napoleonic wars found that hitting a target the size of a man at 73m was only possible 47% of the time (Nafziger 1996: 32; Mandzy 2012: 71). During the Napoleonic wars, the British would begin firing their muskets between 70m to 91m (Muir 1998: 81; Mandzy 2012: 72).

The Graz firing experiments (Chapter Three, section 3.1) seems to confirm the Prussian experimental results. The Graz experiments performed range and accuracy tests by firing the firearms at rectangular shaped paper targets roughly 167cm x30cm and measured the scatter pattern of bullets passing through the targets at ranges of 100m for muskets and rifled muskets and 30m for pistols. The results show that the accuracy of all smoothbore firearms was just above 50% (Krenn 1991: 36; Krenn *et al.* 1995: 103-105). The estimated maximum range of the muskets in the Graz study was concluded to be anywhere from 834m to 1,279m, if the musket was fired at a 60° elevation (Krenn 1991: 38; Krenn *et al.* 1995: 105). Krenn never explained how the distance was calculated, but firing a musket at a 60° elevation more than likely never happened on the battlefield during combat as it is extremely impractical. A more pragmatic firing experiment conducted by Miller (2009) demonstrated the range of a musket when fired from a 0° to 5° elevation as previously discussed in Chapter Two, section 2.4.1.2. Miller demonstrated that a bullet fired from a 0° to 5° elevation travelled, unimpeded between 169m to 629m depending on the angle of elevation of the barrel (Miller 2009: 120). Furthermore, Miller determined with long distance experimental firing that the average distance a 12-bore bullet would travel when fired at a 0° elevation, 1.39m height from the ground surface, before impacting the ground is roughly 172m (Miller 2009: 124-149). If bullets fired from muskets in the early modern period could travel beyond 200m, as seems suggested by the literature, it appears that they were firing at an unspecified angle of elevation. However, if this distance was possible in the early modern period from a 0° elevation, it has not been reproduced thus far through experimental firing.

6.1.1 Smoothbore Musket Range and Accuracy Discussion

After the investigation into the accuracy and range of smoothbore muskets, a pattern begins to emerge. This pattern does seem to fit for the whole of the early modern period. The recommended engagement distance in which to begin firing at the enemy is between 46m to 91m if one planned on hitting someone with relative certainty. However, it does not seem to be out of the ordinary to fire at the enemy as far as 137m to 183m, while there is less than chance probability of hitting anyone. Engaging the enemy beyond 183m was almost futile, as the experimental firing results from Miller suggests that the bullet’s trajectory would have decayed at this point and the bullet would have impacted the ground.

This raises an important question from an experimental standpoint, how can a bullet be fired into a target at 150m without missing 60% of the time? If long distance musket firing is largely inaccurate, how can this be reconciled while maintaining correct, comparable velocities at all distances while ensuring every bullet impacts the target? The answer can be found by using an external ballistic trajectory modelling program.

6.2 External Ballistic Trajectory Modelling

External ballistic trajectory modelling has existed since at least 1742, as Robins' (1742) experiments with the ballistics pendulum was the beginning. Hutton (1778) expanded and refined Robin's ballistics pendulum (Hutton 1778), and later Bashforth (1865) conducted a series of firing experiments with cannons to determine the aerodynamic drag of a cannon ball. Bashforth determined that to properly measure the projectile's variations in velocity with distance was to determine how long it took the cannon ball to travel in between equally spaced points; however, he determined that the Bashforth chronograph was ineffective at recording these points (Bashforth 1870). A later study by Miller and Bailey (1979) confirmed and expanded upon Bashforth's results, and furthermore, they noted that intermediately sized spheres (smaller artillery than Bashforth tested) carried unexpectedly further than musket bullets, even when the experiments were properly scaled down (Miller & Bailey 1979).

While the modelling of external ballistic trajectory to discern the origin of firing positions in relation to battlefield archaeological bullet finds has met with reasonable success using conical bullets (Athanson 2010), a sphere is a 'bluff body' as opposed to the streamline conical bullet and the drag on a sphere is heavily influenced by its cross-section as noted in Chapter Two, sections 2.33 and 2.35. The drag a sphere experiences is due to the roughness of its surface, so a smooth sphere will experiences more drag than a sphere containing a rougher surface; this is the same reason that golf balls have dimpled surfaces (Compton 1996: 36-37).

Most experimental firing trials conducted and supervised by Dr Derek Allsop at Cranfield university between 2006-2011 sought the use of external ballistic trajectory modelling programs for a multitude of reasons. As an interesting caveat before proceeding further: computer programs designed to model the trajectory of a bullet cannot account or correct for every single variable that can happen during the bullet's flight, therefore computer modelling programs can never be 100% accurate (Kisak 2014: 74). Eyers (2006) sought to use a modelling program to discern the origin of soldier firing positions on the battlefield based on the location of the bullet found during an archaeological survey. Roberts et al (2008) sought to find the terminal velocity of a bullet at certain ranges by discovering its muzzle velocity and, Miller (2009) sought to predict long distance firing and velocity of the bullet at ground impact (Eyers 2006; Roberts *et al.* 2008; Miller 2009). What all of these studies have in common is that they model their musket bullet data sets off of Braun's (1973) experimental results based on recording the drag of a perfect sphere (Braun 1973). All of these studies make the same statement of justification that the drag coefficient against Mach number for a perfect sphere has already been experimentally defined by Braun in his 1973 study (Eyers 2006: 29-30; Allsop & Foard 2008: 119-120; Clarke 2008: 54-55; Roberts *et al.* 2008: 9-10; Miller 2009: 48-49). However, the following statement from each of these studies is that a musket bullet suffers deformation during the firing process which changes its shape considerably from that of a perfect sphere and that their predicted data sets collected from their modelling programs will, as a result, be wrong, by saying that the bullet will cover less distance and produce more drag than Braun's data predicts (Eyers 2006: 29-30; Allsop & Foard 2008: 119-120; Clarke 2008: 54-55; Roberts *et al.* 2008: 9-10; Miller 2009: 48-49).

Braun did in fact experimentally discover the drag coefficient against Mach number for a perfect sphere, and a reproduction of his results can be found in figure 6.1 below. As previously stated in Chapter Two, section 2.3, to predict the trajectory of a bullet, the relationship between the bullet's coefficient of drag and Mach number must be known (Moss *et al.* 1995: 81). This is done by graphing coefficient of drag versus the Mach number of a bullet during its flight.

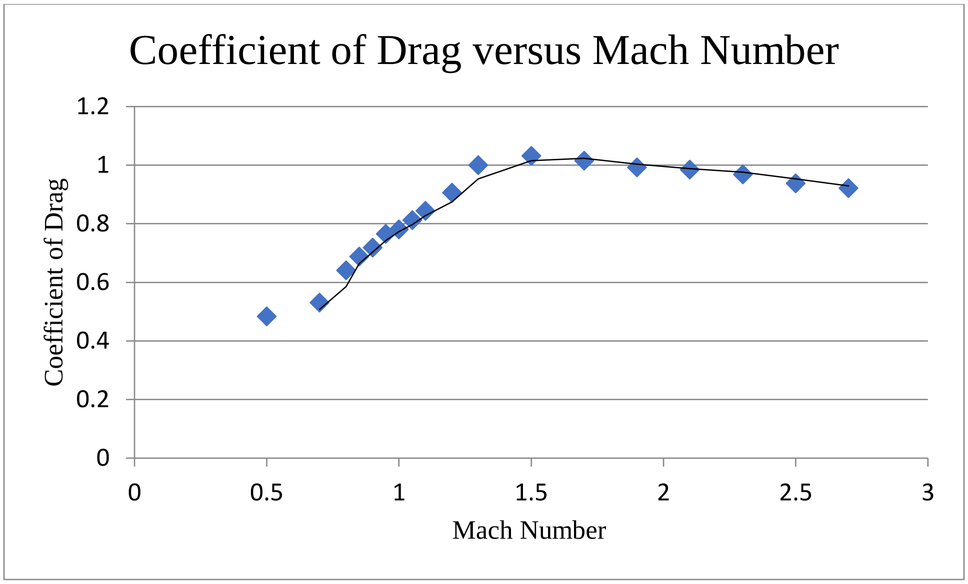

Figure 6.1: Drag coefficient against Mach number for a perfect sphere, from (Braun 1973).

The problem with using Braun's data set is exactly what the previous studies claimed, that upon firing, a musket bullet loses its spherical shape, therefore the two data sets are not directly comparable. A perfect sphere has the same body proportions on both sides of its axis (Compton 1996: 36-37), whereas a musket bullet is in fact never a perfect sphere, and to go one step further, deformation from firing is just the end of its spherical appearance. When all of the possible manufacture flaws are taken into account, such as how much of the casting sprue was left attached, how much flashing occurred and remains on the bullet and how well cast the bullet was, just adds to the point that a musket bullet is not a perfect sphere. All of these variables will add to the drag of the bullet during flight, and all of these variables are not considered in Braun's study because Braun was using a perfect sphere, not a musket bullet.

A round ball ballistics calculator for muzzleloaders can be found on the internet (http://www.ctmuzzleloaders.com/ctml_experiments/rbballistics/rbballistics.html). The website claims that the ballistic calculator can simulate and analyse the behaviour of a 'round ball' musket bullet during its flight, from the muzzle straight to the target (Anonymous). There is a simple input centre where all the information needed is entered to model the trajectory of a bullet. Once the desired parameters are input, the program simulates the flight behaviour of the musket bullet and gives the results for velocity, distance, bullet drop and other variables.

However, after continued reading into how the data set was formed some immediate concerns begin to rise. First, the data set is based on 20th century British artillery firing round nosed, one to three-pound projectiles. An assumption is made in their data set that the back end of a round nosed bullet will produce the same amount of drag as a small arms musket bullet that weighs considerably less. The usage of the phrase *'The trick is then to find (or guess) the relationship of the bullet you are interested in to the reference projectile'* is concerning, to say the least. As is the usage of words and phrases such as *'close enough'*, *'fudge factor'* and any mention of *'I performed measurements'* without discussing them in further detail (Anonymous).

There clearly is an issue with using the existing external ballistic trajectory modelling programs for smoothbore muskets and the spherical bullet as seen above. The only way to answer this question definitively is by experimentation, which was completed as the second experiment in this thesis and can be found below.

6.3 Experimental Purpose

The aim of this experimental firing trial was to create a method of firing that could reconcile the inaccuracy of smoothbore muskets at medium to long ranges by modelling the trajectory of spherical bullets. Not satisfied with current modelling programs that are based on Braun's perfect sphere data sets, or nebulous online round ball calculators, it was decided to conduct an experiment where the drag coefficient for a 19-bore (24g) bullet would be experimentally discovered. This was completed by firing twenty-one bullets unimpeded down range and recording their velocity at predetermined time steps using Doppler radar. This method for discovering the drag coefficient of a bullet was first created by Bashforth as noted in section 6.2 above and is still used in modern ballistics today in absence of a wind tunnel (Champion 2015 *pers. comm.* 15 May 2015). The mathematical data sets (found in appendix 2A-2B) represents the supersonic, transonic and subsonic effects of drag on the bullet that was collected by the Doppler radar. The mathematical analysis of this data set allowed the modelling program to be populated with the bullet's drag data that allowed for external ballistic modelling of the bullet's trajectory. This was completed to 'shorten' the firing distance from the firearm to the target without sacrificing impact accuracy and potency while being able to examine the bullet's impact at different velocities.

Since the firing range was 20m in total distance, the experiment had to vary the initial velocity of the bullet to cover all potential velocities of the bullet along the Mach curve. Mach is the ratio of the bullet speed to the local area speed of sound (Moss *et al.* 1995: 69-70; Allsop & Foard 2008: 119; Denny 2011: 88). The Mach curve shows the relationship between the Mach number and the coefficient of drag throughout the bullet's flight. It's important to understand these relationships to properly model a bullet's trajectory and therefore understand how to mimic longer distances and varying velocities to inform future experiments.

This means that only firing a bullet at a full charge of 12g would continuously give the same readings. By changing the gunpowder charge size, the bullet's behaviour could be observed at lower velocities than a 20m range would normally allow. The raw data collected by the Doppler radar, which can be found in appendix section 2A, was mathematically analysed using the following formulas: acceleration, drag force, then coefficient of drag. More information on these formulas can be found in appendix section 1A-1F, along with their results in appendix section 2B. This collected raw data was used to build a data set to generate the coefficient of drag for a 19-bore bullet that was then input into a computer modelling program. With these formulae, range and velocity can be modelled by adjusting charge size, regardless of the weapon system.

6.3.1 Materials and Methods

The experimental firing work was conducted at the Defence Academy at Shrivenham, Cranfield University. Firing took place in the Enfield Small Arms Experimental Range (No 3 Range), under the guidance of Mr Dave Miller and Mr Steve Champion.

The diameter measurements and weights of all bullets were taken and tabled before firing to inform ballistic equations post firing. A reproduction 17-bore matchlock musket with a 41inch barrel was loaded with a predetermined amount of TS2 black powder (12g to 1.5g charge), firing a 19-bore bullet (24g). The musket was fixed to a universal gun mount at a horizontal firing height of 1.39m at 0° elevation parallel to the ground. The musket was remote fired using an ISFE 9-volt electric match to prevent human error. Doppler radar was used to measure the time and velocity of each bullet during flight. The data was collected by firing a bullet down range into a sand embankment. The Doppler radar measurements began with an initial measurement (muzzle velocity), then in 10 millisecond intervals until the bullet reached the sand embankment at the end of the firing range. The data was recorded in metres per second. 21 bullets were fired down range and allowed to hit the sand embankment to measure the entire flight path for each bullet. No attempt was made to collect the bullets. The musket set up, along with the Doppler radar can be seen in figures 6.2 and 6.3.

Figure 6.2: 17-bore musket on the mount with Doppler radar.

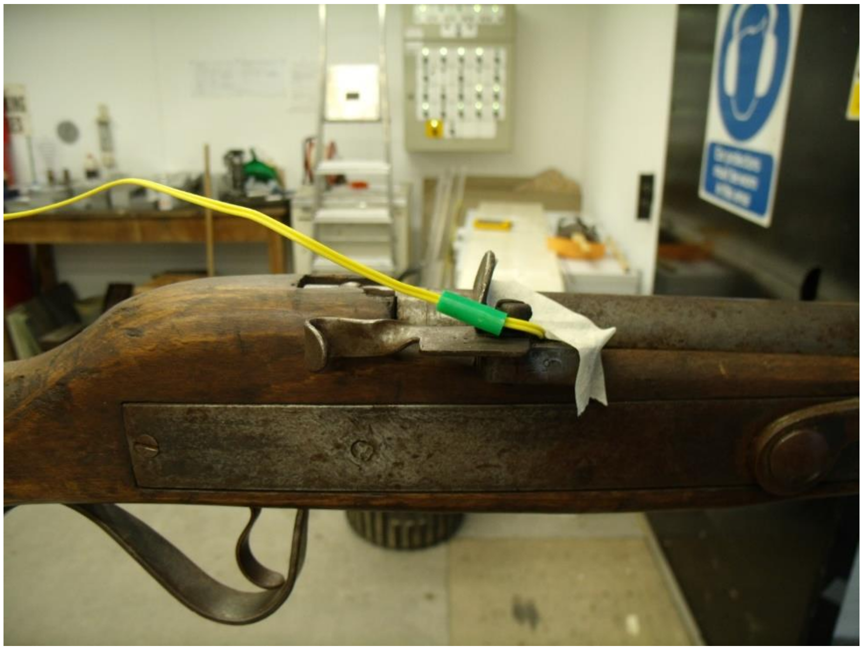

Figure 6.3: Musket with an electric trigger.

A More exact method during firing:

1) Set up musket on universal mount with a horizontal firing height of 1.39m at 0° elevation parallel to the ground

2) Weigh out powder and priming powder

3) Clear touch hole of fouling

4) Pour powder into muzzle using a funnel

5) Roll the ball in, giving a light tap with a ram rod to ensure bullet is seated properly

6) Put musket on universal gun mount, tighten mount

7) Put in priming powder into the flash pan

8) Attach electric trigger to flash pan, use a small amount of tape to keep in place

9) Retreat to the bunker, arm Doppler radar, remote fire

10) Look at Doppler radar for velocity and time data

11) Repeat

6.3.2 Results

An example of the results recorded from the Doppler radar can be seen in table 6.2 below, along with the bullet's weight, diameter measurements and SI unit conversions that were needed for ballistic equations. The remaining results from all 21 bullets fired can be found in appendix section 2A.

Bullet 1 Bullet weight: 24.18g Bullet weight (kg): 0.02418kg Mean Velocity: 440.33m/s	Charge weight: 12g Bullet Diameter 90°: 16.26mm Bullet Radius: 8.13mm Bullet Radius (m): 0.00813m
Time Step (ms)	Velocity m/s
5ms	457m/s
10ms	456m/s
20ms	447m/s
30ms	434m/s
40ms	426m/s
48ms	422m/s

Table 6.2: Doppler radar data recorded from bullet 1.

The results from the Doppler radar are then input into the following formulae: acceleration, drag force, and coefficient of drag, a further explanation of calculations can be found in appendix section 2B. Table 6.3 below is an example of the resultant data sets from the formulae from bullet 1.

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	Coefficient of Drag
457	456	0.01	100	2.418	0.09294244
456	447	0.01	900	21.762	0.840154765
447	434	0.01	1300	31.434	1.262916905
434	426	0.01	800	19.344	0.824436097
426	422	0.008	500	12.09	0.534807239

Table 6.3: Example of formulae results from Bullet 1.

The graphed math results found in figures 6.4, 6.5 and 6.6 can be found below and are for a visualisation to verify that the math results were correct.

6.3.2.1 Velocity versus Time

Figure 6.4; found below, demonstrates the relationship between velocity and time. As time increases, velocity decreases. All graphed bullets were fired with a full 12g charge size.

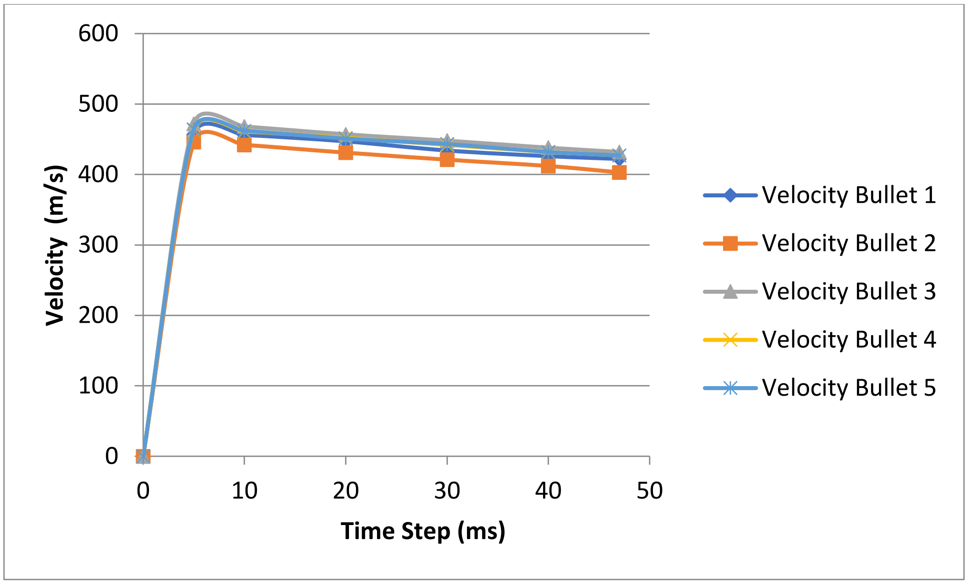

Figure 6.4: Bullet velocity versus time. All bullets have a 12g charge.

6.3.2.2 Acceleration versus Time

Figure 6.5 found below shows the bullet's acceleration versus time. The bullet will continue to slow during its flight, but the rate of change in the acceleration (or deceleration in this case) changes. The forces acting on a bullet during its flight are aerodynamic drag and gravity. Drag substantially affects the bullet's velocity, and the higher the velocity of the bullet, the higher the amount of total drag (Moss *et al.* 1995: 71); this was previously discussed in Chapter Two, section 2.3.

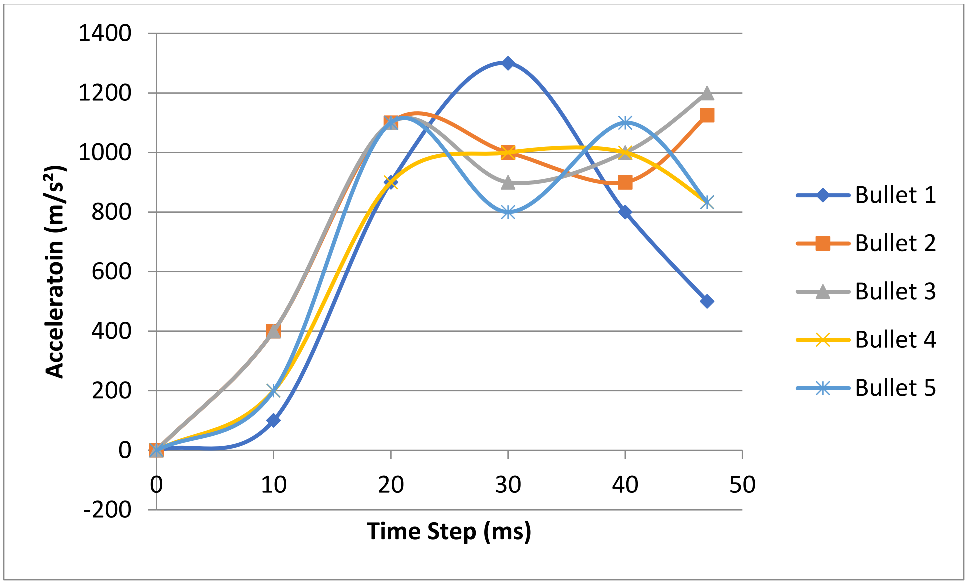

Figure 6.5: Bullet acceleration versus time. 12g charge.

6.3.2.3 Coefficient of Drag versus Time

The Coefficient of Drag of the bullet is the total drag force that is applied to the bullet during its flight (Moss *et al.* 1995: 79). The coefficient of drag appears very similar to the acceleration of the bullet. This is due to the same types of drag affecting the bullet during its flight. Below, figure 6.6 shows this relationship.

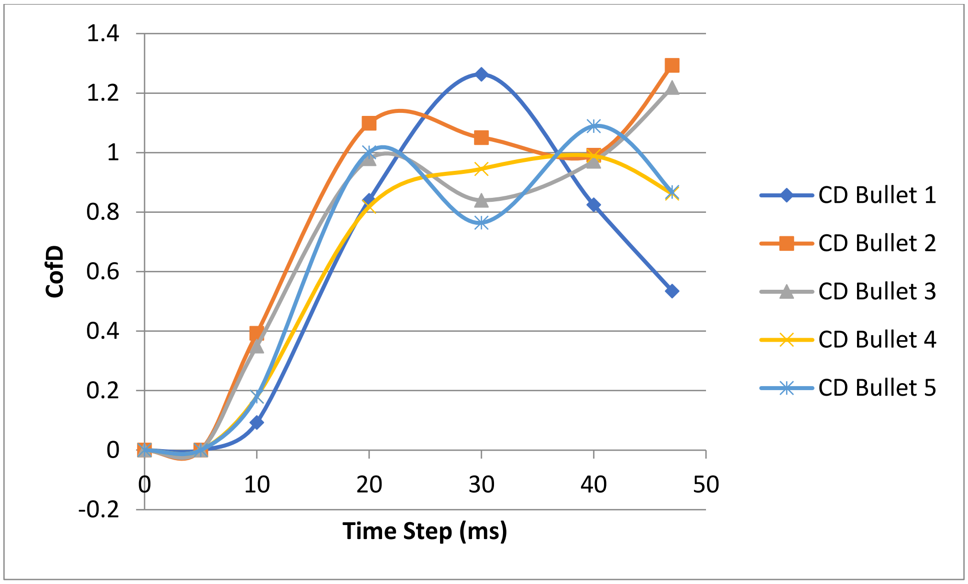

Figure 6.6: Bullet Coefficient of drag versus time. 12g charge.

6.3.2.4 Mach Number and Coefficient of Drag

The data collected from the Doppler radar once mathematically analysed places points on the spherical bullets coefficient of drag curve in relation to its Mach number. So, at a Mach number of 0.5, a 19-bore bullet will have a coefficient of drag of 0.435. At a Mach number of 1.0, the coefficient of drag will be 0.7. Eventually, it builds a table like the one seen in table 6.4 below.

Mach Number	Coefficient of Drag
0.335	0.44
0.575	0.435
0.68	0.37
0.78	0.45
0.84	0.915
0.955	1.36
1.045	0.715
1.14	0.705
1.25	0.99
1.345	0.725

Table 6.4: Mach number and Coefficient of Drag.

Once the table is completed the data can be used to create a graph of the coefficient of drag curve as seen in figure 6.7 below. In order to predict the trajectory of a bullet, the relationship between coefficient of drag and Mach number must be known (Moss *et al.* 1995: 81). This is done by graphing coefficient of drag versus the Mach number of a bullet during its flight.

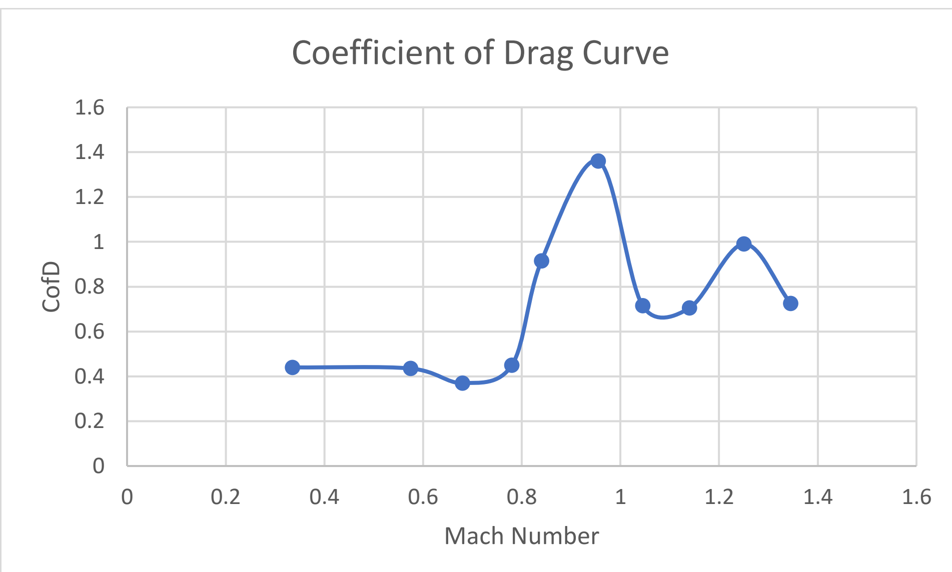

Figure 6.7: Coefficient of drag curve for a 19-bore spherical bullet.

From this drag curve, an external ballistic calculator can be used to calculate the velocity of a bullet at a predetermined range. The results from the formulae are then input into a computer modelling program originally designed by Mr Steve Champion at the Defence Academy at Shrivenham, Cranfield University to model the trajectory of NATO 7.62mm bullet. The results of the ballistic equations are then input in the computer modelling program to update the model for spherical bullets by removing the data sets belonging to the NATO 7.62mm bullet. This is necessary because the aerodynamic forces acting on a spherical bullet (drag and air resistance) are quite different than those for a conical NATO 7.62mm bullet. By imputing the results into the modelling program, the velocity and theoretical distance of a bullet can be determined at different moments in its flight path.

Table 6.5 and figure 6.8 below is an example of the information that can be collected from the computer modelling program. This figure shows the velocity of six bullets at theoretical ranges. Note that the charge size changed from one bullet to another to show variation in velocity at differing distances and to demonstrate the concept that adjusting charge size of the gunpowder can bring about a change in velocity of the bullet.

Bullet Number- Weight (g)/ Diameter (mm)	Charge Size	0m (muzzle velocity)	25m	50m	75m
Bullet 1- 24.18g/ 16.26mm	12g	457m/s	407 m/s	371 m/s	335 m/s
Bullet 13- 24.08g/ 16.24mm	10g	443m/s	398m/s	362m/s	318m/s
Bullet 9- 24.23g/ 16.25mm	9g	392m/s	355m/s	307m/s	275m/s
Bullet 14- 24.21g/ 16.28mm	7.5g	333m/s	284m/s	265m/s	251m/s
Bullet 17- 24.26g/ 16.26mm	5g	278m/s	261m/s	248m/s	236m/s
Bullet 20- 23.97g/ 16.19mm	3g	200m/s	188m/s	176m/s	164m/s

Table 6.5: Velocity of bullets at theoretical ranges with different charge sizes

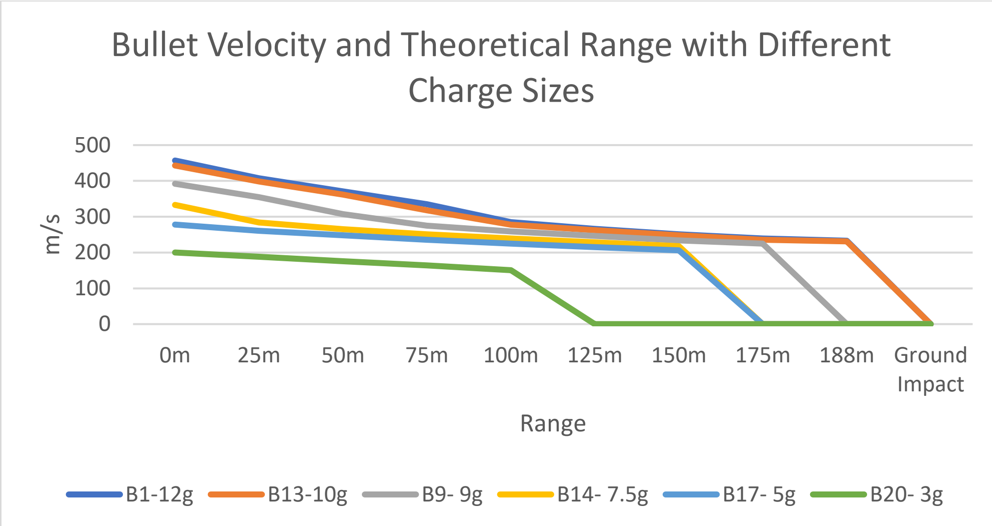

Figure 6.8: Velocity of bullets at theoretical ranges with different charge sizes.

Figure 6.9 below demonstrates an example of the information that can be collected from the computer modelling program. This figure shows the velocity of five bullets at theoretical ranges all fired with a 12g charge. Note that bullets fired with the same charge size can have slight variation in their velocity. This variation is due to variables that cannot always be controlled, such as the bullet weight and shape from one cast bullet to another, and the inconsistent burn rate of black powder.

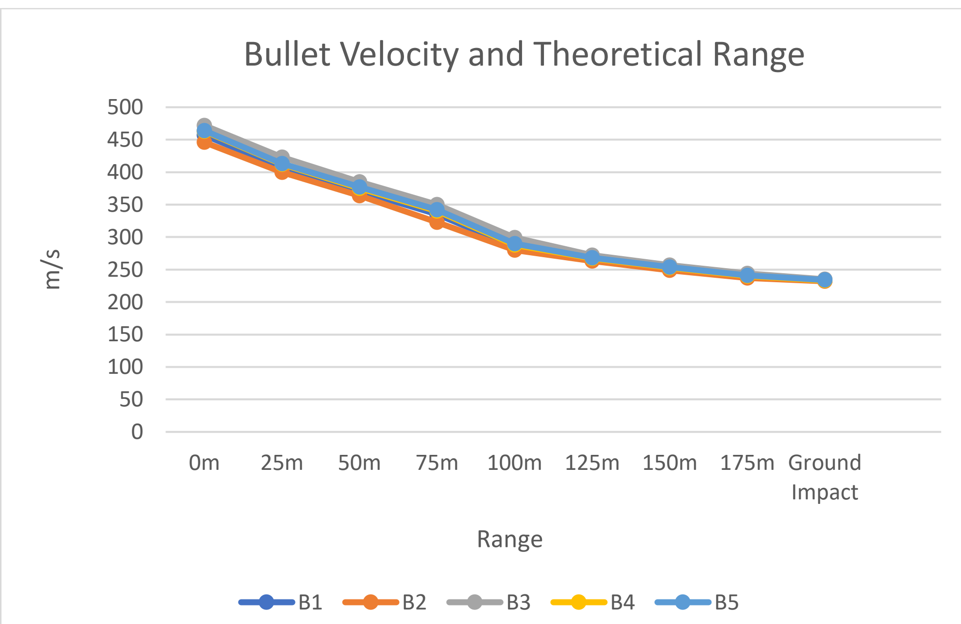

Figure 6.9: Velocity of bullets fired using a 12g charge size at theoretical ranges.

6.3.3 Discussion

All bullets fired with a full charge (12g) were tabled, as can be seen in appendix section 2C. All bullet weights, diameters, and muzzle velocities were added. Each of these bullets was then input into the19-bore external ballistic trajectory calculator. Bullet velocity was recorded every 25m until the bullet impacted the ground. Distance and velocity at ground impact were recorded as well. This information was then averaged to create an ideal 19-bore bullet. The averaged bullet was then input into the computer modelling program and the bullet's velocity was recorded at 25m intervals. This information will serve to determine distance for each bullet fired in the following experimental firing trials. See table 6.6 below for the averaged bullet model.

Bullet Number- Weight (g)/ Diameter (mm)	Charge Size	0m (muzzle velocity)	25m	50m	75m	100m	125m	150m	175m	Ground Impact Distance and Velocity
[redacted]										
Model of Averaged Bullet- 24.18g/ 16.24mm	12g	467m/s	416 m/s	380 m/s	345 m/s	293 m/s	269 m/s	255 m/s	242 m/s	191m@ 234 m/s

Table 6.6: Model of averaged bullet at 25m intervals.

Long distance experimental firing by Miller (2009) demonstrated that a 12-bore musket bullet fired from 0° elevation would impact the ground at close to 230m/s, between 150m to180m down range (Miller 2009: 145), the above table 6.6 and all bullets fired with a full 12g charge (appendix section 2C) show that the average 19-bore bullet should impact the ground close to 191m from the muzzle of the firearm at 234m/s. These computed results are a close fit with Miller's experimental results and therefore give a degree of confidence in the modelling program. There is an added 20m of total distance travelled by the 19-bore bullet over the 12-bore bullet used by Miller. This could be the result of the smaller bullet used in this thesis. A smaller bullet should create less drag, but the total amount of drag experienced by the 12-bore bullet is currently unknown and thus there is no comparable data. This could also reflect drag and resistance variables that cannot be controlled or simulated as Miller's experimental firing was conducted at an outdoor range and the experiments conducted by this thesis were in an indoor range. Furthermore, the results in table 6.6 will assist in determining the range for all bullets fired during the experimental firing trials found in Chapter Seven, as will be discussed in further detail in section 6.4 below.

In section 6.2, there was a discussion over the issues of using both the Online BC calculator and the Braun (1973) perfect sphere data set to model the trajectory of a musket bullet. Instead of dismissing both Braun's data set and the online BC calculator outright, a comparison was run between the three data sets, including the 19-bore modelling data set created by this thesis to explore how the results would compare.

The information input into each modelling program was the same, although conversions had to be made as not all units of measurement were the same for each program:

Muzzle Velocity- 457m/s Calibre- 16.26mm

Bullet weight- 24.18g Sight height- 10mm

Temperature 23°C

Data Set	0m	25m	50m	75m	100m	125m	150m	175m	200m

Online BC Calculator	457m/s	396m/s	349m/s	320m/s	300m/s	281m/s	265m/s	251m/s	237m/s
Braun (1973) data set	457m/s	408m/s	368m/s	335m/s	308m/s	284m/s	263m/s	246m/s	231m/s
19-Bore Modelling Program	457m/s	410m/s	377m/s	345m/s	298m/s	273m/s	259m/s	246m/s	235m/s

Table 6.7: Comparison of modelling data sets.

The results from each of the programs are relatively different. The online BC calculator's data set comes from a round nose artillery bullet. Braun's data set comes from experimental results involving a perfect sphere. The 19-bore modelling data set that was collected experimentally in this thesis and was specifically for and from multiple 19-bore bullets flight behaviour. The initial decay of the online BC calculator and Braun is quicker, although there is no significant difference. However, once the bullets' velocity drops below the speed of sound (340m/s) there is a greater deceleration on the 19-bore musket bullet when compared to the perfect sphere. Once the bullets reach subsonic, the 19-bore bullet slows less rapidly than the perfect sphere. The 19-bore bullet will have a more complicated shock pattern when traversing the speed of sound and therefore have a higher drag force, but at subsonic, the imperfect surface of the 19-bore bullet will reduce the drag as mentioned in section 6.2, when discussing the example of a golf ball.

6.4 Modelling Program Limitations

Initially, the 19-bore trajectory modelling program was created to establish a regimented, rigorous experimental firing methodology, along with solving the issue of musket inaccuracy. The original desire was to create a series of points of know velocities at 25m intervals, to investigate how well impact evidence could be determined. If multiple bullets impacted the same surface but from different distances, could one be able to determine the distance based on the impacted bullet? Then, to experimentally establish what gunpowder charge size would correspond with that distance. For example, if one wanted to collect impact evidence at a specific target that was located 50m from the muzzle of the firearm, all one had to do was load the firearm with a 9g charge of gunpowder, which would give a velocity reading equivalent to a bullet having covered 50m, or a 380m/s impact velocity. This can be seen in table 6.6 above.

However, what was not considered was the variability of velocity readings when using the same gunpowder charge size. This issue arose from the inconsistency of the burn rate of black powder. As inconsistent readings from the same charge size could not be reconciled, it was decided that the gunpowder charge size would be regimented instead, as will be seen throughout Chapter Seven. After each bullet was fired and soft captured, the known velocity data would be input into the modelling program and the modelling program would then inform of the distance the bullet would have travelled before impacting the target. The purpose of this was to establish if there was a correlation between impact velocity or distance travelled by the bullet and the distortion level of the bullet on impact, as well as the varying bullet impact evidence with distance. This discussion will be further examined in Chapter Seven of this thesis. The charge sizes chosen for each experimental firing trial was varied, but attempts were made to make them as consistent as possible. The choice of charge sizes came to reflect the limitations within the burn rate of black powder, and not with the modelling program. All experimental firing trials charge sizes were chosen to simulate distance along the maximum range of the musket, this will be seen in more detail throughout Chapter Seven.

6.5 Conclusion

The purpose of this chapter was to examine the range and accuracy of smoothbore muskets and then to create an external ballistic trajectory modelling program to reconcile musket inaccuracy. With this knowledge, a more rigorous and regimented experimental firing trial can be implemented. Knowledge of the maximum firing range of a musket was determined to be just over 172m according to experimental firing conducted by Miller. What this means for the experimental firing trials is that each target type chosen in Chapter Five, section 5.7, will be tested at varying distances to investigate bullet impact evidence more closely.

Sources state that the accuracy of early modern muskets at medium to long ranges; that is any range beyond 73m to 91m, that one would have a chance probability of hitting the target being aimed at. This knowledge has profound implication for the experimental firing trials when considering collecting impact evidence at predetermined points along the musket's maximum range. In order to investigate impact evidence at medium to long ranges, the inaccuracy of the musket was overcome with the creation of an external ballistic trajectory modelling program that was created by using data collected from firing experiments originated in this thesis.

The purpose of the firing experiment was to record the flight behaviour of a 19-bore bullet using Doppler radar. The resultant data was collected from predetermined points along the bullets flight path. This enabled mathematical analysis and the resultant data was input into the computer modelling program. The modelling program can predict a given velocity at a given distance. This provides valuable insight into accomplishing accurate firing by enabling the prediction of the bullet's distance and velocity at predetermined points. As gunpowder is the propellant of the bullet and influences its trajectory, it can, therefore, be manipulated in charge size to mimic target distances and velocities based on the modelling data. This means that by changing the charge size of the gunpowder, a shorter distance and a lower velocity can be mimicked without sacrificing impact accuracy and velocity.

This experiment has laid the ground work for the experimental firing trials, which is the subject of the following Chapter Seven. The experiment above also represents the first time that an external ballistic trajectory modelling program was created for the purpose of modelling 'musket balls' and is the first time that the drag coefficient of a 'musket ball' has been discovered experimentally.

Chapter 7: Proof of Concept Experimental Firing Trials

The purpose of the proof of concept experimental firing trials is to create a reference collection of known bullets impacts. This reference collection will then be used for comparative analysis against the archaeologically recovered bullet assemblages from the Edgehill and Oudenaarde battlefields in Chapter Eight. The bullets were examined for impact evidence using the bullet impact analysis methodology discussed in Chapter One (section 1.5).

To compete this, an experimental firing methodology had to be created as seen throughout Chapter Four of this thesis. The firing methodology was created after having first identified specific variables using internal ballistics from Chapter Two (section 2.1) and previous firing experiments from Chapter Three. This data was used to lay a foundation on which the experimental firing methodology was built. This experimental firing methodology was used throughout the experimental firing trials, with some slight and unexpected changes as will be noted below.

The next step was creating a series of experimental designs that were in accordance with common landscape features that best reflected the reconstructed historic landscape from both the battlefields of Edgehill and Oudenaarde. As discussed in Chapter Five, both battles were examined with specific attention being paid to the tactical terrain and the overall landscape in which the battles were fought. In doing this it was discovered that the most common landscape features in both battles were the ground surface and hedged enclosures. Due to the variability of the ground surface and hedgerow species, type and construction, it was decided that the best course of action was to begin by creating a baseline for future comparison. The experimental firing trials will examine wood impact evidence on the bullet's surface from three species of wood, as well as comparing the evidence collected from living and dead wood. The experimental firing trials will also examine the transfer of surface characteristics from the bullet's impact with the ground surface, first in the form of a simulated ploughed field with sterile soil and secondly with a simulated ploughed field with the inclusion of stones.

The experimental firing methodology and the experimental designs were further bolstered by the examination of musket range and accuracy, as well as the creation of an external ballistic modelling program as discussed in Chapter Six. However, as noted in Chapter Six the original methodology of firing in 25m intervals was not plausible due to the variable burn rate of black powder. Instead, charge sizes were chosen for each experiment that would range from a full charge of 12g to a 1.5g charge size to simulate the firing distances along the maximum range of the musket. This was completed to investigate impact evidence along the range of the musket and to examine impact evidence and distortion levels between the velocity of the bullet and the target at impact. Muzzle velocity and terminal velocity were recorded for every experiment, and that velocity data was input into the modelling program to inform the experiment of the distance simulated during the experiment. Further rationale will be discussed before all experiments. The experimental designs will examine bullet impact evidence fired from varying distances from point blank range to the maximum range of the musket, this will be completed by manipulating the gunpowder charge size imparted on the bullet to simulate distance. This chapter encompasses both the experimentation and the results from the proof of concept experimental firing trials.

7.1 Experimental Materials, Loading and Firing Procedure

The experimental materials and the loading and firing procedure will be the same for all experiments listed below, unless otherwise stated. The diameter measurements and weights of all bullets were taken and tabled before firing to inform bullet analysis post firing and to investigate bullet weight loss due to the firing and impact process. The experimental firing was conducted at the Defence Academy at Shrivenham, Cranfield University. Firing took place in the Enfield Small Arms Experimental Range (No 3 Range), under the guidance of Mr Steve Champion and Mr Dave Miller.

A reproduction 17-bore musket with a 41inch barrel was loaded with a predetermined amount of TS2 black powder (12g to 1.5g charge in various increments) and fired a 19-bore bullet (24g). The musket was fixed to a universal gun mount at a horizontal firing height of 1.39m at 0° elevation parallel to the ground. The musket was remote fired using an ISFE 9-volt electric match to prevent human error. Doppler radar was used to measure the muzzle velocity and terminal velocity for each bullet. All targets were placed 10m from the muzzle of the firearm. The charge size was varied with each bullet to simulate distance as explored and verified with the bullet modelling program in Chapter Six. Each bullet was fired at the target with the soft capture mechanism located behind the target. The soft capture system consisted of multiple layers of Plastzoate foam and two boxes containing soft cotton toy stuffing that would slow down and capture the bullet without leaving any additional characteristics on the bullet’s surface. Bullet numbers were set as a continuation from the previous firing experiment to avoid confusion.

Firing experiment set-up method and steps:

- Set up musket on universal mount with a horizontal firing height of 1.39m at 0° elevation parallel to the ground
- Weigh out desired powder and priming powder amount
- Clear musket touch hole of fouling
- Pick up musket from mount and pour powder into muzzle using a funnel
- Roll bullet into muzzle of musket barrel, giving the bullet a light tap with a wooden ramrod to ensure bullet is seated properly and does not leave ramrod impressions
- Put musket back on universal gun mount and tighten mount
- Put in priming powder into flash pan of the musket
- Attach electric trigger to flash pan, use small amount of tape to keep trigger place
- Retreat person(s) to the bunker
- Arm Doppler radar
- Remote fire the musket
- Look at Doppler radar for velocity and time data

Repeat steps

7.2 Oak Fence Rail Test Firing

The aim of this experiment was to fire multiple bullets at varying velocities and angles of incidence at 60mm thick planks of wood to begin the collection of known bullet impacts. The charge sizes were chosen to range from a full charge of 12g to a 1.5g charge, to investigate impact evidence along the range of the musket. Wood was chosen as it is mentioned by many battlefield reports and primary accounts of soldiers taking cover behind wooden fences, trees and hedgerows during combat in the early modern period. Planks of oak were selected as mock fence rails as oak has been noted for use as field boundaries, in Chapter Five. Firing directly at oak or wooden planks will also shed light onto whether distinctive and separate wood impressions can be identified on the bullet's surface to distinguish between wooden fence impacts and hedgerow impacts or if both wood impact impressions would be too similar regardless of wood or species type. 15 bullets were fired at planks of seasoned oak that had a thickness of 60mm. The soft capture system was placed behind the planks of wood to successfully secure the bullets after they impacted the wood, as seen in figure 7.1 below. Bullet numbers are set as a continuation from the previous firing experiment to avoid confusion.

Figure 7.1: Wooden planks with soft capture system behind.

7.2.1 90° Angle of Incidence Results

The first six bullets were fired at the 60mm thick plank of wood with varying charge sizes to simulate varying distances and velocities at the same 90° angle of incidence. The 90° angle of incidence is the normal impact angle if one is firing at a target straight in front of the gun muzzle, as discussed in Chapter Two (2.4.1). The results from the firing experiment can be found in the table 7.1 below.

Bullet Number	Bullet weight pre-firing (g)	Bullet weight post-firing (g)	Bullet diameter pre-firing (mm)	Charge weight (g)	Target type	Angle of incidence	Impact velocity (m/s)
Bullet 22	24.17g	24.04g	16.23mm	1.5g	60mm thick wooden plank	90°	107m/s
Bullet 23	24.27g	23.25g	16.27mm	4g	60mm thick wooden plank	90°	232m/s
Bullet 24	24.24g	23.03g	16.26mm	5g	60mm thick wooden plank	90°	269m/s
Bullet 25	24.13g	22.78g	16.25mm	6g	60mm thick wooden plank	90°	306m/s
Bullet 26	24.08g	22.44g	16.26mm	8g	60mm thick wooden plank	90°	356m/s
Bullet 27	24.27g	23.10g	16.23mm	12g	60mm thick wooden plank	90°	492m/s

Table 7.1: 60mm wooden plank fired at 90° angle of incidence.

Bullet 22 (figure 7.2) was fired with a 1.5g charge and impacted the fence at 107m/s; well below the average velocity for ground impact according to both the Miller experiments, and the modelling data from Chapter Six. While it was fired at such a low velocity, this is beneficial when investigating low velocity impact evidence as potentially seen during bounce and roll after ground impact. B22 is slightly distorted after penetrating and imbedding into the 60mm thick wooden plank. Manufacture evidence is apparent as the sprue cut and mould seam were visible on the non-impact side of the bullet, although impact damage did erase the mould seam on the impacted section of the bullet. A post-firing diameter measurement was taken and found to be 17.17mm. The increase in diameter is larger than pre-firing by 0.94 mm, although this is clearly from impacting the wooden board. This is to be expected as the bullet would have mass displacement due to the impact process. B22 also had visible firing evidence in the form of powder pitting and melting of the bullet that is visible inside the impact region, confusing any potential wood impressions. The central point of impact contains the transfer of bits of wood to the surface of the bullet. Under 10X magnification linear striations and grooves can be seen from where the bullet impacted the wood as it penetrated the wooden plank. The bullet had a 0.13g weight loss from firing and impact.

Figure 7.2: Impact surface of B22 under 10X magnification.

Bullet 23 (figure 7.3) was fired with a 4g charge and impacted the fence at 232m/s; simulated distance at impact was 192m when input in the computer modelling program from Chapter Six. B23 perforated the 60mm thick fence at 228m/s and was recovered in the soft capture system. The bullet is moderately distorted from impact. The impact surface contains a discoloured, disorganised surface structure as a result of melting from firing. Very pronounced wood grain impressions are seen on the main impact surface, hence termed the central point of impact. Long linear striations are noticeable from where the bullet impacted the wooden surface. The perimeter of the impact surface contains wood imbedded in the surface of the bullet, with linear grooves and striations from where the bullet perforated the wooden plank. This region also contained a polished surface from the lead melting. The bullet had lost 1.02g weight from firing and impact.

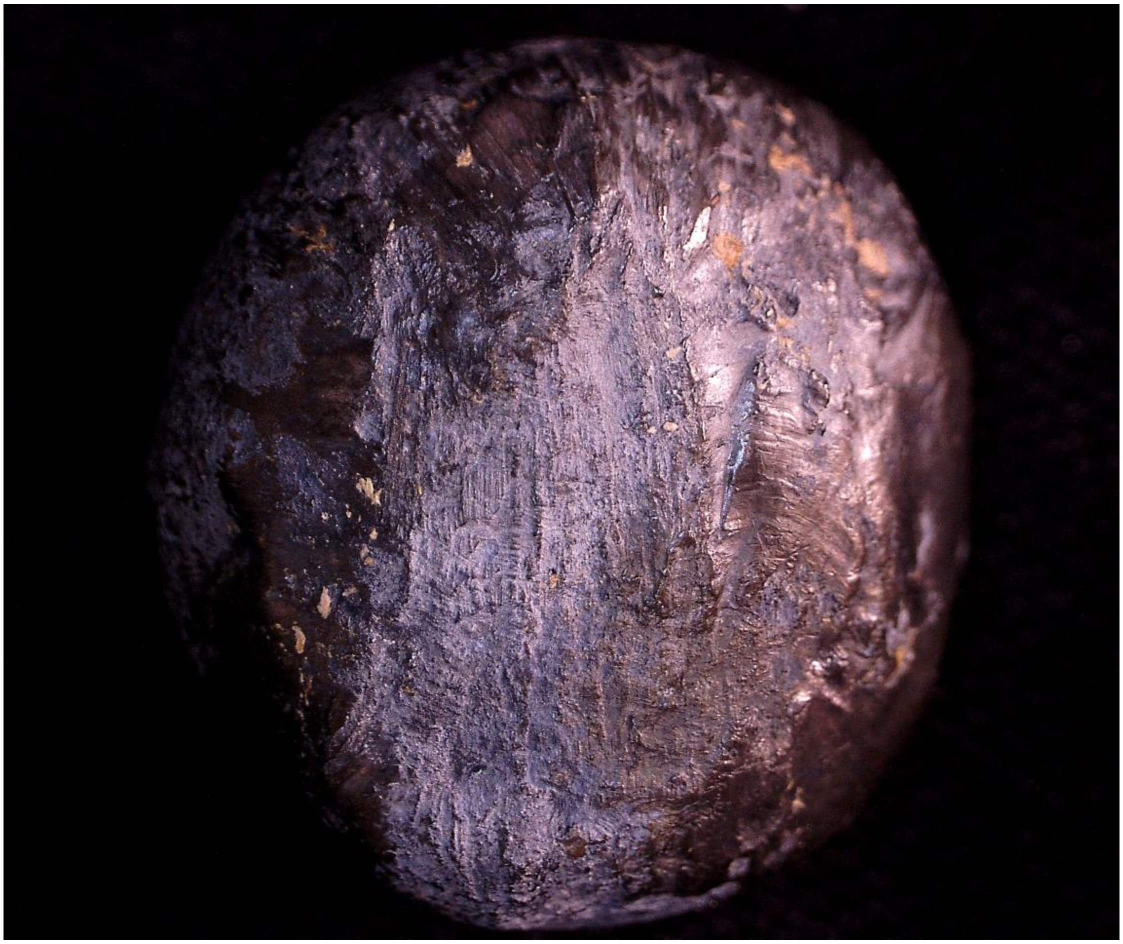

Figure 7.3: Impact surface of B23 under 10X magnification.

Bullet 24 (figure 7.4) was fired with a 5g charge and impacted the fence at 269m/s; the simulated distance at impact was 126m. B24 perforated the 60mm thick fence at 263m/s. The bullet is moderately distorted from the impact process. Macroscopic inspection revealed the central bar from the sprue cut, but the twin half-moon features are difficult to make out and no mould seam is visible. Powder pitting and a firing band were also visible. Under 10X magnification the central point of impact can be located as it is a flat region containing linear striations. The area directly around the point of impact appears disorganised and slightly polished from melting. The area outside of that forms a perimeter of linear grooves and striations with bits of wood imbedded into the surface from where the bullet perforated the wood. The bullet had lost 1.21g weight from firing and impact.

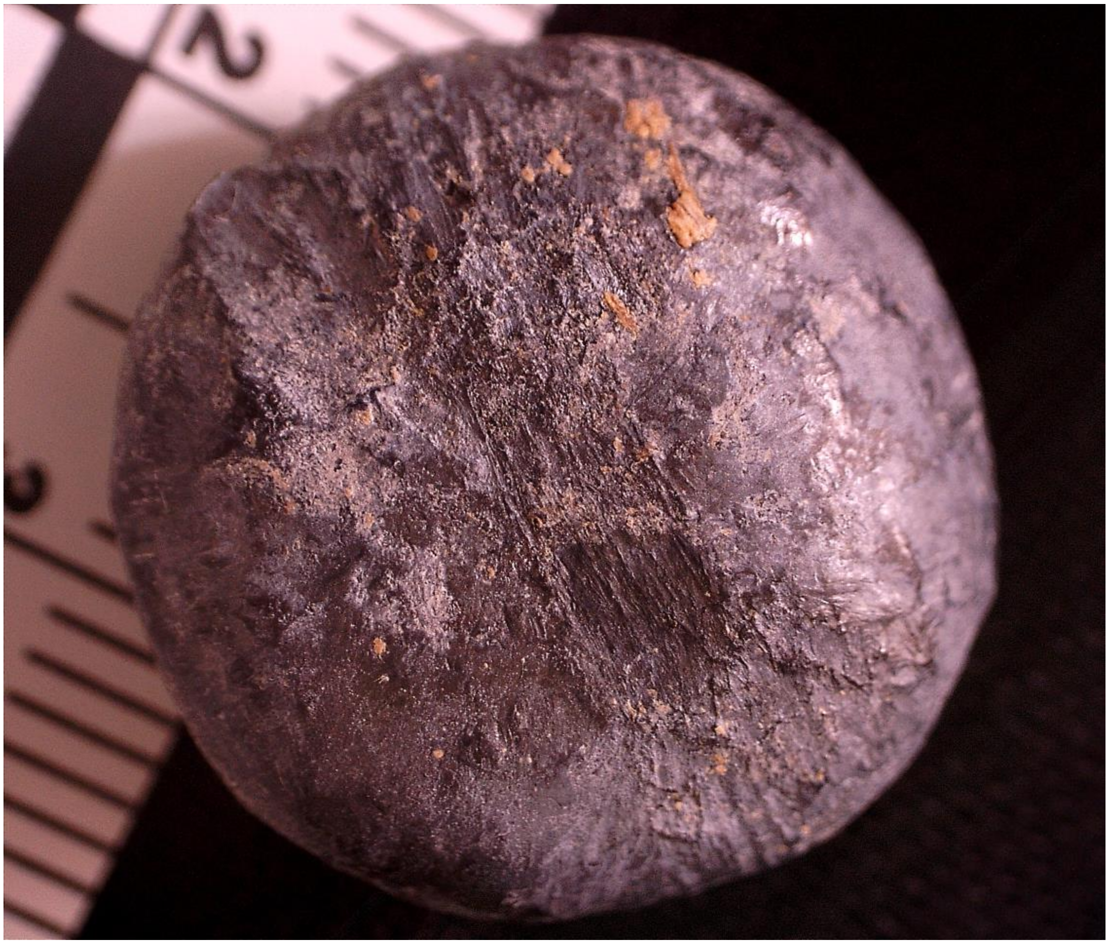

Figure 7.4: Impact surface of B24 under 10X magnification.

Bullet 25 (figure 7.5) was fired with a 6g charge and impacted the fence at 306m/s; the simulated distance at impact was 93m. B25 perforated the 60mm thick fence at 289m/s. The bullet is heavily distorted from the impact process. The bullet contained no visible manufacturing evidence, although powder pitting was visible from firing. The central point of impact is visible and retains a darkened colour from the firing process. There are very pronounced linear striations in the central point of impact. The impact area is surrounded by a ridge line of polished linear striations and grooves from where the bullet perforated the wood (as seen in figure 7.6 below), with bits of wood imbedded in the surface. The bullet had lost 1.35g weight from firing and impact.

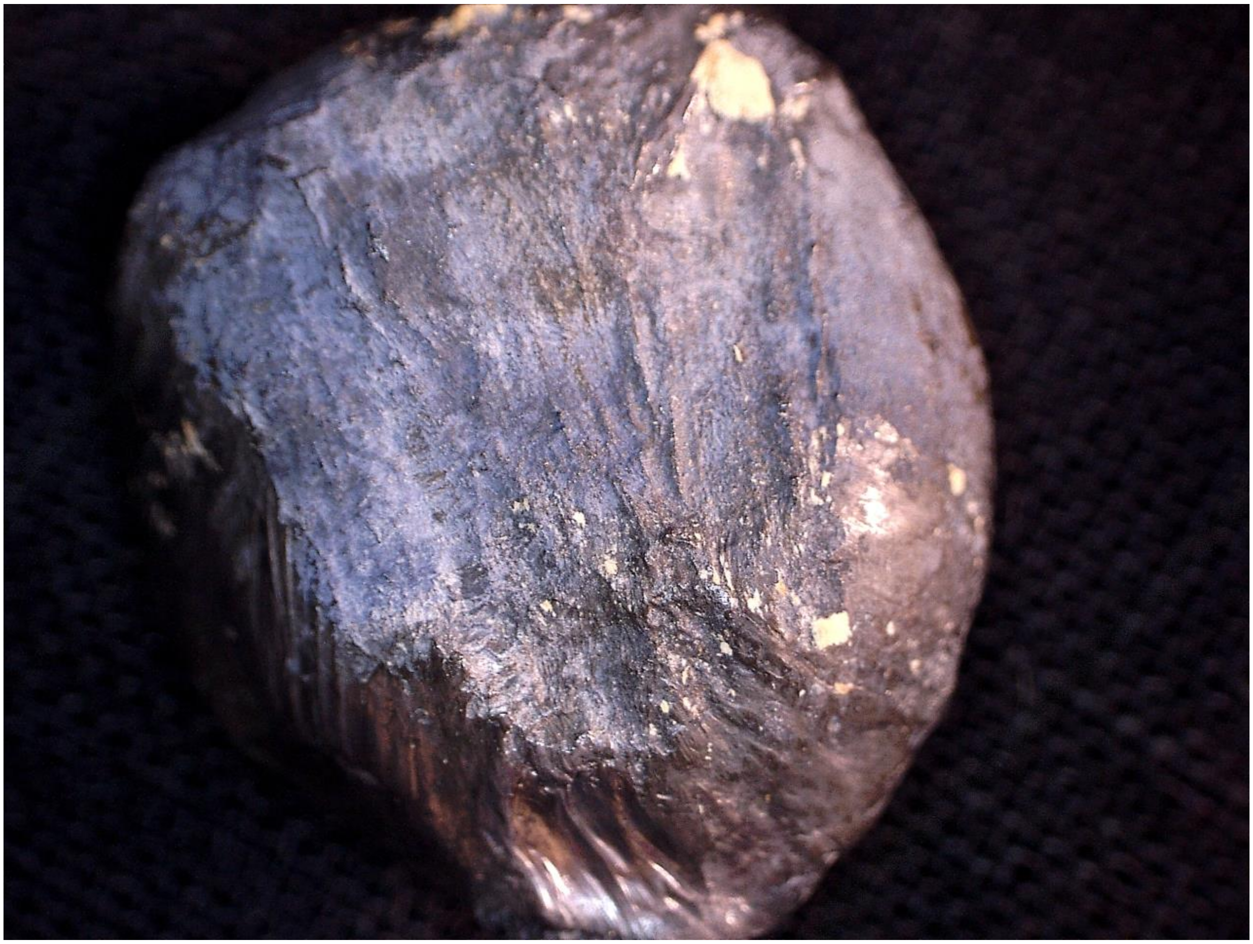

Figure 7.5: Impact surface of B25 under 10X magnification.

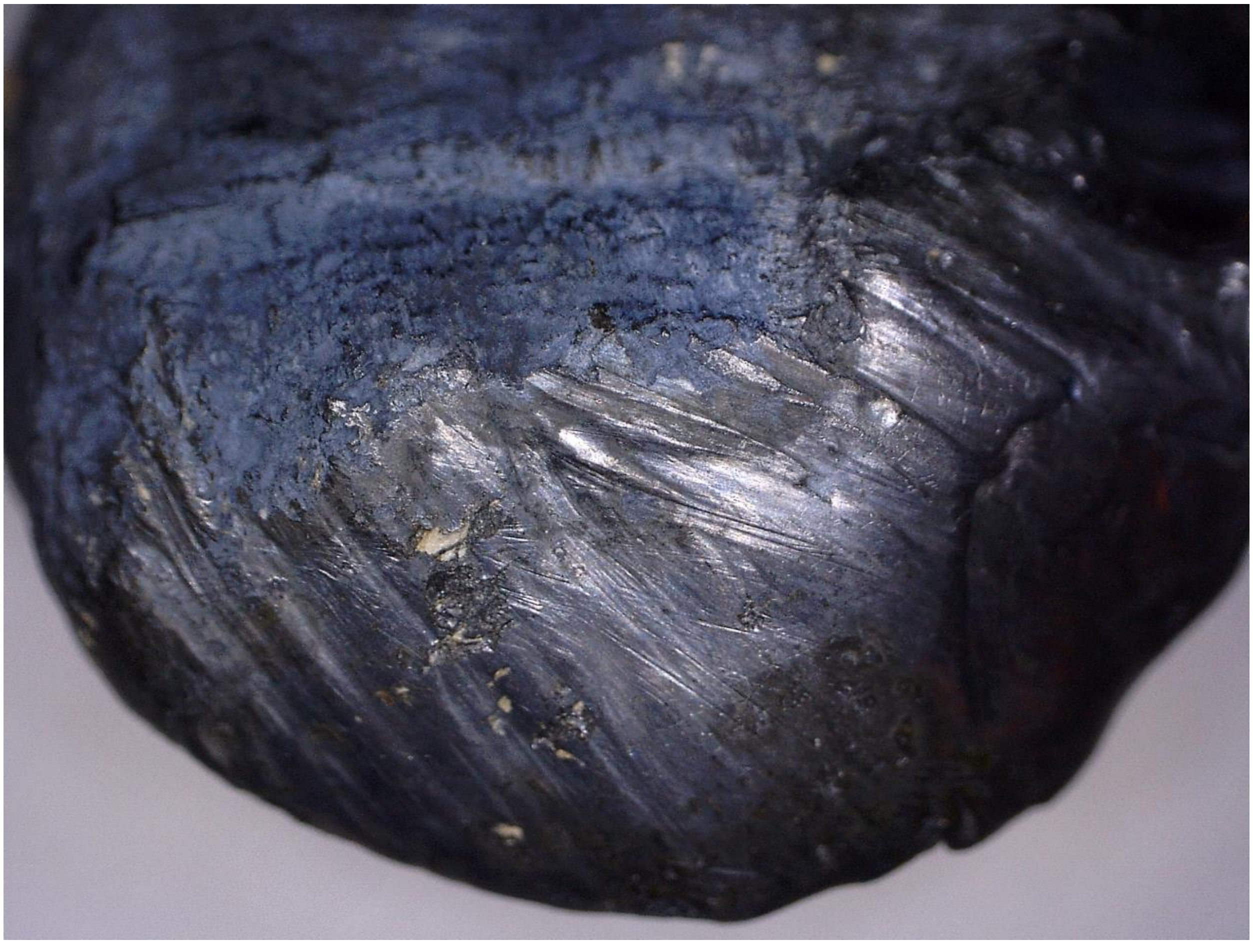

Figure 7.6: B25 under 10X magnification, view of the perimeter edge showing linear striations from perforating the wooden plank.

Bullet 26 (figure 7.7) was fired with an 8g charge and impacted the fence at 356m/s; the simulated distance at impact was 67m. B26 perforated the 60mm thick plank at 341m/s. The bullet is heavily distorted with the outside perimeter of the bullet appearing polished and containing linear striations that flow towards the backside of the bullet. The bullet contained no visible manufacture evidence, although powder pitting and banding were visible from firing. Wood is imbedded in the perimeter surface of the bullet as well. The outer perimeter of the bullet has begun to fold towards the backside of the bullet away from the initial point of impact. Under 10X magnification, wood grain impression can be seen in the central point of impact and within the polished perimeter edges, both contain linear grooves and striations. The bullet had lost 1.64g weight from firing and impact.

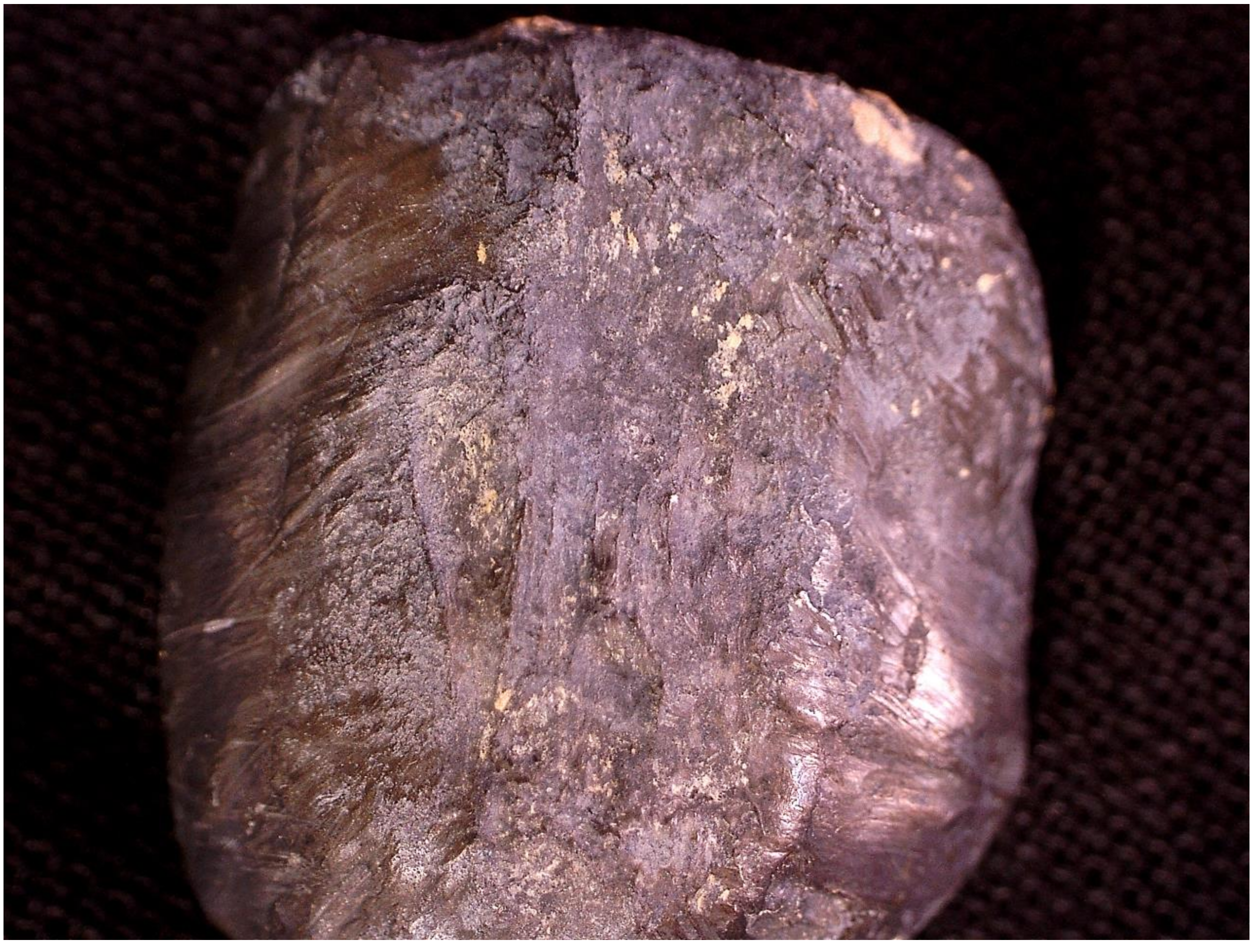

Figure 7.7: Impact surface of B26 under 10X magnification.

Bullet 27 (figure 7.8) was fired with 12g charge and impacted the fence at 492m/s; the simulated distance was point blank. B27 perforated the 60mm thick fence at 483m/s. The bullet was heavily distorted upon impact and contained no visible wood grain impressions. The bullet's surface at the point of impact appears very disorganised and polished as it underwent a tremendous amount of melting as it perforated the wooden plank. The outside perimeter shows very faint linear striations as the lead flowed toward the perimeter of the bullet and formed a ridge along the outside of the bullet. The bullet had lost 1.17g weight from firing and impact.

Figure 7.8: Impact surface of B27 under 10X magnification.

7.2.1.1 Discussion

Table 7.2 below is a summary of the experimental results.

Bullet Number	Charge Size (g)	Impact Velocity (m/s)	Exit Velocity (m/s)	Simulated Distance (m)	Weight Loss (g)	Distortion Level	Visibility of Wood Grain Impressions
B22	1.5g	107m/s	Imbedded	Ground Impact	0.13g	SD	10X Magnification
B23	4g	232m/s	228m/s	192m	1.02g	MD	Present
B24	5g	269m/s	263m/s	126m	1.21g	MD	Present
B25	6g	306m/s	289m/s	93m	1.35g	HD	Present
B26	8g	356m/s	341m/s	67m	1.64g	HD	10X Magnification
B27	12g	492m/s	483m/s	Point Blank	1.17g	HD	None

Table 7.2: Discussion data.

A statistical analysis was used known as the Pearson correlation coefficient to determine if there was a correlation between gunpowder charge size and bullet weight loss due to firing in this experiment. There is a moderate positive correlation with the value of R being 0.6389. This implies that there is a slight correlation between an increase in the gunpowder charge size used and the amount of weight loss to the bullet. However, B27 fired with a full charge of 12g at point blank range defies this trend, the reasoning behind this outlier is unknown.

As seen from the experimental firing, there is a correlation between the bullet's impact velocity and simulated distance and the distortion level upon impact. Generally, the higher the velocity at impact equates to the proximity of the shooter to the target being impacted, therefore the higher the bullet's velocity on impact means more distortion to the bullet's surface excluding the outlier just mentioned. The Pearson correlation coefficient statistical analysis was used to determine this correlation, and the variables examined were the bullet impact velocity and the distortion level.

The distortion level was assigned a numerical quantity as seen in table 7.3 below, based off the percentage of distortion from ideal shape as mentioned in Chapter One (section 1.5). The R value is 0.8759 indicating a strong positive correlation.

Numerical Quantity	Distortion Level
0	S
0.25	SD
0.50	MD
0.75	HD
1.00	I

Table 7.3: Numerical quantity for distortion levels.

The number of characteristic traits transferred to the bullets' surfaces from impact is varied. Occasionally wood grain impressions are clearly visible, whereas sometimes they are only clearly visible under 10X magnification. When a bullet perforates wood, wood grain impressions are found in two distinct locations on the bullet's surface: the central point of impact and on the bullets' perimeter edges. Both sections of the bullet generally contain linear striations. The surface evidence at the central point of impact is a localised series of linear striations that retain bits of adhering wood from the impact surface. When this adhering wood is removed, the surface area contains multiple miniscule pockmarks. The linear striations on the perimeter edges of the bullet radiate towards the backside of the bullet from where the bullet perforated the wood. From this experiment, there is no correlation between level of distortion, velocity or range and the transfer of characteristic traits. The exception is the high velocity impact of B27 which exhibits no wood grain impressions. The surface texture of B27 is highly disorganised and has the appearance of melted lead, although the outside perimeter does shows very faint linear striations radiating towards the back of the bullet.

One immediate concern that arises is that most of the surface traits are much more visible under 10X magnification then by macroscopic examination. This is concerning because much of these traits, while visible on an experimental bullet, will more than likely be lost due to corrosion in the burial environment depending on site conditions.

The modelling program data shows that bullets impacting the 60mm thick fence rail at a 90° angle of incidence will perforate the plank beyond 192m. Meaning, the shooter could be firing at a distance of up to 192m away from the fence rail and the bullet will still perforate the fence. The bullet's velocity loss after perforating the 60mm thick fence rail at a 90° angle of incidence was averaged to 8.2m/s.

7.2.2 60° Angle of Incidence Results

Four bullets were fired at varying velocities at the 60mm thick plank of wood with a 30° angle of obliquity, meaning the bullet will impact the wood at a 60° angle of incidence, instead of the 90° angle of incidence as per normal. Charge sizes were varied from 12g to 1.5g to collect data on impact damage and simulated distance. The results can be found in the table 7.4 below.

Bullet Number	Bullet weight pre-firing (g)	Bullet weight post-firing (g)	Bullet diameter pre-firing (mm)	Charge weight (g)	Target type	Angle of incidence	Impact velocity (m/s)
Bullet 28	24.01g	23.45g	16.20mm	1.5g	60mm thick wooden plank	60°	98m/s
Bullet 29	24.26g	22.67g	16.26mm	6g	60mm thick wooden plank	60°	298m/s
Bullet 30	24.03g	22.61g	16.18mm	8g	60mm thick wooden plank	60°	352m/s
Bullet 31	24.09g	22.72g	16.23mm	12g	60mm thick wooden plank	60°	494m/s

Table 7.4: 60mm wooden plank fired at a 60° angle of incidence.

Bullet 28 (figure 7.9) was fired with a 1.5g charge and impacted the plank at 98m/s; well below the average velocity for ground impact. B28 perforated the 60mm thick fence at 60° angle, but the Doppler radar failed to measure the velocity upon exiting the fence. The bullet is moderately distorted and appears hemispherical. The bullet contained evidence of powder pitting from the firing process. There are wood grain impressions with linear striations in the centre of the bullet. The area directly around that area to the outside edge of the bullet appears disorganised from melting with no clear linear striations as would be expected to find from the 90° impact. The very edges of the bullet that have begun to fold toward the back end of the bullet contain linear striations and imbedded wood. The bullet had a loss of 0.56g weight from firing and impact.

Figure 7.9: Impact surface of B28 under 10X magnification.

Bullet 29 (figure 7.10) was fired with a 6g charge and impacted the fence at 298m/s; the simulated distance at impact was 97m. B29 perforated the 60mm thick fence at 284m/s. The bullet is moderately distorted from the impact process. The bullet contained manufacture evidence as the sprue and mould seam were visible, although not on the impact side of the bullet. It is possible to identify which side of the bullet went through the longer section of the fence, because that side contains a sweeping, elongated tail that is much more polished with large linear striations and grooves with edges that have flowed toward the backside of the bullet. The opposite side of the bullet that seems to have taken the shorter route through the wood is much more rounded with the edges flowing toward the backside of the bullet which also contains less of a ridge and are more rounded. Under 10X magnification, the central point of impact contains wood grain impressions and a disorganised surface from melting. The point of impact is interrupted at its edges by the linear striations from the bullet perforating the wooden fence. Bits of wood are found imbedded along the edges of the central point of impact. The bullet had a loss of 1.59g weight from firing and impact.

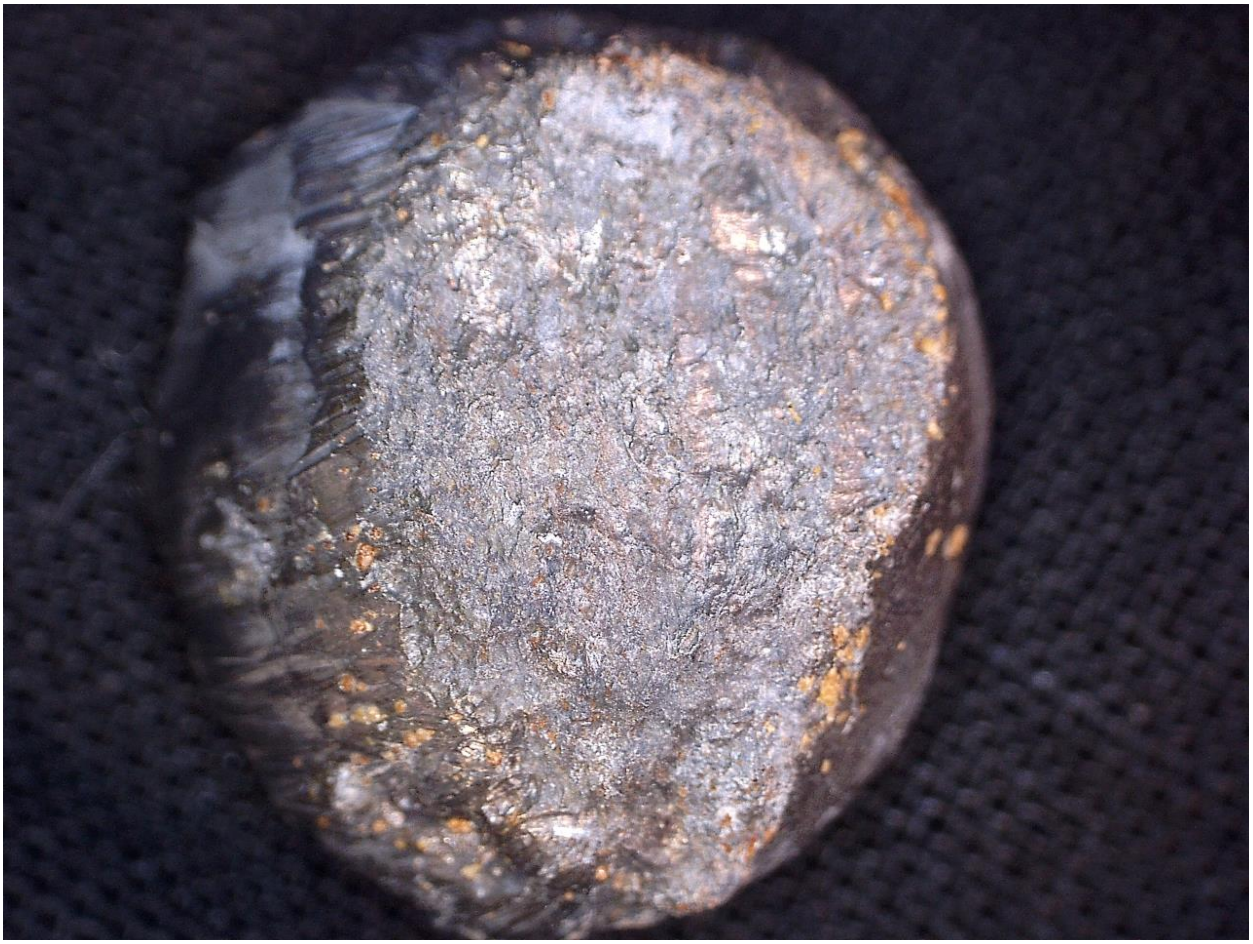

Figure 7.10: Impact surface of B29 under 10X magnification.

Bullet 30 (figure 7.11) was fired with an 8g charge and impacted the fence at 352m/s; the simulated distance at impact was 70m. B30 perforated the 60mm thick fence at 336m/s. The bullet is classified as moderately distorted from impact. The bullet contained evidence of powder pitting and barrel banding from the firing process. The bullet has central point of impact containing wood imbedded in its surface. The perimeter around this point has linear striations flowing towards the backside of the bullet, with melted lead folding the outer edges backwards. It is easy to identify which side of the bullet took the long way through the wood as the area is more polished with a larger sweeping tail containing longer linear striations and deeper grooves flowing toward the backside of the bullet. The opposite side of the bullet is more squared and flattened with shorter linear striations flowing towards the back of the bullet. The bullet had a loss of 1.42g weight from firing and impact.

Figure 7.11: Impact surface of B30 under 10X magnification.

Bullet 31 (figure 7.12) was fired with a 12g charge and impacted the fence at 494m/s; the simulated distance was point blank. B31 perforated the 60mm thick fence at 486m/s. The bullet is heavily distorted from impact. The impact surface is polished from melting due to the impact process, the surface texture is very disorganised as a result. The potential central point of impact can be seen under 10X magnification. One side of the bullet contains a squared region while the other side seems elongated, this region could be the sweeping tail, but it is very difficult to tell. The outside edges of bullet contain some linear striations that flow towards the back side of the bullet which have melted wand have folded inwards. The bullet had a loss of 1.37g weight from firing and impact.

Figure 7.12: Impact surface of B31.

7.2.2.1 Discussion

Table 7.5 below is a summary of the experimental results.

Bullet Number	Charge Size (g)	Impact Velocity (m/s)	Exit Velocity (m/s)	Simulated Distance (m)	Weight Loss (g)	Distortion Level	Visibility of Wood Grain Impressions
B28	1.5g	98m/s	Perforated, No data	Ground Impact	0.56g	MD	None
B29	6g	298m/s	284m/s	97m	1.59g	MD	Present
B30	8g	352m/s	336m/s	70m	1.42g	MD	Present
B31	12g	494m/s	486m/s	Point Blank	1.37g	HD	None

Table 7.5: Discussion data.

The sample size is too small to allow for a reliable statistical analysis to determine if there is a correlation between bullet weight loss and charge size, as well as the distortion level upon impact and the impact velocity. The small sample size was due to constraints and limitations mentioned in Chapter Five, section 5.6.

The bullets entering the plank of wood at a 60° angle of incidence suffered greater impact damage at lower velocities than in the previous firing experiment where bullets were fired at a 90° angle of incidence. This is to be expected as the bullet must effectively travel through the wood for a longer duration of time when perforating it.

All bullets fired at a 60° angle of incidence in this experiment show the same characteristic traits, albeit in varying levels due to velocity on impact. Bullets fired at a 60° angle of incidence show three distinct regions of impact evidence. The central point of impact for all bullets show varying levels of the transfer of wood grain impressions, as described above. The bullets also show that one side of the bullets contains an elongated sweeping tail that contains linear striations that radiate towards the backside of the bullet. The other side of the bullet show either a squared or rounded, truncated region that also contain linear striations that radiate towards the backside of the bullet. When the bullet perforates the wood at a 60° angle of incidence, one side of the bullet must travel through more of the wood than the other side of the bullet, which is believed to be the cause of the elongated tail. The visibility of the wood grain impressions is inconsistent and generally seen much more clearly under 10X magnification. Again, this is may prove to be problematic when corrosion is considered, and the fine detail of the linear striation may be obfuscated. The surface of the bullet that impacted at a high velocity has a highly disorganised surface texture with the appearance of melted lead, although it is still possible to determine the elongated tail from the squared region of the bullet.

The modelling data shows that a bullet travelling at 98m/s could still perforated the 60mm thick fence rail when fired at a 60° angle of incidence, this is well below the average of ground impact as noted in Chapter Six by the modelling data. The 60mm thick fence rail barely slowed the bullet down and the bullet velocity loss on average was 12.66m/s

7.2.3 45° Angle of Incidence Results

The final five bullets were fired at varying velocities at 60mm thick planks of wood. The wooden plank was moved to a 45° angle of obliquity, which means the bullet will impact the wood at a 45° angle of incidence. The charge sizes were chosen to cover the range of the musket, although two bullets repeat the same charge size of 6g and 12g respectively, this was done because the first bullets fired from that charge size was lost and a second attempt was made to collect data from that impact velocity. This came at a detriment to collecting evidence from other points along the musket’s range. The results can be found in the table 7.6 below.

Bullet Number	Bullet weight pre-firing (g)	Bullet weight post-firing (g)	Bullet diameter pre-firing (mm)	Charge weight (g)	Target type	Angle of incidence	Impact velocity (m/s)
Bullet 32	24.23g	23.96g	16.28mm	1.5g	60mm thick wooden plank	45°	104m/s
Bullet 33	24.25g	X	16.29mm	6g	60mm thick wooden plank	45°	254m/s
Bullet 34	24.16g	22.96g	16.23mm	6g	60mm thick wooden plank	45°	295m/s
Bullet 35	24.27g	22.71g	16.25mm	12g	60mm thick wooden plank	45°	476m/s
Bullet 36	24.41g	X	16.28mm	12g	60mm thick wooden plank	45°	420m/s

Table 7.6: 60mm wooden plank fired at a 45° angle of incidence.

Bullet 32 (figure 7.13) was fired with a 1.5g charge and impacted the fence at 104m/s; well below the average velocity of ground impact. B32 did not penetrate the 60mm thick fence, rather it rebounded off the wood and was found 3m from the target towards the firing position. This bullet has a slight to moderate distortion level. The bullet contained a slight band and powder pitting due to firing. The surface of impact was polished with long linear striations and grooves covering the surface. The distortion of the bullet is lopsided with part of the bullet appearing pinched inwards. This end may represent the sweeping tail, although it is difficult to determine. A very deep groove with wood imbedded in the surface was found on the opposite side of the sweeping tail. The bullet had a loss of 0.27g weight from firing and impact.

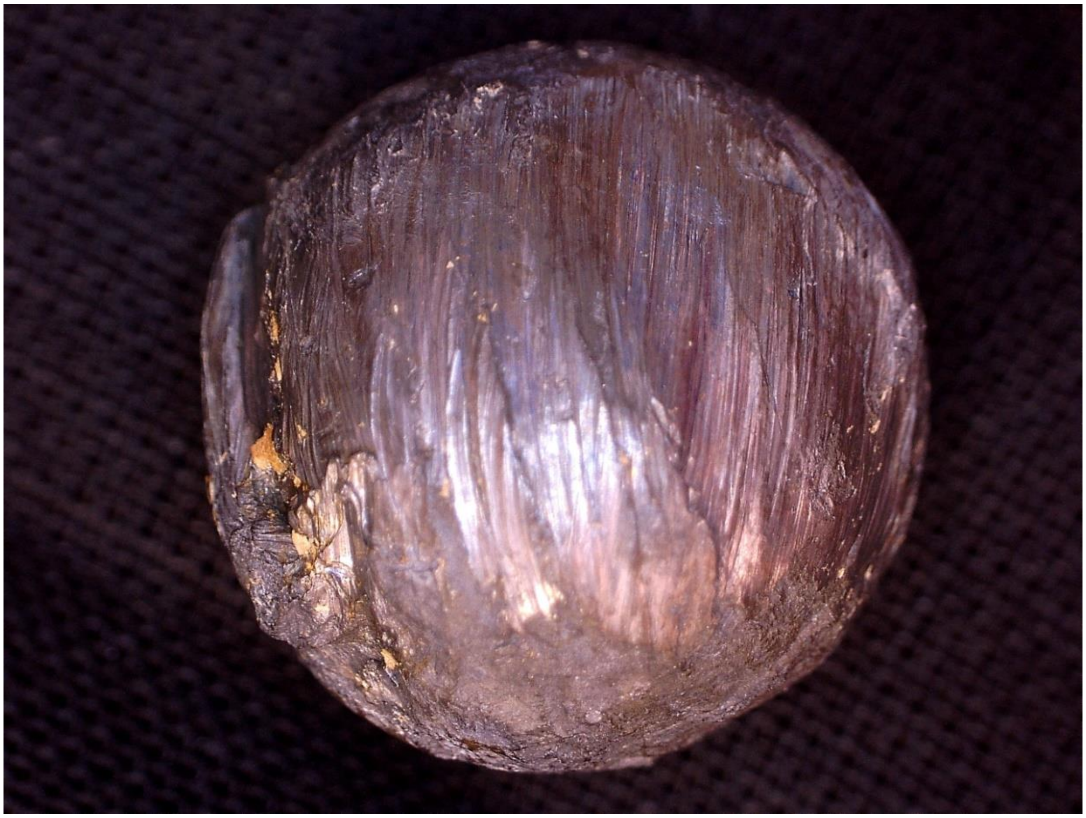

Figure 7.13: Impact surface of B32 under 10X magnification.

Bullet 33 was fired with a 6g charge and impacted the fence at 254m/s; the simulated distance at impact was 151m. However, B33 ricocheted off the 60mm thick fence and was subsequently lost and unable to be analysed further.

Bullet 34 (figure 7.14 and 7.15) was fired with a 6g charge and impacted the fence at 295m/s; the simulated distance at impact was 99m. B34 perforated the 60mm thick fence at 282m/s and has a moderate distortion level. The bullet contained firing evidence in the form of powder pitting. The bullet impact surface appears disorganised from melting. The central point in between the sweeping tail and the squared off end of the bullet has formed a pointed ridge. Faint linear striations are present on the bullet’s edges. The bullet had a loss of 1.20g weight from firing and impact.

Figure 7.14: Impact surface of B34.

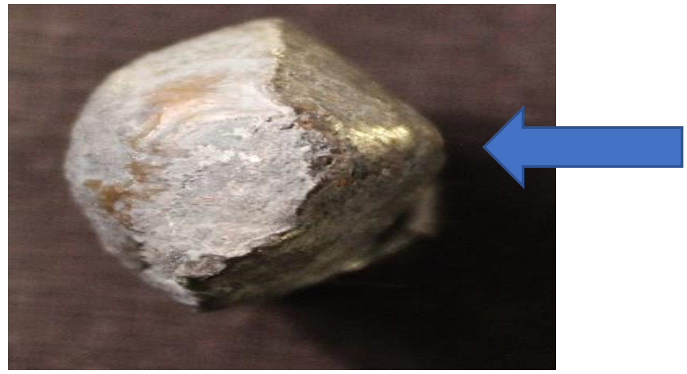

Figure 7.15: Overhead view of B34, on the right side of the picture one can see the ‘pinched in’ ridge.

Bullet 35 (figure 7.16) was fired with a 12g charge and impacted the fence at 476m/s; the simulated distance was point blank. B35 perforated the 60mm thick fence at 460m/s. The potential central point of impact shows a dimpled and pockmarked surface that is highly disorganised from melting during the impact process. The polished surface contains linear striations that flow outwards towards the backside of the bullet. The bullet had a loss of 1.56 weight from firing and impact.

Figure 7.16: Impact surface of B35.

Bullet 36 was fired with a 12g charge and impacted the metal clamp that held the wooden plank against the frame. As a result, the bullet was discarded from the experiment due to irrelevant impact damage.

7.2.3.1 Discussion

Table 7.7 below is a summary of the experimental results.

Bullet Number	Charge Size (g)	Impact Velocity (m/s)	Exit Velocity (m/s)	Simulated Distance (m)	Weight Loss (g)	Distortion Level	Visibility of Wood Grain Impressions
B32	1.5g	104m/s	Rebound	Ground Impact	0.27g	SD-MD	Present
B33	6g	254m/s	Rebound	151m	NA	NA	NA
B34	6g	295m/s	282m/s	99m	1.20g	MD	Present
B35	12g	476m/s	460m/s	Point Blank	1.56g	HD	None

Table 7.7: Discussion data.

The sample size from this experiment is too low for reliable statistical analysis. The small sample size is due to experimental limitations discussed in Chapter Five, section 5.6, and compounded by the fact that two bullets were lost during the experiment. Bullets fired from a 45° angle of incidence show three distinct regions of impact. The central point of impact contains linear striations with adhering wood in the impact surface. The other two regions have a ‘pinched in’ appearance containing a small ridge between the indented regions. A faint elongated sweeping tail can be seen, although much less pronounced than bullets fired from a 60° angle of incidence. Both sides of the ‘pinched in’ region show linear striations that radiate towards the backside of the bullet. However, an increase in sample size may either further flush out the types of impact evidence from this experiment or may render the above results as outliers.

The bullet that impacted at a high velocity (B35) contains a highly disorganised surface organisation and texture with the appearance of melted lead. The elongated sweeping tail can be seen more clearly on B35, although it has begun to bend towards the backside of the bullet. The modelling data shows that bullets impacting the 60mm thick fence rail at a 45° angle of incidence that were fired within the distance of 0m to 100m will perforate the fence. There is potential that bullets fired from beyond the150m mark may rebound or ricochet from the fence rail when fired at a 45° angle of incidence. It is not possible to say for certain as there is not enough information collected to be definitive. The bullet's velocity loss after perforating the 60mm thick fence rail at a 45° angle of incidence was averaged to 14.5m/s.

7.2.4 Oak Fence Rail Experimental Discussion

The results below have too small of a sample size to make conclusions with confidence, although this proof of concept demonstrates some general trends that appear in the experimental results, an increase in sample size may overturn or fortify the results discussed below.

It is possible to determine the difference in the experimental bullets fired from 90°, 60°, and 45° angles of incidence. All bullets fired contain a central point of impact that contains a localised transfer of traits from the target to the bullet's surface. The bullets' perimeters all show radiating linear striations flowing towards the backside of the bullet, these traits are transferred to the bullet from the action of the bullet perforating the wooden plank. However, bullets fired from a 60° angle of incidence show two additional regions of impact, the elongated sweeping tail and the shorter rounded or squared region of the bullet. The tail of the bullet is clearly the section of the bullet that took the longer route through the wooden plank, whereas the truncated rounded or squared region took the shorter path. The bullets fired from a 45° angle of incidence show a 'pinched in' surface containing a ridge, and a very faint tail. This could be because the angle of obliquity and the angle of incidence are nearly the same for the bullet, both being 45°. So, in short both sections of the bullet are facing the same long route through the wooden plank.

There is a direct correlation between the bullet's velocity at impact and simulated distance and distortion level. Statistical analysis was completed on all 13 soft captured bullets. The results show an R value of 0.8389, meaning that there is a strong positive correlation. The bullets impacting at a higher velocity show the most distortion. However, more evidence (a greater sample size) is needed to determine how precise that correlation is. There also seems to be a trend in weight loss of the bullet and charge size used. Statistical analysis was performed on all 13 bullets that were successfully soft captured. The results show an R value of 0.7419, meaning that there is a moderate positive correlation, although there are some outliers that defy the trend. Another point of consideration with these correlations is that the bullets from the 45° and 30° angles of incidence could not be calculated independently because they lacked an adequate sample size. These correlations do not assume for those changes in variables and may be incorrect.

7.3 Dead Wood Test Firing

The aim of this experiment was to fire multiple bullets at varying velocities at dead wood. Multiple branches of hazel of similar thickness were woven together as a loose simulation of a dead hedge. The branches consisted of the 1st, 2nd and 3rd years growth from a hazel tree and had been cut six months prior to firing and left to dry out and can be seen in figure 7.17 below. Five bullets were fired at the dead wood with the soft capture system located behind the target. The first bullet fired was from a full 12g charge size that immediately perforated and broke apart the dead wood, and then perforated the soft capture system. As a result, the remaining charge sizes of 6g to 1.5g were chosen to investigate impact evidence along the terminal end of the musket's range. Bullet numbers are set as a continuation from the previous firing experiments to avoid confusion.

Figure 7.17: Woven together dead wood experimental set up.

7.3.1 Results

Four of the five bullets fired through the dead wood were soft captured. One bullet went through the dead wood, then through the soft capture system and was lost in the sand backstop at the end of the firing range. Results can be found in table 7.8 below.

Bullet Number	Bullet weight pre-firing (g)	Bullet weight post-firing (g)	Bullet diameter pre-firing (mm)	Charge weight (g)	Target type	Angle of incidence	Impact velocity (m/s)
Bullet 37	24.03g	23.86g	16.22mm	1.5g	Dead Wood	90°	110m/s
Bullet 38	24.22g	23.59g	16.21mm	3g	Dead Wood	90°	176m/s
Bullet 39	24.32g	23.06g	16.27mm	6g	Dead Wood	90°	305m/s
Bullet 40	23.99g	22.60g	16.21mm	6g	Dead Wood	90°	278m/s

Table 7.8: Four bullets fired through a dead wood.

Bullet 37 (figure 7.18) was fired with a 1.5g charge and impacted the wood at 110m/s; well below the average velocity of ground impact, although it was still fired at such a low velocity to investigate low velocity impact evidence as potentially seen during bounce and roll. B37 is slightly distorted. It entered the dead hedge impacting a small twig (3mm thickness), and perforated the hedge at 90m/s. The bullet shows small regions across its surface that contain linear striations and alternating grooves from making brief contact with the wooden surface, but no central point of impact was located. These regions appear polished and lighter than the rest of the bullet's surface, and small bits of wood were imbedded in the surface of the bullet. The bullet had a loss of 0.17g weight from firing and impact.

Figure 7.18: Impact surface of B37.

Bullet 38 (figure 7.19) was fired with a 3g charge and impacted the hedge at 176m/s; below the average velocity of ground impact. The bullet impacted a branch in the hedge 14.71mm in thickness and perforated the hedge at 171m/s. B38 is slightly distorted and contains regions across its surface that have linear striations and alternating grooves from impacting multiple branches. There appears to be a point of central impact where the bullet either impacted the centre of the 14.71mm thick branch or impacted the side of the branch. The side of the bullet contains an oblong facet that contains linear striations rounded in the front of the bullet and has a slight tail flowing towards the back side of the bullet where the lead has been pushed into a small ridge, this region contains imbedded bits of wood. Adjacent to this region is a thin area of lead that contains a wood grain impression with long linear striations that also contain imbedded bits of wood. Figures 7.20 and 7.21 show a view of B38’ trajectory through the dead hedge. The bullet had a loss of 0.63g weight from firing and impact.

Figure 7.19: Impact surface of B38. Note the top half of the bullet is the oblong facet which contains linear striations.

Figure 7.20: B38’s trajectory through the dead branches.

Figure 7.21: B38’s trajectory through the dead branches, side view.

Bullet 39 (figure 7.22) was fired with 6g charge and impacted the hedge at 305m/s; and the simulated distance at impact was 93m from muzzle to target. B39 is moderately distorted from the impact process. The bullet impacted a branch in the hedge 23.53mm in thickness, and perforated the hedge at 288m/s. Its surface contains a central point of impact, but no visible wood grain impressions are present although the perimeter edges of the bullet have linear striations leading towards the backside of the bullet. Wood is also imbedded in the perimeter edges of the bullet. The bullet had a loss of 1.26g weight from firing and impact.

Figure 7.22: Impact surface of B39.

Bullet 40 (figure 7.23) was fired with a 6g charge and impacted the hedge at 278m/s; the simulated distance at impact was 113m. The bullet is oblong and slightly distorted, this distortion is due to the presence of a firing band. B40 impacted a branch in the hedge 5.54mm in thickness, and perforated the hedge at 270m/s. The visibly raised sprue can be mistaken for impact damage as one of the linear striations crossed the sprue region, although one can make out a break in the striations due to the presence of a small depression in the pattern. The surface of the bullet contains regions and patches of linear striations caused by the bullet impacting the wooden branches. Wood is imbedded on the bullet's surface, possible location of central impact with the 5.54mm thick branch; however, it is not clear. The bullet had a loss of 1.39g weight from firing and impact.

Figure 7.23: Impact surface of B40.

7.3.2 Discussion

Table 7.9 below is a summary of experimental results.

Bullet Number	Charge Size (g)	Impact Velocity (m/s)	Exit Velocity (m/s)	Simulated Distance (m)	Weight Loss (g)	Distortion Level	Visibility of Wood Grain Impressions
B37	15g	110m/s	90m/s	Ground Impact	0.17g	SD	None
B38	3g	176m/s	171m/s	Ground Impact	0.63g	SD	Present
B39	6g	305m/s	288m/s	93m	1.26g	MD	None
B40	6g	278m/s	270m/s	113m	1.39g	SD	None

Table 7.9: Discussion data.

The relationship between the bullets' distortion and impact velocity demonstration a trend in this experiment, where the higher the velocity the higher the rate of distortion; however, the sample size is too small for statistical analysis. Bullet 39 defies this trend by exhibiting the most surface distortion. However, the bullet also impacted multiple branches in the simulated dead hedge which may account for the increased level of distortion. This means that two additional variables are now introduced; the number of impact events the bullet experiences in its trajectory and the overall thickness of each individual target the bullet impacts. Multiple impact events will leave several regions of impact evidence on a bullet's surface, although it may not be possible to reconstruct the sequence of impact events. Three out of four bullets in this experiment did not retain wood grain impressions, but all bullets retained the linear striations from impacting or grazing the wooden targets. This could indicate that dead wood is not as likely to leave impact evidence on the bullet's surface, although the sample size is too small to be definitive.

7.4 Simulated Laid Hedge (Hazel)

The aim of this experiment was to create a mock laid hedge, since for legal reasons firing at an actual laid hedge was not feasible, as mentioned earlier in Chapter Five, section 5.6. The simulated laid hedge was made up of hazel branches cut less than 24 hours before the firing experiment, from a hazel tree that was 12-15 years old. The branches were woven together to create a simulated hedge of 12-15 years growth. The complete experiment consisted of three steps which increased the thickness of the simulated laid hedge with each step. 16 bullets were fired at the simulated laid hedge with the soft capture system located behind the hedge to capture all bullets for analysis. Charge sizes ranged for every experiment to collect impact evidence from varying velocities and simulated ranges along the musket's maximum range. Bullet numbers are set as a continuation from the previous firing experiment to avoid confusion.

7.4.1 Test Firing One

Five bullets were fired at individual branches of grouped thicknesses to investigate bullet impact evidence and bullet distortion level on the specific thickness of branches. The set up consisted of two large branches set in the front rank (70mm to 71mm thickness) with three to four smaller branches (25mm to 31mm) behind them in the second rank. The branches were attached to a metal rig to keep them in place, pictured in figure 7.24 below. The results from the firing experiment can be found in the table 7.10 below.

Figure 7.24: Front view of large branches.

7.4.1.1 Results

Bullet Number	Bullet weight pre-firing (g)	Bullet weight post-firing (g)	Bullet diameter pre-firing (mm)	Charge weight (g)	Target type	Angle of incidence	Impact velocity (m/s)
Bullet 41	24.26g	23.05g	16.20mm	6g	Simulated Hazel Hedge	90°	287m/s
Bullet 42	24.19g	23.71g	16.24mm	3g	Simulated Hazel Hedge	90°	191m/s
Bullet 43	24.47g	23.54g	16.31mm	4g	Simulated Hazel Hedge	90°	229m/s
Bullet 44	24.33g	23.50g	16.23mm	4g	Simulated Hazel Hedge	90°	239m/s
Bullet 45	24.81g	23.32g	16.24mm	6g	Simulated Hazel Hedge	90°	303m/s

Table 7.10: All five bullets fired at a simulated hazel hedge.

Bullet 41 (figure 7.25) was fired with a 6g charge and impacted the hedge at 287m/s; the simulated distance at impact was 104m. B41 impacted the front-rank branch (70.9mm thickness). Despite hitting the branch head on, the bullet rolled off and to the side of the branch and then impacted the smaller branch (26.66mm) behind it. Figure 7.26 below pictures B41's trajectory through the hedge. The bullet perforated the second branch and entered the soft capture system sideways at 282m/s. The bullet has been heavily distorted from impact leaving the bullet in a pancaked shape. Pitting and melting from firing can be seen on the back of the bullet, but melting from impact with the target has obscured the impact surface. No wood grain patterns are present, and the central point of impact appears less melted than the other sections of the bullet. However, it is worth noting that the central point of impact has taken on a different texture and slight discolouration than the surrounding bullet's surface. The bullet had a loss of 1.21g weight from firing and impact.

Figure 7.25: Impact surface of B41 under 10X magnification.

Figure 7.26: B41's trajectory through the hedge.

Bullet 42 (figure 7.27) was fired with a 3g charge and impacted the hedge at 191m/s; the simulated distance is below the average of ground impact. B42 missed the large branch in the front rank but impacted the small branch (31.29mm thickness) behind it and was found in the soft capture system. The Doppler radar did not record the velocity of the bullet as it exited the hedge for unknown reasons. The bullet perforated the branch at its centre and fractured the branch. B42 is slightly distorted from the impact process. The central point of impact appears to be the same location that contains pitting from firing, except that some small wood grains are imbedded in the surface, the pitting is much more noticeable than any impact evidence. A small region on the side of the bullet from where it perforated the branch has some wood grain impressions (thick linear striations) but this is only visible under 10X magnification. The bullet had a loss of 0.48g weight from firing and impact.

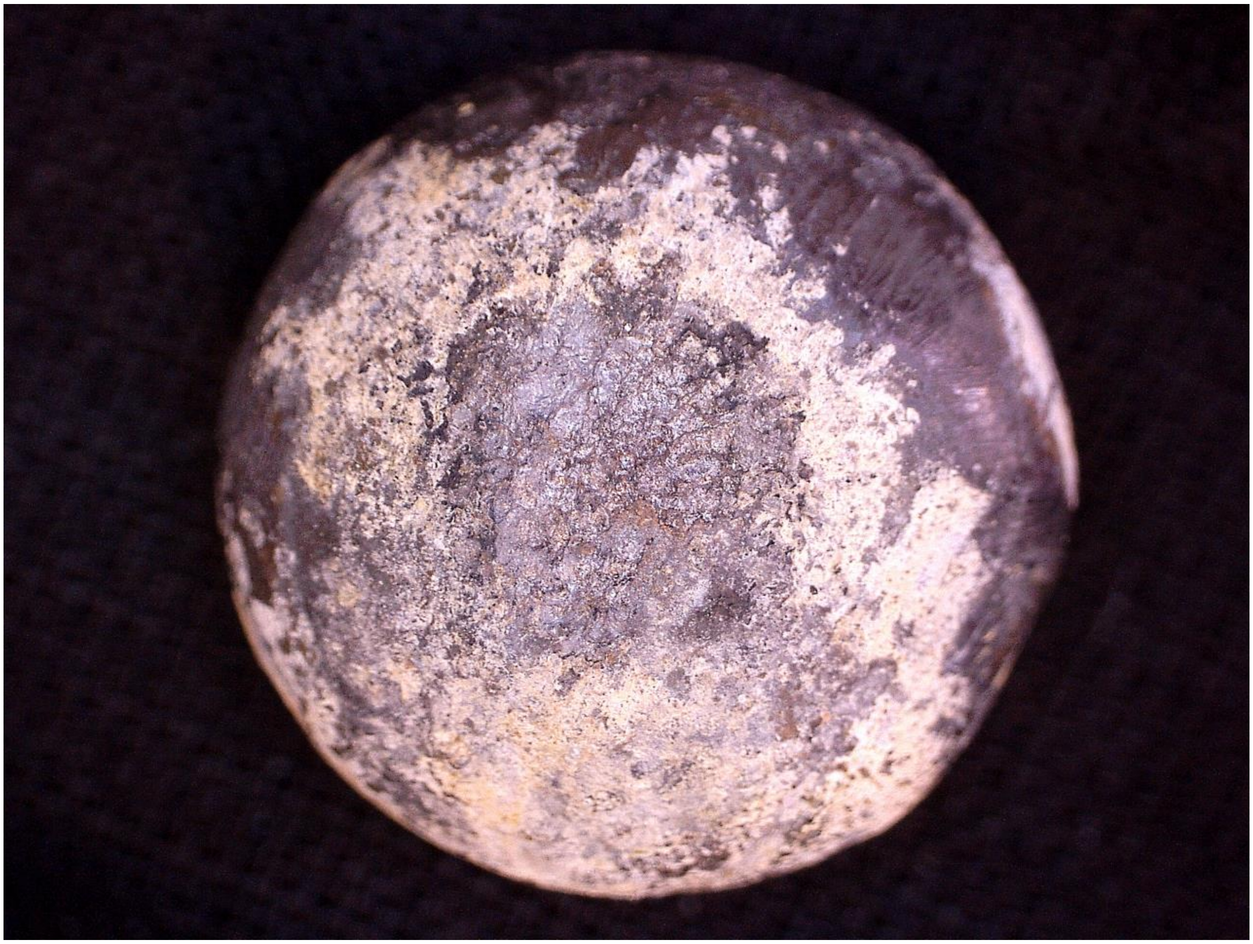

Figure 7.27: Impact surface of B42 under 10X magnification.

Bullet 43 (figure 7.28) was fired with a 4g charge and impacted the hedge at 229m/s; the simulated distance was around ground impact close to 192m. B43 impacted the large branch in the front rank (70.9mm thickness) fracturing it in half (figure 7.29) and rebounded before reaching the soft capture system, and the bullet was found located within the hedge. The bullet is heavily distorted from the impact process. Pitting and melting from the firing process denote the majority of the bullet's surface. The central point of impact is present but melting from the impact process has obscured the surface. The central point of impact has taken on a different texture and coloration from the rest of the bullet. The bullet had a loss of 0.93g weight from firing and impact.

Figure 7.28: Impact surface of B43 under 10X magnification.

Figure 7.29: 70.90mm thick branch fractured by B43.

Bullet 44 (figure 7.30) was fired with a 4g charge and impacted the hedge at 239m/s; with a simulated distance at impact of 181m. B44 impacted the large branch in the front rank (71.24mm thickness) fracturing it in half and then rebounded at an angle and was later found on the ground.

The bullet is heavily distorted from impact and is in a pancaked shaped piece. Melting and pitting from firing has obscured most of the impact surface. Some thick linear striations from wood grain impressions can be seen under 10X magnification. The bullet had a loss of 0.83g weight from firing and impact.

Figure 7.30: Impact surface of B44 under 10X magnification.

Bullet 45 (figure 7.31) was fired with a 6g charge and impacted the hedge at 303m/s; the simulated distance at impact was 94m. B45 missed the large branch in the front rank but impacted the small branch (29.48mm thickness) behind it and perforated it entering the soft capture system at 296m/s. The bullet is moderately distorted, slight linear striations can be seen in the central point of impact as wood grain impressions with some bits of wood adhering to the impact surface. The rest of the bullet is unremarkable as melting has obscured the surface. The bullet had a loss of 1.49g weight from firing and impact.

Figure 7.31: Impact surface of B45 under 10X magnification.

7.4.1.2 Discussion

Table 7.11 below is a summary of the experimental results.

Bullet Number	Charge Size (g)	Impact Velocity (m/s)	Exit Velocity (m/s)	Simulated Distance (m)	Weight Loss (g)	Distortion Level	Visibility of Wood Grain Impressions
B41	6g	287m/s	282m/s	104m	1.21g	HD	None
B42	3g	191m/s	Exited hedge, but NA	Ground Impact	0.48g	SD-MD	Present 10X Magnification
B43	4g	229m/s	Rebound	192m	0.93g	HD	None
B44	4g	239m/s	Rebound	181m	0.83g	HD	Present 10X Magnification
B45	6g	303m/s	296m/s	94m	1.49g	MD	Present

Table 7.11: Discussion data.

There is a strong correlation between charge size and bullet weight loss, as the R value from statistical analysis shows 0.09509. However, the amount of impact damage on the bullet is becoming a factor in the weight loss of the bullet as well. As bullets impacted the thicker logs in the hedge, smears of lead could be seen left behind. Such is the case for both sets of bullets fired with the same charge size. B43 and B44 were both fired with a 4g charge and their bullet's weight loss difference was 0.10g. However, impact velocity of both bullets was different, as were the levels of distortion from impact as both bullets impacted hedge branches of roughly the same size. B43 did perforate the branch it impacted, whereas B44 ricocheted. Could this act of perforation account for the 0.10g loss differential? The answer is currently unknown, although future experimentation may be able to answer this question. B41 and B45 were also fired with the same charge size for both bullets, although their velocities were different. The major difference between these two bullets is what they impacted. B41 impacted a branch 70.90mm thickness, whereas B45 impacted a branch of 29.48mm thickness. This may account for the weight loss differential of 0.28g.

Only one bullet had clear, visible wood grain impression at the central point of impact. Two other bullets did contain wood grain impressions but were only visible under 10X magnification. The final two bullets demonstrated no signs of wood grain impressions. All bullets fired in this experiment exhibited a higher than normal level of melting on their surfaces from the impact process. The reason for this is currently unknown, although it could be assumed that it is the result of impacting either thicker targets or multiple targets.

Impact velocity and simulated distance, when compared to the level of distortion on the bullet’s surface does not seem to be a major trend in this experiment. B45 had an impact velocity of 303m/s but recorded a low level of surface distortion. This is due to the thickness of the branch it impacted. The major factor that correlates to impact velocity now seems to be target thickness. Bullets 41, 43 and 44 have the most surface distortion and they all impacted the front-rank branches of 70mm thickness or more, and bullets 42 and 45 impacted branches of no more than 31mm and have a lower level of surface distortion.

The modelling data shows that hedges of this construction could in theory slow or influence the trajectory of a bullet, in relation to the thickness of the target in which the bullet impacted as well as the velocity of the bullet and how it impacted the branches. Bullets 43 and 44 both rebounded off branches of 70.9mm and 71.24mm thickness respectively from a simulated distance of 181m to 192m. However, Bullet 41 grazed a branch of 70.9mm thickness at a velocity well below ground impact (191m/s) but exited the hedge.

7.4.2 Test Firing Two

The Next 4 bullets were fired at configuration of a mock hedge 17.78cm in total thickness. The branches were grouped by thickness and made up of five ranks. The branches were cross hatched in rank four to simulate shoots of growing branches. Rank one was made up of the thickest branches between 50mm to 70mm thick. Rank two was made up of branches 10mm to 14mm thick, also to simulate shoots of new growth. Rank three was made up of branches 26mm to 30mm thick. Rank four was made up of a cross hatch of branches 12mm to 15mm thick to simulate new growth and rank five was made up of branches 26mm to 34mm thick. The branches were attached to a metal rig to secure them as can be seen in figure 7.32 below. The results from the firing experiment can be found in the table 7.12 below.

Figure 7.32: Front view of simulated hedge, five ranks deep.

7.4.2.1 Results

Bullet Number	Bullet weight pre-firing (g)	Bullet weight post-firing (g)	Bullet diameter pre-firing (mm)	Charge weight (g)	Target type	Angle of incidence	Impact velocity (m/s)
Bullet 46	24.51g	22.94g	16.30mm	6g	Simulated Hazel Hedge	90°	303m/s
Bullet 47	24.29g	22.87	16.29mm	6g	Simulated Hazel Hedge	90°	297m/s
Bullet 48	24.28g	23.14g	16.22mm	4g	Simulated Hazel Hedge	90°	230m/s
Bullet 49	24.37g	22.06g	16.17mm	12g	Simulated Hazel Hedge	90°	502m/s

Table 7.12: All four bullets fired at the simulated hazel hedge.

Bullet 46 was fired with a 6g charge and impacted the hedge at 303m/s; the simulated distance at impact was 94m. B46 impacted the front-rank branch (66.40mm thickness), then, impacted a knot in the wood and rebounded backwards into the metal rig holding the configuration together. The bullet is heavily distorted from impacting the metal rig and the bullet was discarded from the study. The bullet had a loss of 1.57g weight from firing and impact.

Bullet 47 (figure 7.33) was fired with a 6g charge and impacted the hedge at 297m/s; the simulated distance at impact was 97m. B47 entered the hedge by grazing a large branch in the first rank (50.73mm thickness), then missed the second rank. The bullet impacted a branch of 26.86mm thickness in the third rank, then missed all branches in the fourth rank. The bullet finally grazed a branch of 33.93mm thickness in the 5th rank, before entering the soft capture system at 291m/s. The bullet entered the soft capture mechanism at an angle and was not slowed down enough to remain in the soft capture system. The bullet was found on the ground wrapped in cotton, which in turn protected the bullet from further damage when it landed on the ground. The bullet is heavily distorted from the impact process. Pitting and melting are present, along with a thick barrel band that had the wood grain impressions superimposed over it. Two major points of impact are on the bullet’s surface creating a large spine of lead to separate them, impossible to say which came first or which branch caused the effect. However, the section of superimposition is better preserved from melting. The bullet had a loss of 1.42g weight from firing and impact.

Figure 7.33: Impact surface of B47.

Bullet 48 (figure 7.34) was fired with a 4g charge and impacted the hedge at 230m/s; the simulated distance at impact was just after ground impact, close to 191m. B48 impacted every rank of branches and the bullet's trajectory through the hedge was impossible to record. The bullet exited the hedge at 228m/s. The bullet contains thick linear striations with adhering bits of wood in the impact surface. The bullet has moderate distortion, and the central point of impact contains wood grain impressions. The bullet had a loss of 1.14g weight from firing and impact.

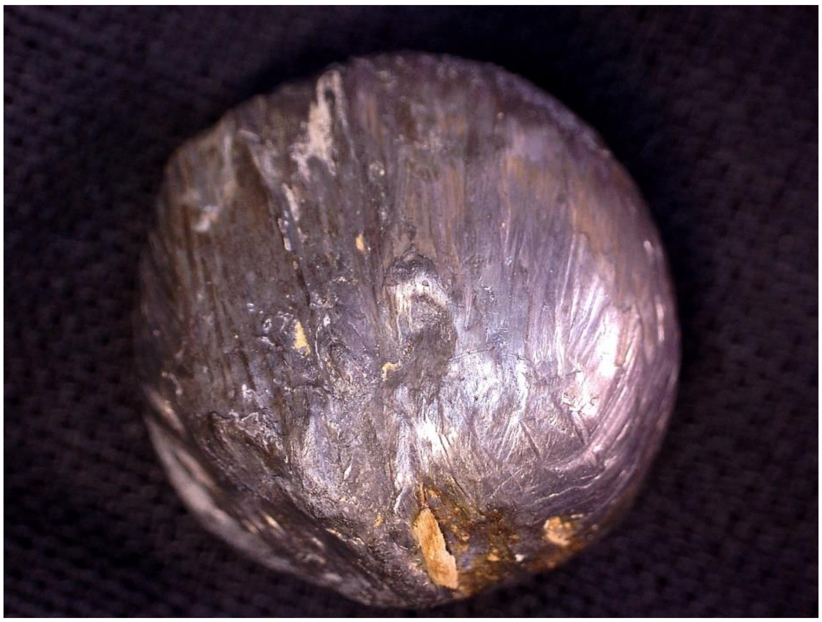

Figure 7.34: Impact surface of B48 under 10X magnification.

Bullet 49 (figure 7.35) was fired with a 12g charge and impacted the hedge at 502m/s. The simulated distance was point blank. The trajectory of the bullet through the hedge was impossible to identify as the branches shattered in all directions once the bullet entered the hedge. At some point the bullet rebounded from contact with one or multiple branches in the hedge and was discovered on the floor a few meters to the left of the hedge. B49 is heavily distorted and irregular in shape. It is difficult to determine if the irregular shape is due to the high velocity at impact, and the multiple impact events or due to the bullet ricocheting from the hedge and hitting the ground. Bits of lead are folded over in a seemingly random fashion. There are splinters of wood adhering to the impact surface, and thick linear striations are recorded on the impact surface. The bullet had a loss of 2.31g weight from firing and impact.

Figure 7.35: Impact surface of B49 under 10X magnification.

7.4.2.2 Discussion

Table 7.13 below is a summary of the experimental results.

Bullet Number	Charge Size (g)	Impact Velocity (m/s)	Exit Velocity (m/s)	Simulated Distance (m)	Weight Loss (g)	Distortion Level	Visibility of Wood Grain Impressions
B46	6g	303m/s	Impacted Knot and Rebounded	94m	1.57g	HD	NA
B47	6g	297m/s	291m/s	97m	1.42g	HD	Present
B48	4g	230m/s	228m/s	191m	1.14g	MD	Present
B49	12g	502m/s	Rebound	Point Blank	2.31g	HD-I	Present

Table 7.13: Discussion data.

Bullet weight loss and charge size continue to show a trend, as does impact velocity, simulated distance and distortion level; however, the sample size was too low for statistical analysis. All bullets fired in this experiment, with the exception of B46 which was discarded because it rebounded and impacted the steel rig securing the hedge in place, show wood grain impressions at the central point of impact with linear striations on other regions of the bullet.

The thickness of the target impacted as well as the number of targets impacted influence the distortion level of the bullet. B48 was rated as moderately distorted although it impacted a branch in every rank of the hedge; however, it was not possible to record the trajectory through the hedge as a result of the large amount of debris from the multiple impact events. B48 did contain thick linear striations with adhering wood in the impact surface, along with wood grain impressions in the central point of impact. Alternatively, B47 grazed a branch 50.73mm thick, then impacted a branch 26.86mmin thickness, before finally grazing a 33.93mm thick branch. B47 impacted several branches in the hedge and was rated as heavily distorted. B47 shows two major impact points, either from perforating the second branch or from grazing both branches; it was not possible to definitively determine the sequence of impacts.

The ability to determine the trajectory of B49 through the hedge was not possible either. The bullet did impact multiple branches and rebounded from the hedge and was located on the ground within the hedge. It could be possible that the bullet impacted a knot in the wood as did B46, but due to the damage sustained to B46 when impacting the metal rig, comparison was not possible. The bullet did contain thick linear striations as well as wood grain impressions.
The modelling data shows that the simulated hedge with an increased thickness of five ranks, could influence the trajectory of the bullet as it penetrated or perforated through the hedge. B46 rebounded from the hedge as a result of impacting a knot in the branch it impacted, whereas B47, fired with a similar charge size and impacted the hedge with a similar velocity and simulated distance, perforated the hedge only losing 6m/s from its velocity. B48 was fired from a simulated distance of 191m and perforated the hedge at 228m/s, having only lost 2m/s from its velocity. B49 is the curious case, as the bullet was fired from point blank range and impacted the hedge at 502m/s but rebounded. It could be as a result of impacting a knot in one of the branches, as B46 did; however, it was not possible to track B49's trajectory so there is no definitive explanation.

7.4.3 Test Firing Three

The next 7 bullets were fired at configuration of a simulated hedge 60.96cm in total thickness and was made up of a total of nine ranks. The branches were not grouped by thickness but were carefully placed and labelled to be identified after the bullet passed through them in anticipation of the previous experiment in which the hedge branches shattered in every direction upon impact creating a debris field that made it impossible to track the bullet's trajectory through the hedge. However, even with careful recording of every branch in every rank, the bullet's trajectory could not be recorded for the same reason. The charge sizes selected for this firing experiment, range from a full charge of 12g to 1.5g charge; this was completed to explore impact evidence and bullet distortion level along the musket's maximum range. The results from the firing experiment can be found in the table 7.14 below.

7.4.3.1 Results

Bullet Number	Bullet weight pre-firing (g)	Bullet weight post-firing (g)	Bullet diameter pre-firing (mm)	Charge weight (g)	Target type	Angle of incidence	Impact velocity (m/s)
Bullet 50	24.33g	24.24g	16.22mm	1.5g	Simulated Hazel Hedge	90°	98m/s
Bullet 51	24.41g	23.60g	16.24mm	4g	Simulated Hazel Hedge	90°	240m/s
Bullet 52	24.34g	22.80g	16.13mm	6g	Simulated Hazel Hedge	90°	290m/s
Bullet 53	24.04g	22.82g	16.15mm	8g	Simulated Hazel Hedge	90°	370m/s
Bullet 54	24.31g	X	16.20mm	10g	Simulated Hazel Hedge	90°	437m/s
Bullet 55	23.98g	18.67g	16.22mm	10g	Simulated Hazel Hedge	90°	442m/s
Bullet 56	24.37g	22.51g	16.17mm	12g	Simulated Hazel Hedge	90°	500m/s

Table 7.14: All seven bullets fired at the simulated hazel hedge.

Bullet 50 (figure 7.36) was fired with a 1.5g charge and impacted the hedge at 98m/s. The simulated distance to impact was well below the average of ground impact. It was not possible to track the trajectory of the bullet through the hedge, even with all the branches labelled before the firing took place. The bullet impacted the hedge and rebounded having never fully penetrated the hedge. B50 is moderately distorted, with thick linear striations on the outer perimeter of the bullet. The central point of impact contains wood grain impressions, is discoloured and of a different texture. The bullet had a loss of 0.09g weight from firing and impact.

Figure 7.36: Impact surface of B50.

Bullet 51 (figure 7.37) was fired with a 4g charge and impacted the hedge at 240m/s; the simulated distance at impact was 179m. The bullet was found in between ranks five and six of the hedge and the trajectory of the bullet was not possible to record. B51 is heavily distorted and pancaked. A flat facet is found on the bottom of the bullet, although this is likely from hitting the ground after it fell from the hedge. The impact surface of the bullet contains some thick and somewhat disorganised linear striations from impact. The bullet had a loss of 0.81g weight from firing and impact.

Figure 7.37: Impact surface of B51.

Bullet 52 (figure 7.38) was fired with a 6g charge and impacted the hedge at 290m/s; the simulated distance at impact was 102m. It was not possible to track the trajectory of the bullet through the hedge. The bullet entered the hedge and was found in the soft capture system, having exited the hedge at 285m/s. B52 is heavily distorted and pancaked. The level of surface melting obfuscates any indication of what it impacted. No striations are present other than lead flow from the point of impact towards the outer perimeter of the bullet. The bullet had a loss of 1.54g weight from firing and impact.

Figure 7.38: Impact surface of B52.

Bullet 53 (figure 7.39) was fired with an 8g charge and impacted the hedge at 370m/s; the simulated distance at impact was 56m. It was not possible to track the trajectory of the bullet through the hedge. The bullet entered the hedge and was found in the soft capture system, having exited the hedge at 366m/s. B53 is heavily distorted, remaining in a hemispherical shape. The outer portions of the bullet’s surface and the regions around the central point of impact show linear striations from wood grain impressions; however, the central point of impact on the bullet is disorganised and discoloured along with a slight texture change due to melting from impact. The bullet had a loss of 1.22g weight from firing and impact.

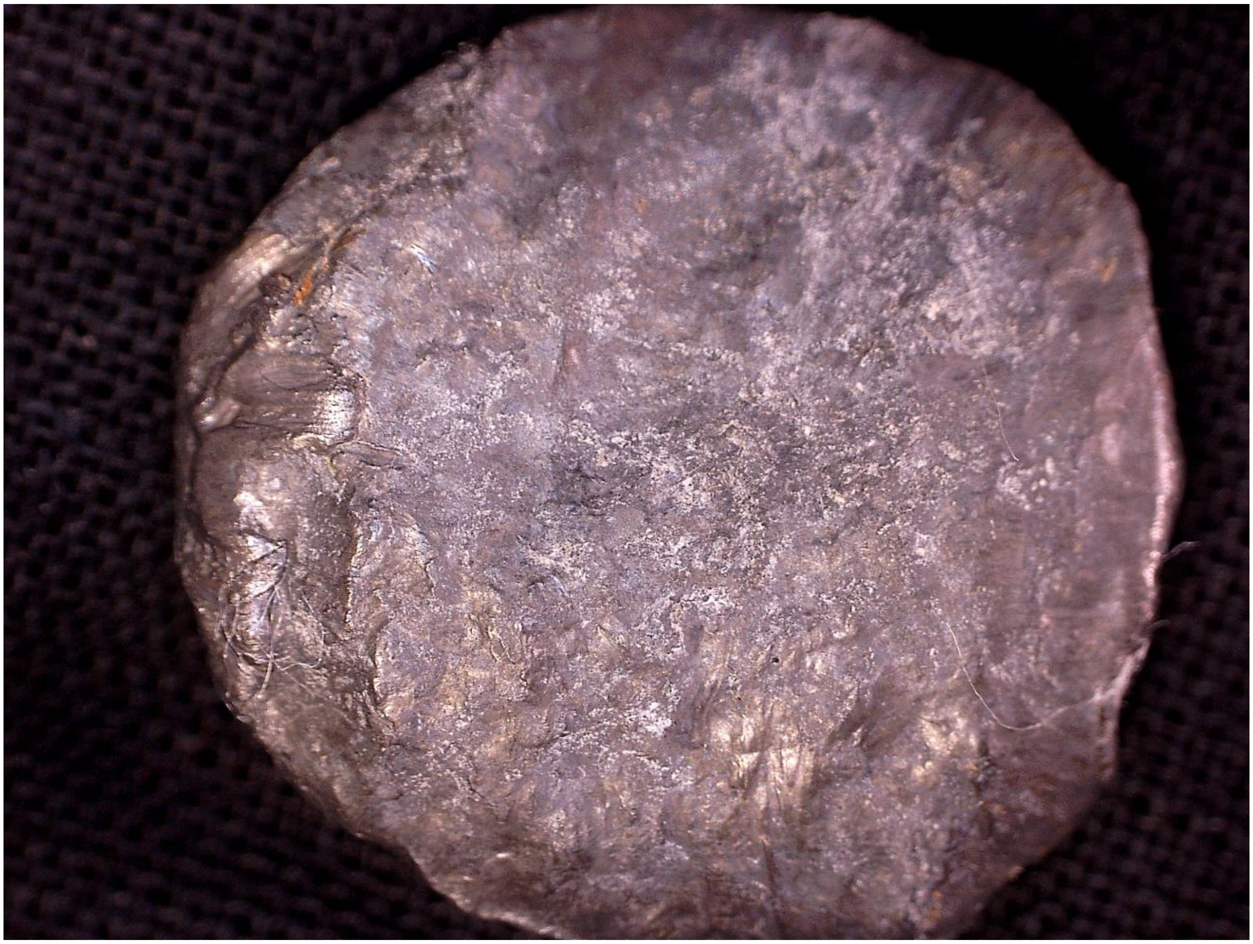

Figure 7.39: Impact surface of B53 under 10X magnification.

Bullet 54 was fired with a 10g charge and impacted the hedge at 437m/s; the simulated distance at impact was 15m. It was not possible to track the trajectory of the bullet through the hedge. The bullet entered the hedge, cleared the soft capture system and was lost in the sand embankment at the end of the firing range.

Bullet 55 (figure 7.40) was fired with a 10g charge and impacted the hedge at 442m/s; the simulated distance at impact was 13m. It was not possible to track the trajectory of the bullet through the hedge. The bullet entered the hedge and was found in the soft capture system, having exited the hedge at 439m/s. B55 is heavily distorted and irregular in shape. It is possible to tell that it impacted multiple branches while penetrating the hedge, like B47, the bullet contains a spine through its centre from its multiple impact events. In both impact events it is possible to see linear striations and wood grain impressions along with bits of adhering wood to the impact surfaces, although it is easier to make out under 10X magnification. The bullet had a loss of 5.31g weight from firing and impact. The exact reason for the excessive weight loss to this bullet is unknown.

Figure 7.40: Impact surface of B55.

Bullet 56 (figure 7.41 and figure 7.42) was fired with a 12g charge and impacted the hedge at 500m/s, the simulated distance at impact was point blank. The bullet fractured the branch in the front rank with a thickness of 69.51mm and grazed the branch in the second rank with a thickness of 33.92mm. The bullet then cleared the remaining hedge and was found in the soft capture system, having exited the hedge at 495m/s. B56 is heavily distorted to the point where the bullet has begun folding backwards with its impact point bulging outwards and folding back, with the non-impact surface being concave. Melted lead flowing backwards almost covered the wood grain impression. Linear striations can still be observed on the bullet’s surface. The bullet had a loss of 1.86g weight from firing and impact.

Figure 7.41: Impact surface of B56.

Figure 7.42: Non-impact surface of B56.

7.4.3.2 Discussion

Table 7.15 below is a summary of the experimental results.

Bullet Number	Charge Size (g)	Impact Velocity (m/s)	Exit Velocity (m/s)	Simulated Distance (m)	Weight Loss (g)	Distortion Level	Visibility of Wood Grain Impressions
B50	1.5g	98m/s	Rebound	Ground Impact	0.09g	MD	Present
B51	4g	240m/s	Rebound	179m	0.81g	HD	Present
B52	6g	290m/s	285m/s	102m	1.54g	HD	None-Surface Melting
B53	8g	370m/s	366m/s	56m	1.22g	HD	Present
B55	10g	442m/s	439m/s	13m	5.31g	HD	Present
B56	12g	500m/s	495m/s	Point Blank	1.86g	HD	Present

Table 7.15: Discussion data.

Bullet weight loss and charge size continue to show a trend, as does impact velocity, simulated distance and distortion level. However, the true trend developing is the overall thickness of the target and the multiple targets impacted by each bullet. It is not possible to properly quantify this trend due to the inability to track the bullet’s trajectory through the hedge. The bullets fired in this experiment show a high level of surface distortion from impact due to the overall thickness of the hedge and the multiple impact events for each bullet. Despite the best efforts to label each branch to track the bullet’s trajectory through the hedge it was not possible due to the debris created from impact. Splinters of wood were located everywhere in the firing range, including the ceiling above the hedge and within the soft capture system itself.

Most bullets fired in this experiment display wood grain impressions in the central point of impact, followed by thick linear striations along varying regions of the bullet’s surface. The exception was B52 whose surface was obscured from melting due to the impact process.

The modelling data shows that bullets fired from a simulated distance of 179m and beyond, rebounded from the hedge. Bullets fired within a range of 100m to point blank range perforated the hedgerow with minimal velocity loss to the bullet.

7.4.4 Simulated Hazel Hedge Discussion

The developing trend throughout all three test firings with the simulated hazel hedge was the bullet's weight loss to charge size, with the higher the charge size equating to the more weight loss on average to the bullet. Another trend that began to develop was the bullet's distortion level from impact and the bullet's impact velocity or simulated firing distance. The closer the musket was located to the target, the higher the impact velocity and the greater the level of distortion from impact. However, this trend has been further complicated by another developing trend which was the overall thickness of the target and the number of impact events by each bullet as it travelled through the simulated hedge. Even with great effort, it was simply not possible to track the bullet's trajectory through the hedge, which means any attempt to quantify this trend is currently not possible.

Of the fourteen bullets successfully soft captured for analysis, nine bullets contain a central point of impact showing wood grain impressions, along with thick linear striations from perforating or grazing other branches within the hedge. Two bullets display the same impact evidence as described above, but only under 10X magnification and three bullets demonstrate no signs of impacting a wooden target due to the bullet's surface having been obscured by melting from the impact process. This experiment demonstrates that when a bullet impacts a hedge there is a 21% chance that the bullet will not take any impression from the branches it impacts which could make identification during analysis of the archaeological bullet assemblages somewhat problematic. However, there is a 79% chance that the bullet will take on the impact evidence from impacting a hedge, although it may not be possible to definitively determine how many branches it impacted or how thick the target was, as this is all dependent on the bullet's impact velocity and firing distance.

Another issue that may arise is the level of corrosion on the surface of the archaeologically recovered bullets. The two bullets captured in these experiments where the impact evidence is only visible under 10X magnification may have their impact surface obfuscated by corrosion as was demonstrated in the experiments conducted by Stuart Harkins in Chapter Three, section 3.5.

The results from the modelling data suggest that using a hedge during combat as an entrenched position would have provided moderate cover from incoming firing, although this needs to be tested in real world scenarios to be definitive. Multiple bullets perforated the hedge from a simulated firing distance over 191m from musket to target with minimal loss to the bullet's velocity, meaning the bullet would have then continued onward after perforating the hedge. Interestingly, 57% of bullets fired into the hedge construction perforated the hedge. Those bullet's velocities ranged from 191m/s to 500m/s at impact with simulated firing distances covering from below the average of ground impact to point blank range. 43% of bullets rebounded from the hedge construction from either impacting thick branches, knots in the wood, or for unknown reasons. Those bullets' velocities also ranged from 98m/s to 502m/s at impact with simulated firing distances covering from well below the average of ground impact to point blank range. The construction of a hedge could slow the bullet down or influence the bullet's trajectory by means of rebound or ricochet but generally did not prevent the bullet from perforating the hedge entirely. To make matters worse for those standing behind the hedge, copious amounts of debris and splintered wood were sent in every direction upon impact. Significant amounts of wood and large splinters were found in the soft capture system which surely means that the soldiers using the hedges for cover or concealment could have been wounded by the debris as well, but to the degree or severity of those wounds cannot be conclusively stated.

7.5 Hawthorn Wood Test Firing

Six bullets were fired into Hawthorn branches to investigate wood impact impressions of different types and species of wood. The Hawthorn branches were cut 24 hours before the firing experiment and secured in a vertical fashion to a metal rig as pictured in figure 7.43. Gunpowder charge sizes range from 12g to 1.5g to investigate bullet impact evidence and bullet distortion level along the musket’s maximum range. Bullet numbers are set as a continuation from the previous firing experiment to avoid confusion. The results from the firing experiment can be found in the table 7.16 below.

Figure 7.43: Hawthorne construction.

7.5.1 Results

Bullet Number	Bullet weight pre-firing (g)	Bullet weight post-firing (g)	Bullet diameter pre-firing (mm)	Charge weight (g)	Target type	Angle of incidence	Impact Velocity (m/s)
Bullet 57	24.12g	23.98g	16.18mm	1.5g	Hawthorn Branches	90°	NA
Bullet 58	24.29g	23.47g	16.29mm	4g	Hawthorn Branches	90°	235m/s
Bullet 59	24.25g	22.90g	16.28mm	6g	Hawthorn Branches	90°	308m/s
Bullet 60	24.53g	22.80g	16.31mm	8g	Hawthorn Branches	90°	350m/s
Bullet 61	24.25g	22.88g	16.21mm	10g	Hawthorn Branches	90°	433m/s
Bullet 62	24.10g	22.22g	16.28mm	12g	Hawthorn Branches	90°	496m/s

Table 7.16: All six bullets fired into Hawthorn branches.

Bullet 57 (figure 7.44) was fired with a 1.5g charge and impacted the branches at an unknown velocity, because the Doppler radar did not record the impact. The bullet grazed a branch that was 13.11mm thick before entering the soft capture system. B57 is slightly distorted from impact. Striations from the barrel band are clearly seen on the bullet's surface. A slight circular indentation is on the impact surface and linear striations can be seen; however, it is impossible to tell if this is from the barrel band or the wood grain impression. The bullet had a loss of 0.14g weight from firing and impact.

Figure 7.44: Impact surface of B57.

Bullet 58 (figure 7.45) was fired with a 4g charge and impacted the branches at 235m/s; the simulated distance at impact was 190m. The bullet grazed a branch that was 19.72mm thick before entering the soft capture system. B58 is slightly distorted in two different points suggesting the bullet struck two branches before entering the soft capture system. One point of impact shows slight, but deep striations from wood grain impressions, the second point of impact is a depressed circular shape with a polished lip off the edge of the bullet. This lip contains linear striations from wood grain impressions. The bullet had a loss of 0.82g weight from firing and impact.

Figure 7.45: Impact surface of B58 under 10X magnification.

Bullet 59 (figure 7.46) was fired with a 6g charge and impacted the branches at 308m/s; the simulated distance at impact was 92m. The bullet perforated a branch that was 25.34mm thick, creating an entrance hole 23.03mm in width and an exit hole that was 69mm in width. B59 is moderately distorted. The central point of impact shows discolouration and slight texture changes, but no striations or wood grain impressions due to melting from impact. The bullet had a loss of 1.35g weight from firing and impact.

Figure 7.46: Impact surface of B59.

Bullet 60 (figure 7.47 and figure 7.48) was fired with an 8g charge impacting the branches at 350m/s; the simulated distance at impact was 72m. B60 is moderately distorted and much like B47 and B55 struck at least two branches, with a spine separating the two impact surfaces. Impact surfaces show melting of lead but no impact striations. The bullet had a loss of 1.73g weight from firing and impact.

Figure 7.47: Impact surface of B60.

Figure 7.48: The arrow is pointing to the overhead view of the spine on B60.

Bullet 61 (figure 7.49) was fired with a 10g charge and impacted the branches at 433m/s; the simulated distance at impact was 17m. The bullet perforated a branch that was 28.30mm thick and fractured it before entering the soft capture system. B61 is heavily distorted and pancaked, the bullet has a long tail that has begun to fold backwards. Impact surface shows melting with no striations or wood grain patterns. The bullet had a loss of 1.37g weight from firing and impact.

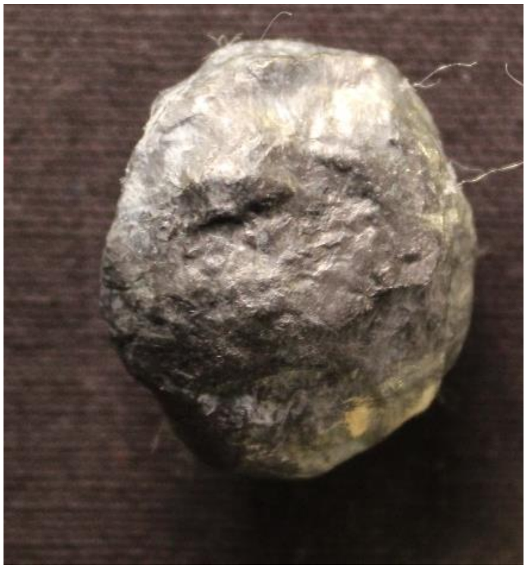

Figure 7.49: Impact surface of B61.

Bullet 62 (figure 7.50) was fired with a 12g charge impacting the branches at 496m/s; the simulated distance was point blank. B62 is heavily distorted and shows signs that it impacted a branch at an angle as the lead is leading off the central axis of the impact surface. No wood grain impressions or linear striations are present as melting obfuscated them. It was not possible to track the bullet’s trajectory though the hedge. The bullet had a loss of 1.88g weight from firing and impact.

Figure 7.50: Impact surface of B62.

7.5.2 Discussion

Table 7.17 below is a summary of the experimental results.

Bullet Number	Charge Size (g)	Impact Velocity (m/s)	Simulated Distance (m)	Weight Loss (g)	Distortion Level	Visibility of Wood Grain Impressions
B57	1.5g	NA	NA	0.14g	SD	Present
B58	4g	235m/s	189m	0.82g	SD-MD	Present
B59	6g	308m/s	92m	1.35g	MD-HD	None
B60	8g	350m/s	71m	1.73g	SD-MD	None
B61	10g	433m/s	17m	1.37g	HD	None
B62	12g	496m/s	Point Blank	1.88g	HD	None

Table 7.17: Discussion data.

The Pearson correlation coefficient statistical analysis was used to determine the correlation between charge size and bullet weight loss, with the R value at 0.9049 showing a strong positive correlation. However, B60 or B61 are potential outliers in this trend, as B60 impacted multiple

branches at a lower velocity, and B61 impacted and perforated a branch of 28.30 thickness. B60’s impact with multiple branches could account for the extra weight loss to the bullet.
The trend between impact velocity and simulated distance against the bullet’s distortion level is also still present, although B59 defies the trend. This could be attributed to the relative thickness of the branch B59 impacted which was 25.34mm in thickness. The relative thickness of that branch is similar the branch impacted by B61, which also received a similar distortion level. Most bullets from this experiment show no signs of wood grain impression or linear striations from impact, as the impact surface of the bullet has been obscured by melting. The two bullets that do contain impact evidence display thick linear striations, along with wood grain impressions and a slight depression circular in shape on the impact surface.

7.6 A New Firing Methodology using Nitro Gunpowder

As noted in Chapters Four and Five of this thesis, a moratorium on the handling and firing of black powder was placed on all Ministry of Defence firing ranges. To continue experimental firing for this thesis a new firing methodology needed to be implemented. This means that the first method of firing the bullet via musket and black powder was now no longer viable, which also meant that the way the firearm and bullet were loaded had to be changed as well. With the creation of the external ballistic trajectory modelling program (Chapter Six), velocity at certain ranges had been previously established using black powder as a propellant. These known data points can be used as reference guide when using or substituting for a different form of gunpowder, such as nitro powder. A potential problem; however, with using nitro powder is the belief that it would increase the destruction to the bullet’s surface during firing. This variable will need to be isolated and minimized. Greene (2010) demonstrated that a ‘musket ball’ could be fired from a shotgun cartridge, using a shotgun barrel. Greene; however, used black powder (see Chapter Three, section 3.8) while in this experiment, this thesis will be substituting black powder for modern nitro powder.

7.6.1 Materials, Method and Loading and Firing Procedure

The diameter measurements and weights of all bullets were taken and tabled before firing to inform bullet analysis post firing, and to investigate bullet weight loss due to the firing and impact process. A 12-gauge shotgun barrel was loaded with a shotgun cartridge, containing both powder and musket bullet. The powder charge was a predetermined amount Noble Sport A1 Nitro powder used for handloading shotgun cartridges (1.5g to 0.9g charge in various increments), firing a 19-bore bullet (24g). The shotgun barrel was fixed to a universal gun mount at a horizontal firing height of 1.39m at a 0° elevation parallel to the ground and can be seen in figure 7.51 below. The shotgun barrel was remote fired using an ISFE 9-volt electric match to prevent human error. Doppler radar was used to measure the muzzle velocity of each bullet as it was fired directly into the soft capture system. The soft capture system remained unchanged.

Figure 7.51: Shotgun barrel set up.

7.6.1.1 Cartridge Loading

Before the firing experiment, the bullets were hand loaded into 12-gauge shotgun cartridges. The cartridges were empty and loaded thusly using a hand loading press:

- An empty 12-gauge shotgun shell was placed on the press, and a predetermined amount of nitro powder was added to the bottom of the cartridge.
- Next, a sabot was loaded into the cartridge.
  The sabot has a small petal cup at the top that holds the ball in place without giving any undue stress to the surface of the bullet. The bullet is held loosely in place in the petal cup, so the sabot can separate from the ball during flight. (A sabot takes up the windage, see figure 7.52)
- Next, a small circular, carboard wad was added to the petal of the sabot
- Next, the bullet was added to the sabot's petal cup
- Finally, the cartridge was crimped shut, see figure 7.53.

Figure 7.52: Sabot.

Figure 7.53: 12-gauge shotgun cartridge loaded with the 24g bullet.

7.7 Experimental Firing into Soft Capture using Nitro Powder

The purpose of this experiment was twofold. First, to create a new firing methodology without using black powder, but using black powder velocity data as a reference point to investigate if this was a viable option. The nitro charge size was varied in each cartridge to examine and collect velocity data for each bullet. This velocity data would be later compared to previous reference points collected from black powder firings to verify the velocity data results and to adjust charge sizes moving forward so that they more closely represent the black powder velocity data. The second aim was to soft capture each bullet and to examine the bullet's surface for the effects that the nitro powder may have on the bullet during the firing process. All bullets would be fired and tracked down range using Doppler radar to measure velocity and all bullets would be fired directly into the soft capture system for macro and microscopic analysis. A paper target was placed down range before the soft capture system to verify the bullet's flight path, this was done due to some original concern that when the bullet separated from the sabot the bullet's flight path may have been altered.

The experimental firing was conducted at the Defence Academy at Shrivenham, Cranfield University. Firing took place in the Enfield Small Arms Experimental Range (No 3 Range), under the guidance of Mr Steve Champion and Mr Dave Miller.

7.7.1 Results and Discussion

15 bullets were fired down range and directly into the soft capture system. Results can be seen in table 7.18 below. Bullet numbers are set as a continuation from the previous firing experiment to avoid confusion. Charge sizes were varied to not only simulate distance, but to examine the muzzle velocity data points produced by the nitro powder, which could be compared to the black powder muzzle velocity data points and enable one to refine the amount of nitro powder needed to equal the black powder data points.

Bullet Number	Bullet weight (grams)	Bullet Diameter (mm)	Nitro Charge size (grains)	Nitro Charge size (grams)	Velocity Data (m/s)	Simulated Firing Distance (m)
Bullet 63	24.41g	16.18mm	25gr	1.62g	386m/s	46m
Bullet 64	24.30g	16.20mm	25gr	1.62g	431m/s	18m
Bullet 65	23.97g	16.21mm	23.5gr	1.5g	370m/s	64m
Bullet 66	24.38g	16.31mm	23.8gr	1.5g	362m/s	64m
Bullet 67	24.07g	16.22mm	23.5gr	1.5g	367m/s	64m
Bullet 68	24.11g	16.23mm	20gr	1.3g	303m/s	95m
Bullet 69	24.47g	16.26mm	20gr	1.3g	303m/s	95m
Bullet 70	24.40g	16.26mm	20gr	1.3g	326m/s	95m

Bullet 71	24.41g	16.26mm	17gr	1.1g	213m/s	Ground Impact-193+
Bullet 72	24.46g	16.26mm	17gr	1.1g	248m/s	Ground Impact-193+
Bullet 73	24.57g	16.29mm	17gr	1.1g	231m/s	Ground Impact-193+
Bullet 74	24.34g	16.22mm	14gr	0.9g	182m/s	Ground Impact-193+
Bullet 75	24.23g	16.29mm	14gr	0.9g	159m/s	Ground Impact-193+
Bullet 76	24.13g	16.26mm	14gr	0.9g	178m/s	Ground Impact-193+

Table 7.18: Nitro soft capture bullet firing.

The charge sizes used varied between 1.5g to 0.9g of nitro powder, and the velocity data recorded is in accordance with the results from previous black powder firing experiments. However, a higher charge size needs to be used to simulate the upper end of firing, closer to true muzzle velocity. Bullet velocity was in the sought-after range between 457m/s and 100m/s, depending on charge size. Velocity data was relatively constant within the same charge. So, all 1.5g charges had a velocity around 365m/s and so on, as can be seen in the table 7.18 above. The sabot had no effect on the bullet's flight path as per original concerns.

14 Bullets were successfully found in the soft capture system, and one bullet was lost due to poor aiming. The damage to the bullet's surface from firing in this manner is minimal to non-existent and what compression from the sabot that is present is easily identified. The velocity data is in the right neighbourhood but does require some slight adjustments moving forward.
The bullet's surface did take on some circular compression from the sabot, and a slight indentation from the petal cup of the sabot; this can be seen in figure 7.54 below. This evidence is easy to identify and is constant regardless of velocity. They are; however, less pronounced with lower charge sizes. Banding is present on all fired bullets as well, but absolutely no pitting was present on any bullet, and absolutely no melting of the lead occurred during the firing process, leading to no weight loss for each bullet. Some bullets seem to have a larger diameter

than others because of how the bullet was loaded into the cartridge and therefore received the compression from being fired.

As the nitro gunpowder velocity data is in accordance with the black powder velocity data, and the damage to the bullet from the firing process was minimal, it was decided that for the remaining ground firing experiments within this thesis would be conducted using this new firing methodology created solely by and for this thesis. This is an innovative new experimental firing methodology never before used during experimental firing with 'musket balls.'

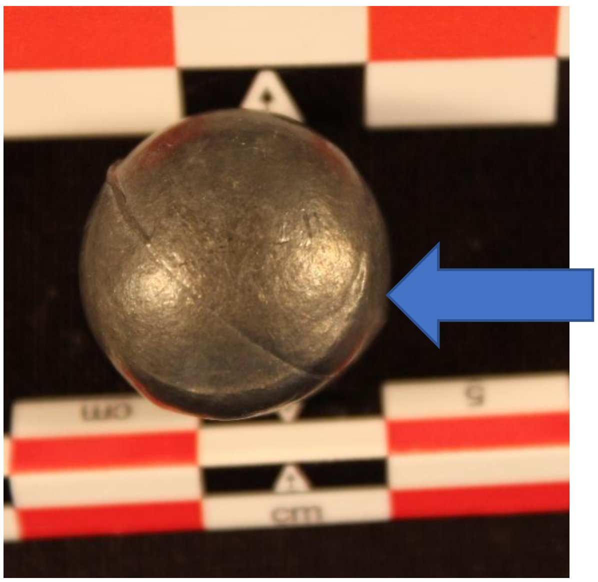

Figure 7.54: Bullet 63 fired using the new nitro method, notice the slight lip around the bullet near the scale, this is from the petal cup in the sabot.

7.8 Ground Firing Experiments: Bounce, Roll and Ricochet

As noted in Chapter Two, section 2.4.1.2, it is believed that most of the bullets recovered during a battlefield survey were the result of the bullet missing its intended target by means of over or under firing. Once the bullet missed its target, it would continue its flight path until its trajectory decayed and the bullet impacted the ground. Once the bullet impacted the ground it proceeded to bounced and roll until its kinetic energy was expended, and the bullet came to a full stop. Previous experiments completed with the bounce and roll of masonry debris demonstrated that the bounce or ricochet of a spherical shaped object can be predicted (Knock *et al.* 2004). It was decided that the only means of collecting evidence of impact from the bounce and roll of a bullet over the ground surface in a controlled setting was to create a box, filled with soil, inside the firing range and to fire bullets into the box at an angle to ricochet the bullet into the soft capture system. As noted in Chapter Five, section 5.6, this experiment could not be conducted in ‘a real-world scenario’ and had to be conducted in the indoor firing range. The ground firing experiment had two aims, one to fire numerous bullets into sterile soil conditions and ricochet them into soft capture for analysis. The second aim was to then add stones to the soil matrix and fire bullets into the soil for capture and analysis.

7.8.1 Materials

The soil box was constructed on top of two shipping pallets, so it could be moved into and out of the firing range. Moisture resistant MDF was used as the bottom baseboard and treated sawed timber planking was used to construct the side and end wall frames. The soil was screened topsoil used for growing vegetables. The soil was screened at 10mm to remove any and all oversized lumps of soil and large stones. Small pebbles were retained in the soil to assist in drainage for growing purposes but were too small to be remove effectively. It was decided to leave those small pebbles in the soil matrix. The soil box construction can be seen in figure 7.55.

Figure 7.55: Sterile soil box construction.

The second stage of the experiment involved adding larger stones into the soil matrix to simulated more stony ground conditions and to collect bullet evidence from these impacts. The stones added were common landscaping decorative stones relatively uniform in size between 2cm to 5cm in total length.

7.8.2 Methods

The diameter measurements and weights of all bullets were taken and tabled before firing to inform bullet analysis post firing, and to investigate bullet weight loss due to the firing and impact process. A 12-gauge shotgun barrel was loaded with a shotgun cartridge, containing both powder and musket bullet. The powder charge was a predetermined amount Noble Sport A1 Nitro powder used for handloading shotgun cartridges (1.5g to 0.9g charge), firing a 19-bore bullet (24g). The shotgun barrel was fixed to a universal gun mount at a horizontal firing height of 1.39m at a 0° elevation parallel to the ground. The shotgun barrel was remote fired using an ISFE 9-volt electric match to prevent human error. Doppler radar was used to measure the muzzle velocity of each bullet as it was fired. Bullet numbers are set as a continuation from the previous firing experiment to avoid confusion.

The universal gun mount was placed 810cm (8.1m) away from the box. The barrel had to be angled downward to facilitate accurate firing of the bullet into the soil. The barrel height was changed in the initial stages of the experiment as the bullet was impacting the wood box frame. The barrel height was finally settled at 118cm. The soil box was constructed to be 243.84cm in length, 91.44cm in width and had a depth of 61cm. The soil was filled into the box to a depth of 46cm. The soft capture system was placed 28cm away from the end of the soil box to allow the bullet to ricochet into the system.

Every bullet fired had a multitude of measurements taken. The first measurement was the impact distance, which was the distance where the bullet first impacted the soil. The second measurement taken was the exit distance, which is the last place the bullet touched in the soil as it ricocheted into the soft capture system. The final measurement taken was the height from that last skid mark in the soil, to the height in which the bullet entered the soft capture system. These measurements allowed the length of the skid mark in the soil, and the angle of impact to be known.

To calculate the angle of impact; the barrel height, impact distance and the distance from the barrel to the box of soil must be recorded for every individual bullet. The information is then placed in the equation below.

$$\alpha = \tan^{-1}\{\frac{BH}{(ID+BD)}\}$$

Where:

α -is the angle of impact in degrees

BH- Barrel Height

ID- Impact Distance

BD- Distance of the box from the barrel

To calculate the angle of exit from the soil box; the height of entrance into the soft capture system, exit distance and the distance from that exit to the soft capture system must be recorded. The information is then placed into the following equation below.

$$\beta = \tan^{-1}\{ \frac{HSC}{(ED+DSC)} \}$$

Where:

β- is the angle of exit in degrees

HSC- Height of entrance into the soft capture system

ED- Exit Distance

DSC- Distance to the soft capture system

7.8.3.1 Experiment One: Sterile Soil Ground Ricochet Experiment

The sterile soil contained small pebbles that could not be removed effectively. Some plant remains (roots, stems, etc.) as plants grew while the soil settled in the box as it was stored outside. All soil was turned and smoothed over by hand to simulate a ploughed field, but having the surface remain visible to record bounce and skid marks from the bullet on the ground surface. Charge sizes were varied to investigate bullet impact evidence and bullet distortion levels along the maximum range of the musket.

7.8.3.1.1 Results

12 bullets were fired into the sterile soil with varying charge sizes to investigate the bullet impact evidence from bounce and roll. The results from the firing experiment can be found in the table 7.19 below.

Bullet Number	Bullet weight (g)	Post firing weight (g)	Impact velocity (m/s)	Impact Distance (cm)	Exit Distance (cm)	Skid Length (cm)	Distance to soft capture (cm)	Height to soft capture (cm)	Barrel Height (cm)
[redacted]									
Bullet 77	24.10	24.08	113	NA	NA	40	28	NA	75.8
Bullet 78	24.22	24.17	144	160	56	28	28	13	75.8
Bullet 79	24.08	24.02	192	120	97	27	28	17.5	75.8
Bullet 80	24.29	24.22	192	163	34.5	46.5	28	27	75.8
Bullet 81	24.27	24.17	229	161	33	50	28	8	75.8
Bullet 82	24.24	23.97	212	148	0	96	28	NA	75.8
Bullet 83	24.31	24.21	241	0	142	102	28	0	117
Bullet 84	24.09	24.07	260	93	103	48	28	11	118
Bullet 85	24.17	23.93	287	97	85	62	28	11	118
Bullet 86	24.40	20.26	352	120	89	35	28	5	118
Bullet 87	24.47	NA	370	96	99	49	36.5	8.5	118
Bullet 88	24.43	23.41	375	87	110	47	36.5	2.5	118

Table 7.19: 12 bullets fired into sterile soil.

Bullet 77 (figure 7.56 and figure 7.57) was fired with a 0.78g charge and impacted the soil at 113m/s; a simulated distance well below the average of ground impact. The bullet impacted the soil at an unknown angle and exited the soil at an unknown angle. The bullet left a skid mark 40cm long in the soil. B77 is slightly distorted and compressed from firing, although no banding is present. There are three irregular impact gouges on the bullet's surface from striking small pebbles in the soil. One long gouge with fine tight striations from striking a very small pebble is superimposed over the mould seam. Bullet 77 had a weight loss of 0.02g from firing and impact.

Figure 7.56: Impact surface of B77 under 10X magnification.

Figure 7.57: Impact surface of B77.

Bullet 78 (figure 7.58) was fired with a 0.78g charge and impacted the soil at 144m/s; a simulated distance well below the average of ground impact. The bullet impacted the soil at 4.5° angle and exited the soil at 8.8° angle, leaving a skid mark 28cm long. The surface of B78 contains multiple gouges and small impact indentations, all of which contain fine tight linear striations from impacting pebbles in the soil. The bullet is slightly distorted from compression during firing. The bullet had a weight loss of 0.05g from firing and impact.

Figure 7.58: Impact surface of B78 under 10X magnification.

Bullet 79 (figure 7.59) was fired with a 0.90g charge and impacted the soil at 192m/s; a simulated distance well below the average of ground impact. The bullet impacted the soil at a 4.7° angle and exited the soil at an 8° angle, leaving a skid mark 27cm in length. B79 appears to have struck small pebbles within the soil matrix. Multiple gouges and apparent small impact indentations on the bullet's surface, all contain fine tight linear striations from pebbles. Some of the indentations still contain bits of pebble in them. Some of the bullet's surface has an appearance that almost resemble characteristics from chewing. Bullet is slightly distorted from compression from firing and impact. The bullet had a weight loss of 0.06g from firing and impact.

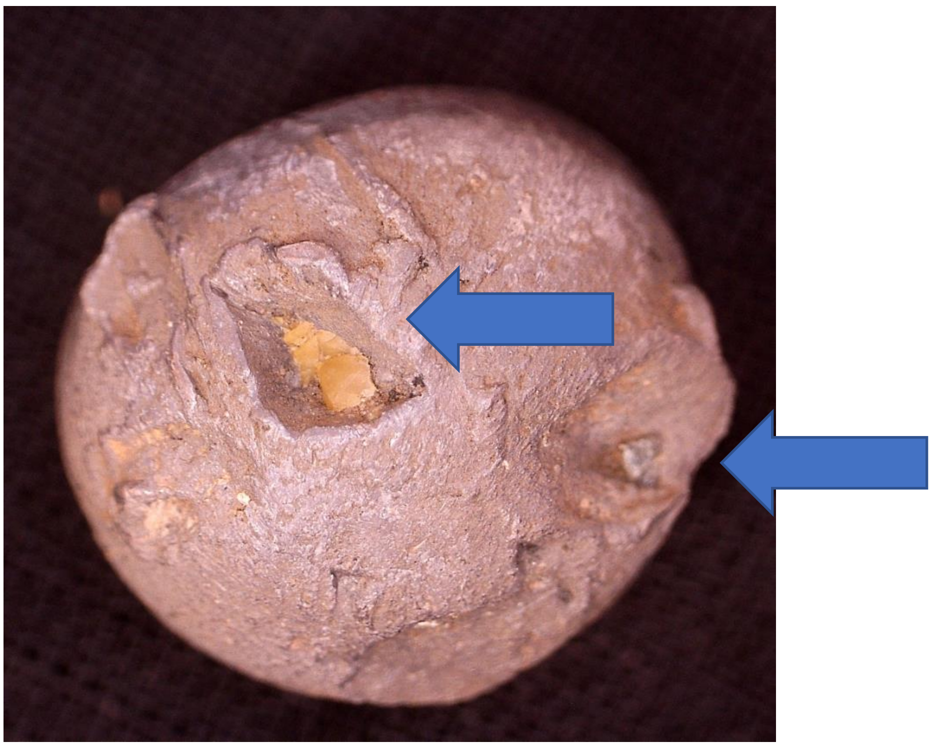

Figure 7.59: Impact surface of B79 under 10X magnification, arrows points to stone inclusions.

Bullet 80 (figure 7.60) was fired with a 0.90g charge and impacted the soil at 192m/s; a simulated distance well below the average of ground impact. The bullet impacted the soil at a 4.5° angle and exited the soil at a 23° angle, leaving a skid mark 46.5cm in length. B80 contained multiple gouges and apparent small impact craters on the bullet's surface, all contain fine tight linear striations from pebbles. Some of these craters contain a smooth surface with fine tight linear striations running along the sides of them. The bullet is slightly distorted from compression from firing and impact. Bullet 80 had a weight loss of 0.07g from firing and impact.

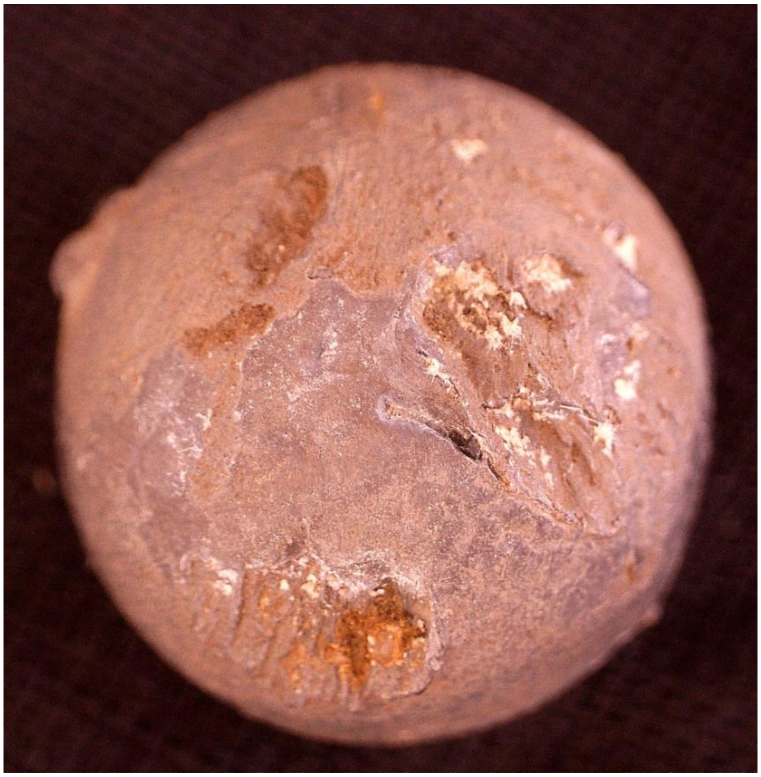

Figure 7.60: Impact surface of B80 under 10X magnification.

Bullet 81 (figure 7.61 and figure 7.62) was fired with a 1.10g charge and impacted the soil at 229m/s; a simulated distance close to ground impact, just beyond 191m. The bullet impacted the soil at a 4.5° angle and exited the soil at a 53° angle, leaving a skid mark 50cm in length. B81 impacted the wooden box frame backstop. This bullet is a good example of the difference between wood grain and stone impressions: even though both leave linear striations upon impact, the striations appear different. Multiple gouges and apparent small impact craters on the bullet's surface, all contain fine tight linear striations from pebbles. Some of these craters contain a smooth surface with fine tight linear striations running along the sides of them. The bullet is slightly distorted from compression from firing and impact. The bullet had a weight loss of 0.10g from impact and firing.

Figure 7.61: Impact surface of B81 under 10X magnification.

Figure 7.62: Impact surface of B81 under 10X magnification, wood impact evidence. Note the small cratering from the soil impact on the bottom right of the bullet.

Bullet 82 (figure 7.63) was fired with a 1.10g charge and impacted the soil at 212m/s; a simulated distance just below the average of ground impact. The bullet impacted the soil at a 4.5° angle and impacted the wooden frame backstop and was pancaked, having not left the soil. The skid mark was 96cm in length. The surface of B82 has radial flow of melted lead and linear striations from wood grain impact, but also contains small pitting like that usually seen from firing; however, firing had been removed from the equation and this pitting is as a result of impacting dirt and soil, because the soil is imbedded into the bullet's impact surface. The bullet is heavily distorted from the impact process. The bullet had a weight loss of 0.27g from impact and firing. The barrel height was changed before this bullet was fired as the bullets were impacting too closely to the back of the wooden frame.

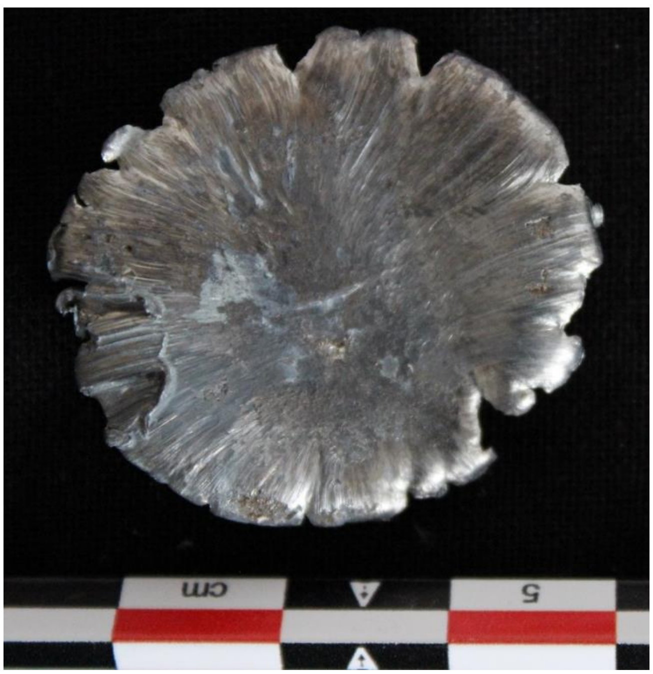

Figure 7.63: Impact surface of B82.

Bullet 83 (figure 7.64 and figure 7.65) was fired with a 1.10g charge and impacted the soil at 241m/s; a simulated distance at impact of 177m. The bullet impacted the soil at an 8.2° angle directly into the wooden frame at the front of the box, then bounced through the soil, and through the soft capture system. The bullet left a skid mark 102cm in length. B83 is another great example of wood impact evidence intermixed with pebble and soil impact evidence. Deep linear striations from wood grain impact along with sharp gouges and fine tight striations from impacting pebbles. The bullet is slightly distorted from firing and impact. The bullet had a weight loss of 0.10g from impact and firing. The barrel height was changed again after this bullet was fired as it impacted the front wooden frame.

Figure 7.64: Impact surface of B83 under 10X magnification. Note the wood impact evidence on the upper right with adhering wood grain. The stone impact evidence can be seen on the bottom left, the slight gouge.

Figure 7.65: Impact surface of B83 showing stone impact evidence, under 10X magnification.

Bullet 84 (figure 7.66) was fired with a 1.20g charge and impacted the soil at 260m/s; the simulated distance at impact was 141m. The bullet impacted the soil at a 7.4° angle and exited the soil at a 4.8° angle, leaving a skid mark 48cm in length. B84 contained multiple gouges from impacting the soil and pebbles. The bullet is slightly distorted from compression from firing and impact. The bullet had a weight loss of 0.02g from impact and firing.

Figure 7.66: Impact surface of B84.

Bullet 85 (figure 7.67 and figure 7.68) was fired with a 1.30g charge and impacted the soil at 287m/s; the simulated distance at impact was 104m. The bullet impacted the soil at a 7.4° angle and exited the soil at a 5.6° angle, leaving a skid mark 62cm in length. B85 contained multiple gouges from impacting pebbles. The bottom of the bullet has been flattened with fine tight linear striations from striking pebbles. The bullet is slightly distorted from compression from firing and impact. The bullet had a weight loss of 0.24g from impact and firing.

Figure 7.67: Impact surface of B85.

Figure 7.68: Impact surface of B85.

Bullet 86 was fired with a 1.52g charge and impacted the soil at 352m/s; the simulated distance at impact was 70m. The bullet impacted the soil at a 7.2° angle and exited the soil at a 2.4° angle, leaving a skid mark 35cm in length. B86’s exit from the soil was too low and the bullet impacted the steel table just below the soft capture system. The bullet was not photographed since it hit the steel table. The bullet is heavily distorted from impact and had a weight loss of 4.14g from impact and firing.

Bullet 87 was fired with a 1.62g charge and impacted the soil at 370m/s; the simulated distance at impact was 56m. The bullet impacted the soil at a 7.4° angle and exited the soil at a 3.6° angle, leaving a skid mark 49cm in length. B87 exited the soil at an odd angle and was not located within the soft capture system and subsequently B87 was lost.

Bullet 88 (figure 7.69) was fired with a 1.62g charge and impacted the soil at 375m/s; the simulated distance at impact was 53m. The bullet impacted the soil at a 7.5° angle and exited the soil at a 1° angle, leaving a skid mark 47cm in length. B88 impacted the back stop of the wooden box frame at the end of its bounce. Multiple gouges and apparent small impact craters on the bullet's surface, all contain fine tight linear striations from pebbles. Some craters still contain bits of soil in them. Some of the bullet's surface has an appearance that almost resembles marks from chewing. It is possible to tell which impact event came first as to how the gouges pushed the remaining lead into other gouges. The bullet is slightly distorted from compression from firing and impact. The bullet had a weight loss of 1.02g from impact and firing.

Figure 7.69: Impact surface of B88 under 10X magnification.

7.8.3.1.2 Discussion

Table 7.20 below is a summary of the experimental results.

Bullet Number	Charge Size (g)	Impact Velocity (m/s)	Simulated Distance (m)	Weight Loss (g)	Distortion Level
B77	0.78	113	Ground Impact	0.02	SD
B78	0.78	144	Ground Impact	0.05	S-SD
B79	0.90	192	Ground Impact	0.06	SD
B80	0.90	192	Ground Impact	0.07	SD
B81	1.10	229	191	0.10	SD
B82	1.10	212	Ground Impact	0.27	I
B83	1.10	241	177	0.10	SD-MD
B84	1.20	260	141	0.02	SD-MD
B85	1.30	287	104	0.24	SD-MD
B86	1.52	352	70	4.14	HD
B88	1.62	375	53	1.02	SD-MD

Table 7.20: Discussion data.

Experimental firing with nitro gunpowder has reduced a trend that was prevalent in the wood firing experiments: that of charge size of weight loss. The weight loss seen on most bullets from the sterile soil experiment were as a result of impacting small pebbles within the soil matrix that could not be removed.

There is a trend between impact velocity and simulated distance and distortion level to the bullet, in that as impact velocity or distance increased so too did the level of distortion. However, the variable of target characteristics, such as target material and thickness played a role. Examples of this can be seen with B82 which was irregular in shape from impacting the wooden box frame and B86 which was heavily distorted from impacting the steel table used to hold the soft capture system. These two bullets were outliers in the distortion level trend, which can be seen in table 7.20 above. They are outliers because they impacted surfaces other than the ground surface, or pebbles within the soil matrix.

Bullets fired into the soft sterile soil displayed small impact indentations on the surface of the bullet; these indentations are small and retained soil from impact. Most of the bullets showed singular to multiple gouges, or small impact craters with fine tight linear striations from impacting very small pebbles within the soil matrix. Retention of small pieces of those impacted pebbles within the bullet is relatively common. Multiple impacts with pebbles have left the surface of bullet 88 with an appearance like that of a chewed bullet.

Bullets 81, 82, 83 and 88 impacted both the wooden box frame and the soil matrix. The bullet's surfaces show the contrast between wood grain impressions and the associated thick linear striations and the fine tight linear striations from impacting small pebbles within the soil.
The total length of the skid mark in the soil does not seem to influence the bullet's levels of distortion; however, the length of time and distance of the skid increases the chances of the bullet impacting more pebbles within the soil matrix.

7.8.3.2 Experiment Two: Stony Soil Ground Ricochet Experiment

Next, small stones were added to the sterile soil. The stones were placed into the soil matrix in a random order, then the soil was turned so that stones could be found both on the surface and under the surface of the soil. The stones were added in a random fashion to increase the chances of the bullets impacting one of the stones. The surface of the soil was smoothed over by hand, to allow skid marks in the soil to be visible. The stones were 2cm to 5cm in total length, the arrangement of the soil box can be seen in figure 7.70 below.

Figure 7.70: Stony soil box construction.

7.8.3.2.1 Results

19 bullets were fired into the stony soil with varying charge sizes to investigate bullet impact evidence associated with the bounce and roll of the bullet. The results from the firing experiment can be found in the table 7.21 below.

Bullet Number	Bullet weight (g)	Post firing weight (g)	Impact velocity (m/s)	Impact Distance (cm)	Exit Distance (cm)	Skid Length (cm)	Distance to soft capture (cm)	Height to soft capture (cm)	Barrel Height (cm)
Bullet 89	24.27	24.25	101	130	74	40	36.5	IM	118
Bullet 90	24.35	24.34	100	NA	NA	NA	36.5	NA	118
Bullet 91	24.28	NA	100	NA	NA	NA	36.5	NA	118
Bullet 92	24.09	24.04	138	113	0	131	36.5	24	118

Bullet 93	24.11	16.85	178	127	86	31	36.5	IM	118
Bullet 94	24.21	8.90	141	123/159	97/68	24/17	36.5	17.5	118
Bullet 95	24.22	12.09	160	107	112	25	36.5	IM	118
Bullet 96	24.27	24.19	178	84	126	34	36.5	NA	118
Bullet 97	24.13	22.01	203	120	89	35	36.5	19	118
Bullet 98	24.38	24.25	236	66	81	97	36.5	4	118
Bullet 99	24.22	15.30	232	121	70	53	36.5	23	118
Bullet 100	24.21	NA	248	42	175	27	36.5	NA	118
Bullet 101	24.44	0.70	255	110	113	21	36.5	14	118
Bullet 102	24.15	22.59	265	132	89	23	36.5	19	118
Bullet 103	24.29	NA	259	163	51	30	36.5	17	118
Bullet 104	24.17	24.06	291	103	115	26	36.5	17	118
Bullet 105	24.28	14.98	311	104	60	80	36.5	3	118
Bullet 106	24.50	17.12	372	120	105	19	36.5	7	118
Bullet 107	24.11	22.63	368	90	121	33	36.5	5	118

Table 7.21: All 19 bullets fired into the stony soil.

Bullet 89 (figure 7.71) was fired with a 0.78g charge and impacted the soil at 101m/s; a simulated distance well below the average of ground impact. The bullet impacted the soil at a 7.2° angle and imbedded itself into the soil, leaving a skid mark 40cm in length. B89 contained a deep gouge with linear striations towards to bottom of the gouge. The stone it impacted created a cleft in the bullet with one side of the cleft appearing straight, while the other side appeared slightly folded over. Tight fine linear striations are seen within this cleft. The bullet is slightly distorted from compression from firing and impact. The bullet had a weight loss of 0.02g from impact and firing.

Figure 7.71: Impact surface of B89 under 10X magnification.

Bullet 90 (figure 7.72) was fired with a 0.78g charge and impacted the soil at 100m/s; a simulated distance well below the average of ground impact. The bullet perforated the wooden frame and ricocheted into soft capture, no bounce or roll. Thick linear striations from wood grain impression, bits of wood adhering to the surface of the impact surface of the bullet. The bullet is slightly distorted from compression from firing and impact. The bullet had a weight loss of 0.01g from impact and firing.

Figure 7.72: Impact surface of B90 under 10X magnification.

Bullet 91 was fired with a 0.78g charge and impacted the soil at 100m/s; a simulated distance well below the average of ground impact. The bullet impacted a stone within the soil, rebounded and was lost.

Bullet 92 (figure 7.73) was fired with a 0.78g charge and impacted the soil at 138m/s; a simulated distance well below the average of ground impact. The bullet impacted the soil at a 7.3° angle and exited the soil at a 3.8° angle, leaving a skid mark 131cm in length. B92 impacted the soil in the sabot, rolled across the ground until it hit the wooden back top, then bounced into the soft capture system. The bullet is heavily distorted from the impact process. The bullet's surface is mangled from a direct impact with a stone, although it does contain tight fine linear striations, and some bits of stone imbedded into the impact surface. The section of the bullet containing wood grain impressions has thicker linear striations with bits of wood adhering to the impact surface. The bullet had a weight loss of 0.05g from impact and firing.

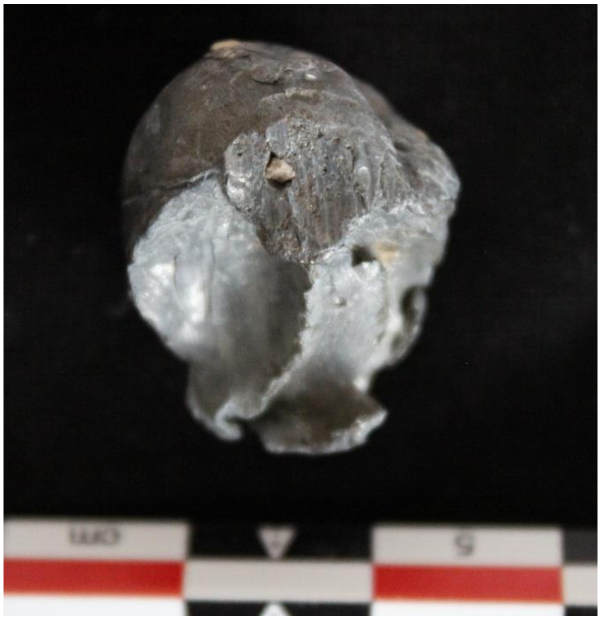

Figure 7.73: Impact surface of B92, note the stone inclusion.

Bullet 93 (figure 7.74) was fired with a 0.90g charge and impacted the soil at 178m/s; a simulated distance well below the average of ground impact. The bullet impacted the soil at a 7.2° angle and imbedded itself within the soil, leaving a skid mark 31cm in length. When B93 impacted the soil, it dispersed stones and imbedded in the soil. The bullet is heavily distorted and has an irregular shape from impact. The impact surface contains fine tight linear striations from stone impacts. The bullet had a weight loss of 7.26g from impact and firing.

Figure 7.74: Impact surface of B93.

Bullet 94 (figure 7.75) was fired with a 0.90g charge and impacted the soil at 141m/s; a simulated distance well below the average of ground impact. The bullet impacted the soil and bounced twice. The first bounce was at a 7.2° angle and exited that bounce at a 7.5° angle, leaving a skid mark of 24cm in length. The second bounce was at a 6.9° angle and exited that bounce at a 9.5° angle, leaving a skid mark of 17cm in length. B94 is heavily distorted and irregular in shape from impact. The impact surface contains fine tight linear striations from stone impacts. The majority of the bullet seems to have been disintegrated or was lost and was not recovered from either the soft capture or from the soil box. What was recovered of the bullet from the soft capture system had a weight loss of 15.31g from impact and firing.

Figure 7.75: Impact surface of B94.

Bullet 95 (figure 7.76) was fired with a 0.90g charge and impacted the soil at 160m/s; a simulated distance well below the average of ground impact. The bullet impacted the soil at a 7.3° angle and imbedded itself into the soil, leaving a skid mark 25cm in length. B95 is heavily distorted and irregular in shape from impact. The impact surface contains fine tight linear striations from the stone impact. Most of the bullet seems to have been disintegrated, the missing aspects of the bullet was not recovered from either the soft capture or from the soil box. What was recovered of the bullet had a weight loss of 12.13g from impact and firing.

Figure 7.76: Impact surface of B95.

Bullet 96 (figure 7.77) was fired with a 0.90g charge and impacted the soil at 178m/s; a simulated distance well below the average of ground impact. The bullet impacted the soil at a 7.5° angle and exited the soil at an unknown angle, leaving a skid mark 34cm in length. The bullet was located in the soft capture system. B96 is moderately distorted from firing and impact. The impact surface contains fine tight linear striations from stone impacts, and pitting from either impacting smaller pebbles or the soil. The pitting is seen at the central point of impact, with the surrounding regions of the bullet contain fine tight linear striations from stone impacts. The bullet had a weight loss of 0.08g from impact and firing.

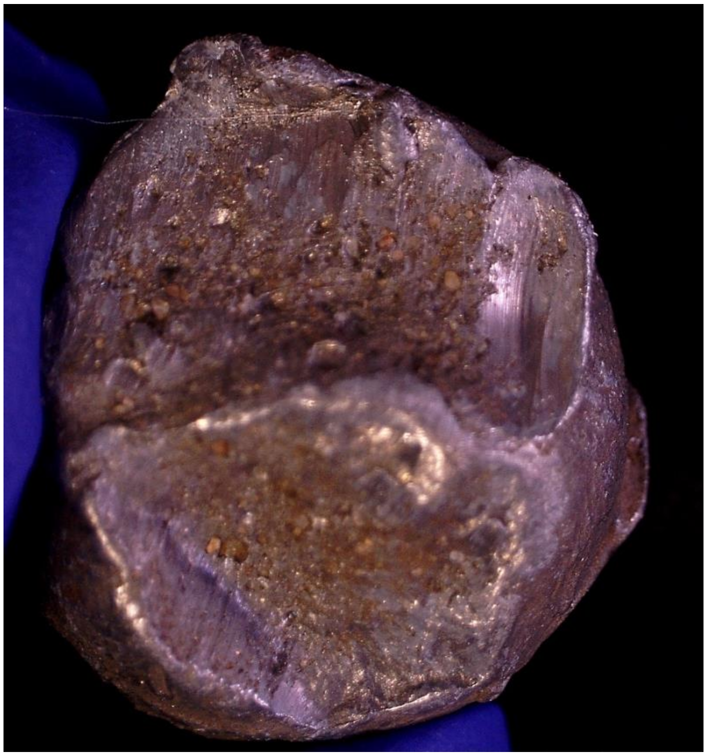

Figure 7.77: Impact surface of B96 under 10X magnification.

Bullet 97 (figure 7.78) was fired with a 1.10g charge and impacted the soil at 203m/s; a simulated distance just below the average of ground impact. The bullet impacted the soil at a 7.2° angle and exited the soil at an 8.6° angle, leaving a skid mark 35cm in length. B97 is heavily distorted and irregular in shape from impact. The impact surface contains fine tight linear striations from stone impacts. A second region of impact is seen on the other side of the bullet. This was a deep and wide gouge with fine tight linear striations and some adhering pebbles and soil. The bullet had a weight loss of 2.12g from impact and firing.

Figure 7.78: Impact surface of B97.

Bullet 98 (figure 7.79) was fired with a 1.10g charge and impacted the soil at 236m/s; the simulated distance at impact was 188m. The bullet impacted the soil at a 7.7° angle and exited the soil at a 1.9° angle, leaving a skid mark 97cm in length. B98 is slightly distorted from firing and impact. The bullet has multiple impact events from soil and small pebbles, and one very large impact region from impacting a stone. This section has deep, yet fine and tight linear striations, which has created a flat facet on the bullet. Bullet had a weight loss of 0.13g from impact and firing.

Figure 7.79: Impact surface of B98 under 10X magnification.

Bullet 99 (figure 7.80) was fired with a 1.10g charge and impacted the soil at 232m/s; the simulated distance at impact was 191m. The bullet impacted the soil at a 7.2° angle and exited the soil at a 12° angle, leaving a skid mark 53cm in length. B99 is heavily distorted and irregular in shape from impact. The impact surface contains fine tight linear striations from stone impacts. The majority of the bullet seems to have disintegrated but was not recovered from either the soft capture or from the soil box. What was recovered of the bullet had a weight loss of 8.92g from impact and firing.

Figure 7.80: Impact surface of B99.

Bullet 100 was fired with a 1.10g charge and impacted the soil at 248m/s; the simulated distance at impact was 163m. The bullet impacted the soil at a 7.9° angle and exited the soil at an unknown angle, leaving a skid mark 27cm in length. The bullet did not enter the soft capture system and was not located.

Bullet 101 was fired with a 1.20g charge and impacted the soil at 255m/s; the simulated distance at impact was 150m. The bullet impacted the soil at a 7.3° angle and exited the soil at a 5.3° angle, leaving a skid mark 21cm in length. Only small fragments of B101 were found and has not been pictured as a result. The bullet is heavily distorted and irregular in shape from impact. The impact surface contains fine tight linear striations from stone impacts. The bullet had a weight loss of 23.74g from impact and firing; this weight loss accounts for almost the entire weight of the bullet.

Bullet 102 (figure 7.81) was fired with a 1.20g charge and impacted the soil at 265m/s; the simulated distance at impact was 132m. The bullet impacted the soil at a 7.1° angle and exited the soil at an 8.6° angle, leaving a skid mark 23cm in length. B102 perforated the soft capture system and was found wrapped in cotton in the sand trap and the end of the firing range. The bullet is heavily distorted and irregular in shape from impact. The impact surface contains fine tight linear striations from stone impact. The bullet had a weight loss of 1.56g from impact and firing.

Figure 7.81: Impact surface of B102.

Bullet 103 was fired with a 1.20g charge and impacted the soil at 259m/s; the simulated distance at impact was 142m. The bullet impacted the soil at a 6.9° angle and exited the soil at an 11° angle, leaving a skid mark 30cm in length. The bullet perforated the soft capture system and was never located.

Bullet 104 (figure 7.82) was fired with a 1.30g charge and impacted the soil at 291m/s; the simulated distance at impact was 100m. The bullet impacted the soil at a 7.6° angle and exited the soil at a 6.4° angle, leaving a skid mark 26cm in length. B104 is moderately distorted with a bit of a sweeping tail towards the backside of the bullet. Fine tight linear striations can be seen in the sweeping tail. The central point of impact contains small pock marks from where soil had imbedded into the bullet but came out when the bullet was cleaned. The bullet had a weight loss of 0.11g from impact and firing.

Figure 7.82: Impact surface of B104 under 10X magnification.

Bullet 105 (figure 7.83) was fired with a 1.30g charge and impacted the soil at 311m/s; the simulated distance at impact was 91m. The bullet impacted the soil at a 7.4° angle and exited the soil at a 0.2° angle, leaving a skid mark 80cm in length. B105 is heavily distorted from impact. Fine tight linear striations with pock marks from soil and pebbles throughout the impact surface. The impact surface also contains melting from the impact process. The bullet had a weight loss of 9.30g from impact and firing.

Figure 7.83: Impact surface of B105.

Bullet 106 (figure 7.84) was fired with a 1.52g charge and impacted the soil at 372m/s; the simulated distance at impact was 55m. The bullet impacted the soil at a 7.2° angle and exited the soil at a 2.8° angle, leaving a skid mark 19cm in length. B106 is heavily distorted and irregular shaped from impact. It was very difficult to tell what the bullet impacted, as the impact surface is highly disorganised, with no linear striations on the bullet's surface. The bullet had a weight loss of 7.38g from impact and firing.

Figure 7.84: Impact surface of B106.

Bullet 107 (figure 7.85) was fired with a 1.52g charge and impacted the soil at 368m/s; the simulated distance at impact was 58m. The bullet impacted the soil at a 7.5° angle and exited the soil at a 1.8° angle, leaving a skid mark 33cm in length. B107 is heavily distorted and irregular in shape from impact. It is very difficult to tell what the bullet impacted with no linear striations present on the bullet's surface. The bullet has turned itself inside out during the impact process, and the impact surface is heavily pockmarked. A small region of the bullet contains fine tight linear striations from the stone impact. The bullet had a weight loss of 1.48g from impact and firing.

Figure 7.85: Impact surface of B107.

7.8.3.2.2 Discussion

Table 7.22 below is a summary of the experimental results.

Bullet Number	Charge Size (g)	Impact Velocity (m/s)	Simulated Distance (m)	Weight Loss (g)	Distortion Level
B89	0.78	101	Ground Impact	0.02	SD
B90	0.78	100	Ground Impact	0.01	S
B92	0.78	138	Ground Impact	0.05	HD
B93	0.90	178	Ground Impact	7.26	HD-I
B94	0.90	141	Ground Impact	15.31	I
B95	0.90	160	Ground Impact	12.13	I
B96	0.90	178	Ground Impact	0.08	MD
B97	1.10	203	Ground Impact	2.12	I-MD STILL DOMED
B98	1.10	236	188	0.13	MD
B99	1.10	232	191	8.92	I
B101	1.20	255	150	23.74	I
B102	1.20	265	132	1.56	I-HD
B104	1.30	291	100	0.11	MD
B105	1.30	311	91	9.30	HD-I
B106	1.52	372	55	7.38	I
B107	1.52	368	58	1.48	I

Table 7.22: Discussion data.

The trend of impact velocity and simulated distances and the level of distortion on the surface of the bullet is no longer present. The distortion level of the bullet at impact in this experiment is dictated by how much of the bullet impacted a stone during its skid through the soil matrix. Even with the usage of a high-speed camera it was not possible to determine what individual stone or stones a bullet impacted during its skid, as the stones were thrown into the air by the transfer of kinetic energy and the stones could not be located with certainty.

The bullets from this firing experiment exhibit varying levels of impact damage and distortion, depending on the above variables. However, the areas and regions of impact on the bullet did display the same classifications of impact evidence. Regions of the bullet that impacted the sterile soil contain the same pitting that was described in the first ground fire experiment above. Regions of the bullet that impacted stone all contained fine tight linear striations, sometimes overlapping one another depending on the sequence of impact events. Superficial to deep gouges, clefts, and flat facets were all noted in the impact surfaces, and all those classifications contained fine tight linear striations from impacting stones. These impact regions could also contain adhering bits of stone, pebbles and soil.

Two bullets did not contain any impact evidence. Bullets 106 and 107 contained no linear striations anywhere on the bullet, although both bullets were heavily distorted. Both bullets' surfaces were obscured from melting from the high impact velocity.

7.9 Experimental Firing Conclusions

Bullets were fired at three different species of wood; oak, hawthorn and hazel to investigate if different species of wood left different impact evidence on the bullet's surface. The conclusion drawn from these experiments show that wood grain impressions are consistent within different species of wood. All species of wood tested imprint the same manner of wood grain impressions on the bullets' surfaces, consisting of a central point of impact, with linear striations found across varying regions of the bullet. With all bullets fired throughout the wood firing experiments, 70% of the bullets demonstrate wood grain impressions and thick linear striations, and 30% of the bullets show no signs of what the bullet impacted due to the surface of the bullet being obscured by melting from the impact process.

Both the dead wood and the hawthorn wood impact testing transferred the least visible wood grain impressions, although both sets of experimental bullets displayed thick linear striations from contact or gazing the targets. The bullets from the oak fence rail testing exhibited the most visible wood grain impressions from all other wood experiments. This could be the result of the wood grain being exposed and coarser in nature than the hazel and hawthorn as both of those woods were covered in bark.

The transfer of wood impact evidence from living wood and dead wood was also investigated. It was found that overall living wood is more likely to leave a wood grain impression on the bullet's surface than dead wood, but both living and dead wood leave similar thick linear striations. It could be that dead wood is not as elastic as living wood, and therefore the wood grain impressions are not as pronounced.

These wood firing experiments reveal two main issues regarding the investigation of bullets recovered from archaeological sites. First, the level of corrosion on the bullet's surface. The wood impact evidence on some of the bullets is only visible under 10X magnification and it is this evidence that is more than likely going to be lost due to corrosion. The second issue is that 30% of the bullets do not take on the characteristic traits of impact from the impact surface. These bullets, while being able to be classified as impacted may not be attributed to the correct impact surface.

31 bullets were fired at two different types of ground conditions to investigate the impact evidence transferred onto the bullets' surfaces from the bounce and roll after ground impact. Both sterile soil with pebbles smaller than 10mm included in the soil and stony soil firing. Sterile soil and small pebble impact evidence consists of pitting from the soil impact, small impact craters and superficial to deep gouges, both of which contain fine tight linear striations with adhering bits of stone within the impact surface. Stoney ground impact evidence is much more varied, and the level of distortion on the bullet's surface equates more to the target being impacted, as well as how the bullet impacted the target. Whether the bullet bounced over the top of a stone or impacted it directly determines the amount of impact damage seen on the bullet's

surface. It was not possible in this experiment to determine how the bullet impacted the stone, or which individual stone was impacted.

Bullets that impacted stony ground conditions during this experiment display superficial to deep gouges, flat facets and clefts that contain one straight edge and one edge that is slightly folded over. This is caused by the bullet skidding over the top of stones in the soil matrix. The bullets can also contain adhering pebbles or bits of stone within the impact surface and all impact surfaces exhibit fine, tight linear striations.

These ground firing experiments reveal two main issues when considering the comparison to bullets from within the archaeological record. First, that the fine tight linear striations may be too faint, and that corrosion may obfuscate the surface evidence over time. Secondly, and most interestingly the experimental bullets show that when impacting stones, that the bullet weight loss from the stone impacts within the soil matrix is high enough to confuse calibre interpretations. Bullets 94, 95 and 101 all lost at least 12g from their total weight. It would be difficult if not impossible to reconcile this issue when examining bullets from an archaeological assemblage.

With the completion of the proof of concept experimental firing trials, came the completion of the proof of concept for the reference collection of known bullet impacts. While the sample sizes for the above experiments were not fully comprehensive, trends in characteristic evidence are evident enough to allow for an advanced comparison of the experimental bullets to those of the two case study battlefields discussed in Chapter Five. This creation of a reference collection of known bullet impacts and their juxtaposition to bullets from the archaeological assemblages with the aim to analyse impact evidence has never before been completed. All that remains to be investigated is the ability of this experimentally assembled reference collection of known bullet impacts to act as a comparative tool against which to compare the impact evidence found on the bullets from both the Edgehill and Oudenaarde battlefield bullet assemblages which is the basis of Chapter Eight.

Chapter 8: Proof of Concept: Comparison of the Experimentally Fired Reference Collection of Known Bullet Impact Evidence to the Edgehill and Oudenaarde Archaeological Bullet Assemblages

The aim of this chapter is to use the reference collection of known bullet impact evidence created throughout Chapter Seven to examine the bullet impact evidence recorded on the Edgehill and Oudenaarde battlefield bullet assemblages. Each bullet in the assemblages was analysed and evaluated individually following the designed methodology described in Chapter One. Once all the bullets had been analysed and categorised, the assemblages were broken down into their respective groups and categories to be interpreted and discussed. Each assemblage will be discussed in the manner that the bullets were examined, beginning with an overall analysis of the bullet evidence seen from each assemblage. Finally, each section of this chapter will single out bullets from within the assemblages that demonstrate how the impact evidence was interpreted using the reference collection of known bullet impact evidence from the experimental firing trials. Finally, bullet impact distribution maps were created using the GIS information from each site to demonstrate where each bullet was found within the battlefield landscape, followed by a brief discussion.

It is not the intention of this thesis to examine the bullet assemblages for calibre interpretations or to examine and create bullet distribution maps as explained in Chapter One, section 1.2.2.2. These sites were chosen because that work had already been completed for the assemblages. It is also not the intention of this chapter to examine any form of cannon or case shot as previously stated. The alternate bullet type known as slugs have also been left out of the analysis of these assemblages as slugs are deserving of their own series of experimental firing trials for impact analysis and to date, their behaviour in flight and upon impact is unknown. This analysis has only included the spherical lead bullets commonly associated with muskets, carbines, and pistols that were found in each assemblage as is the focus of this overall study and experimental firing trials. It is also not the intention of this chapter to challenge the previous bullet analysis completed for each site, but simply to test the ability and prove the concept of the reference collection and the impact analysis methodology to better interpret impact evidence seen on the bullets' surface. No GIS information on the bullet finds locations within the battlefield were consulted before the bullets were analysed for impact evidence as it was viewed that it would bias the interpretation of the bullet assemblages.

8.1 Edgehill Bullet Assemblage

The Edgehill bullet assemblage analysed in this thesis came from the archaeological survey of the Edgehill battlefield that was conducted by Dr Glenn Foard and team from 2004-2007. The survey initially focused on the core area of the battlefield and branched outwards to surrounding fields until the bullet scatters were reduced to a low density (Foard 2012: 147-148). 3250 total artefacts were recovered during the archaeological investigation, although not all finds were battle related. 1096 of the finds were bullets from the early modern period and were originally analysed by Foard. The bullets displayed a wide range of type and calibre (Foard 2012: 154), and of the 1096 bullet finds recovered, 34 were slugs and 127 were case shot from artillery (Foard 2012: 156). As previously stated, case shot and slugs were not explored experimentally in this study and therefore have both been intentionally excluded from the analysis. Of the remaining 947 bullets, this study analysed 803 of those bullets. The reason for the missing 144 bullets is not fully understood. The re-analysis of the Edgehill bullet assemblage by this thesis was not completed until the experimental firing trials were concluded and all known evidence could be accounted for. The calibre graphs and bullet distribution maps for the original analysis can be found in Foard 2012 (155-157) along with detailed discussions. It is not the intent of this thesis to challenge the interpretation of Foard's analysis, but to simply test and compare the ability of the reference collection against bullets from the archaeological assemblage.

All 803 bullets from the Edgehill assemblage were examined using the methodology created in Chapter One, section 1.5 of this thesis. The bullets were broken down into their distortion level categories for further investigation and analysis of overall bullet evidence and then the comparison of impact evidence was undertaken. The following is a step-by-step guide on how to use the bullet analysis methodology in conjunction with the known bullet impact reference collection. Figure 8.1 found below is the bullet distribution map for every bullet find in the Edgehill battlefield survey.

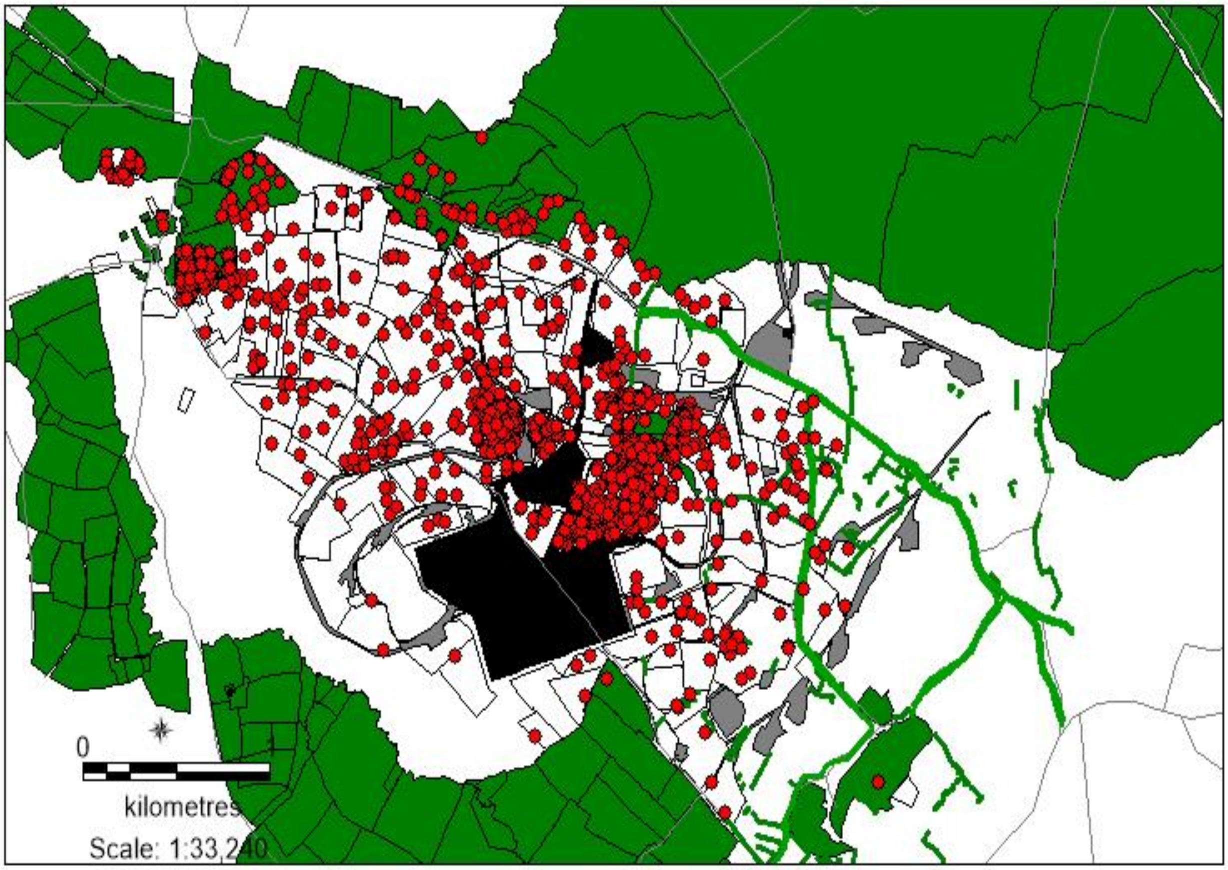

Figure 8.1: All bullet finds from the 2004-2007 Edgehill battlefield survey. The enclosures are highlighted in green. The sections in black on the map are from the Ministry of Defence depot that was built on a portion of the battlefield. GIS data courtesy of Glenn Foard.

8.1.1Spherical Distortion Level

From a total of 803 bullets, 299 bullets were categorised as having a spherical distortion level, comprising 37% of the total assemblage. All bullets designated as spherical in shape can be seen in figure 8.2 below. Most of the spherical bullets are found in two sections of the battlefield, in the core of the battlefield where the infantry action took place, and to the northwest where Rupert's attack on the baggage train occurred (Chapter Five, section 5.2).

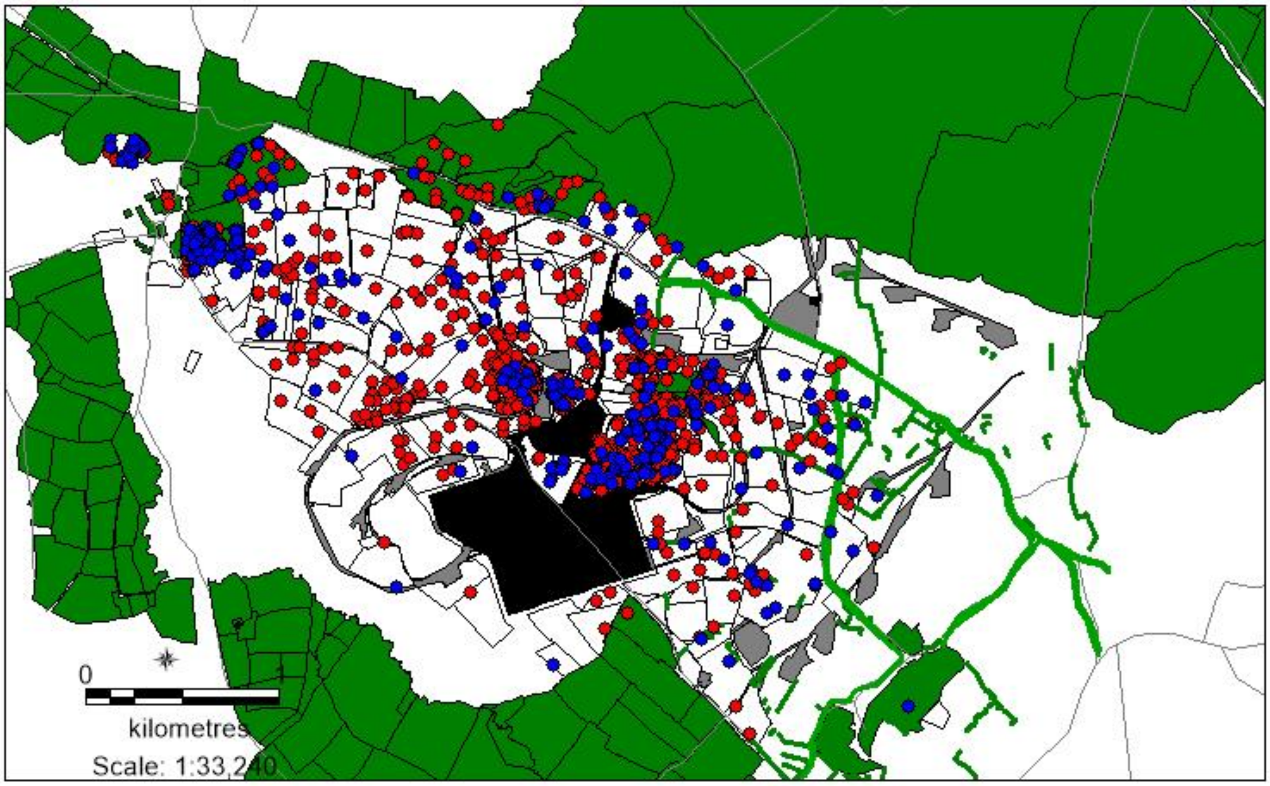

Figure 8.2: All bullets given the spherical distortion level are labelled in blue. The remaining bullets are coloured in red. GIS data courtesy of Glenn Foard.

8.1.1.1 Condition Assessment for Spherical Distortion Level

The condition assessment for the bullets classified as spherical resulted in two categories either good or corroded (figure 8.3). 203 bullets are classified as being in good condition, and 96 bullets as having a corroded surface. 63% of the spherical bullets have a good clean surface in which diagnostic traits are easily identified. The 96 bullets defined as corroded made identification difficult, of which 23 bullets' surfaces were too corroded to allow further diagnostic analysis.

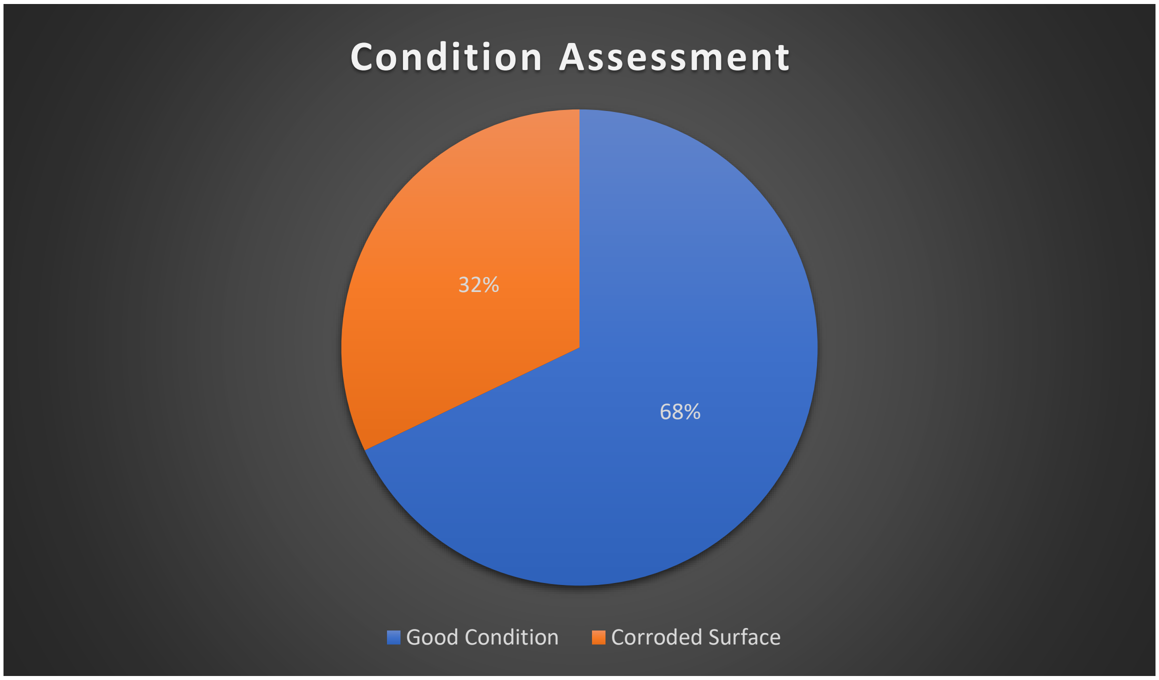

Figure 8.3: Condition assessment.

8.1.1.2 Manufacture Evidence for Spherical Distortion Level

Of the 299 bullets classified as spherical in shape, 213 bullets (71%) show signs of manufacture evidence, of which 68 show multiple forms of manufacture evidence. The remaining 86 bullets show no signs of manufacture evidence but do have various forms of other evidence such as chewing, firing and impact (figure 8.4).

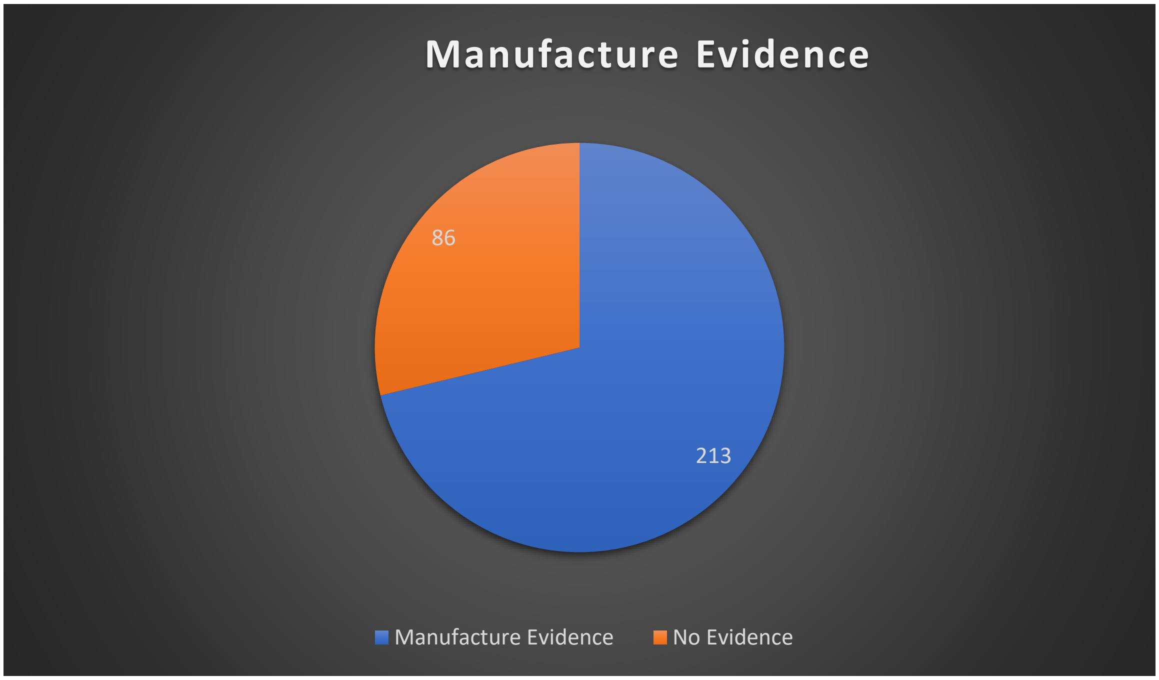

Figure 8.4: Manufacture evidence.

Of the manufacturing evidence present on the spherical bullets, 184 bullets contain a sprue cut, 5 contain an extended sprue and 12 have an extremely deep sprue cut. The deep sprue cuts became difficult to identify with bullets that have a high level of corrosion on the surface. It some instances, a second examination of the bullet was required under magnification to determine if the circular facet remaining was impact evidence. Under magnification, it was determined not to be caused by impact, but rather from a method of removing the sprue where someone deeply cut into the bullet to remove the sprue thereby leaving a deep circular indentation that is distinctly different than impact evidence.

The mould seam is still visible on 63 bullets, allowing for the diameter measurements to be taken. It is worth noting; however, that of the 299 bullets listed as spherical that only 21% of those bullets could be measured using digital callipers. 16 bullets also contain flashing around the mould seam, only one of those bullets showed any signs that the bullet had been fired.

18 casting faults were identified within the spherical bullets. 7 bullets contain voids or possible voids which are seen near the area of sprue removal. 5 bullets show turning lines around the bullet’s surface: one bullet contains a potlid type casting fault, one bullet is an incomplete fill

and one bullet has an offset mould seam. The frequency of the types of manufacturing evidence can be found in figure 8.5.

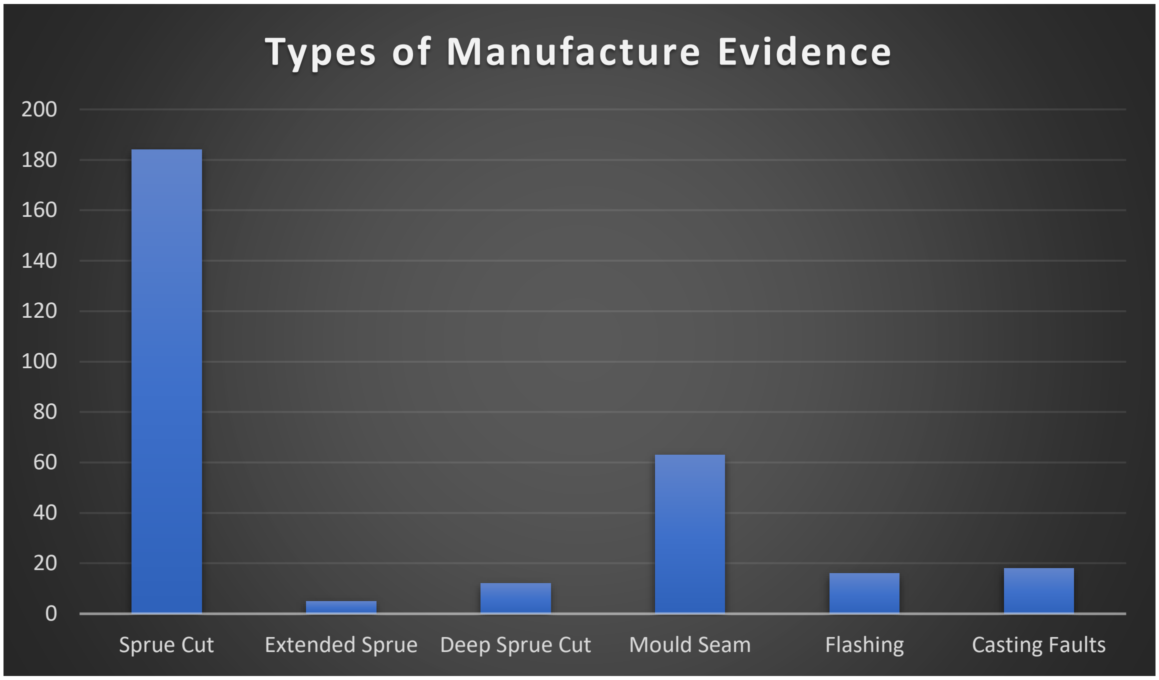

Figure 8.5: Frequency of manufacturing evidence.

8.1.1.3 Firing Evidence for Spherical Distortion Level

Only 14 of the 299 spherical bullets contain firing evidence. Of these 14 bullets, all 14 have barrel bands, and only 2 show signs of powder pitting. It is important to note that only 4 of these bullets that showing firing evidence also contain impact evidence.

285 of the bullets did not show signs of firing evidence and 23 bullets have too much corrosion on the surface rendering evidence obscured. One bullet is heavily chewed (animal), and one bullet shows impact damage. This is summed up in figure 8.6.

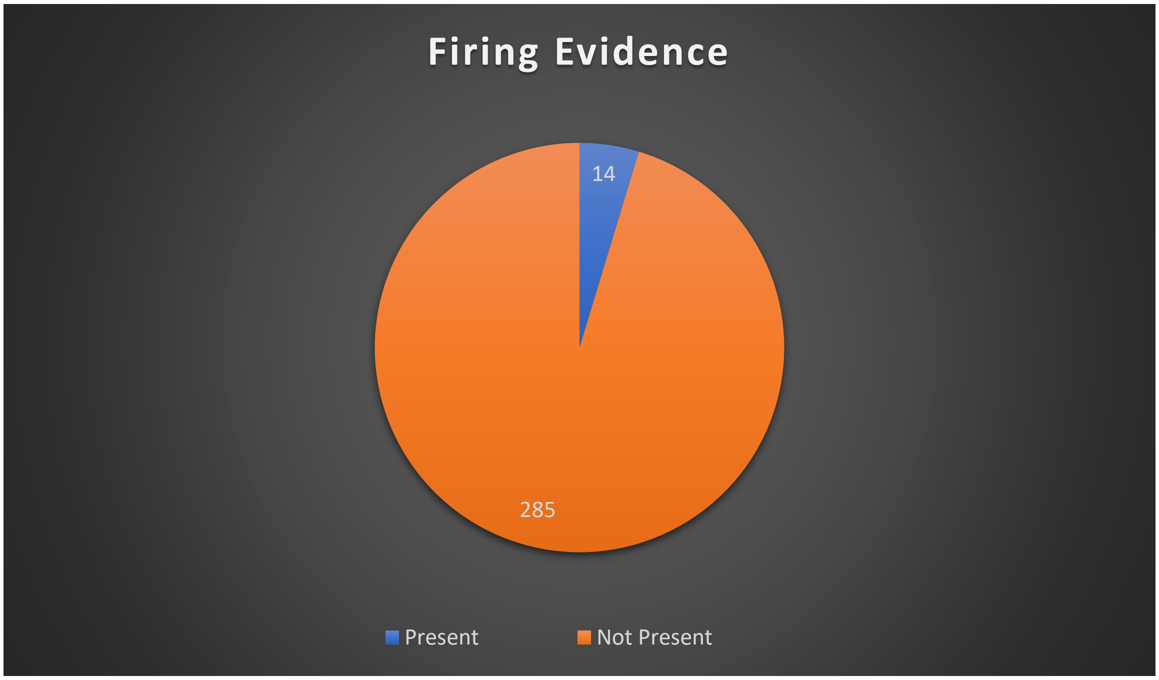

Figure 8.6: Firing evidence.

8.1.1.4 Impact Evidence for Spherical Distortion Level

With the other forms of bullet evidence identified on each bullet in the spherical distortion level, the remaining evidence on the bullets' surfaces can be attributed to either impact evidence or evidence from an unknown source. 64 bullets show signs of impact damage and 235 show no signs of impact damage, even though 10 of those bullets display firing evidence (figure 8.7). Of the 235 bullets that do not have impact evidence, 2 bullets are heavily chewed, and 23 bullets are too corroded to determine any kind of surface evidence.

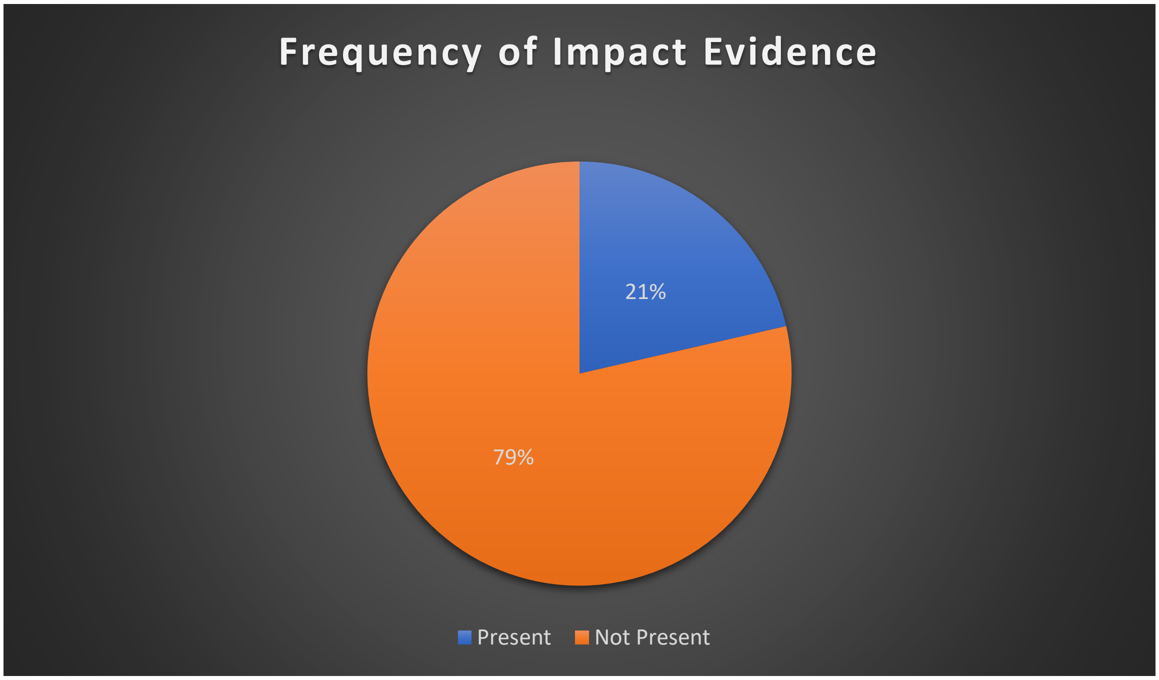

Figure 8.7: Frequency of impact evidence.

Of the 64 impacted bullets, multiple types of impact evidence are noted, and some bullets contain multiple forms of impact evidence. The reference collection bullets from the experimental firing trials were instrumental in determining types of impact evidence as they were juxtaposed to the Edgehill bullet assemblages to compare for impact evidence.

Based on the reference collection, 52 bullets exhibit impact evidence from stones within the soil from bounce and roll; an example can be seen in figure 8.9. 42 of these bullets show impact evidence that can be attributed to single stone impacts. These single stone impacts could be from where the bullet directly impacted a single stone or where the bullet skipped across the surface of the ground and impacted or grazed a single stone in the soil as it continued down field. It is not possible to comment on the size of the stone in the soil nor is it possible to use the modelling program to predict range from impact damage as there are many other variables unaccounted for. The other 10 bullets display multiple stone impact events from the bullet bouncing and rolling through the field after ground impact as there are multiple impressions on the bullet's surface that are consistent with stone impacts. This is summed up in figure 8.8.

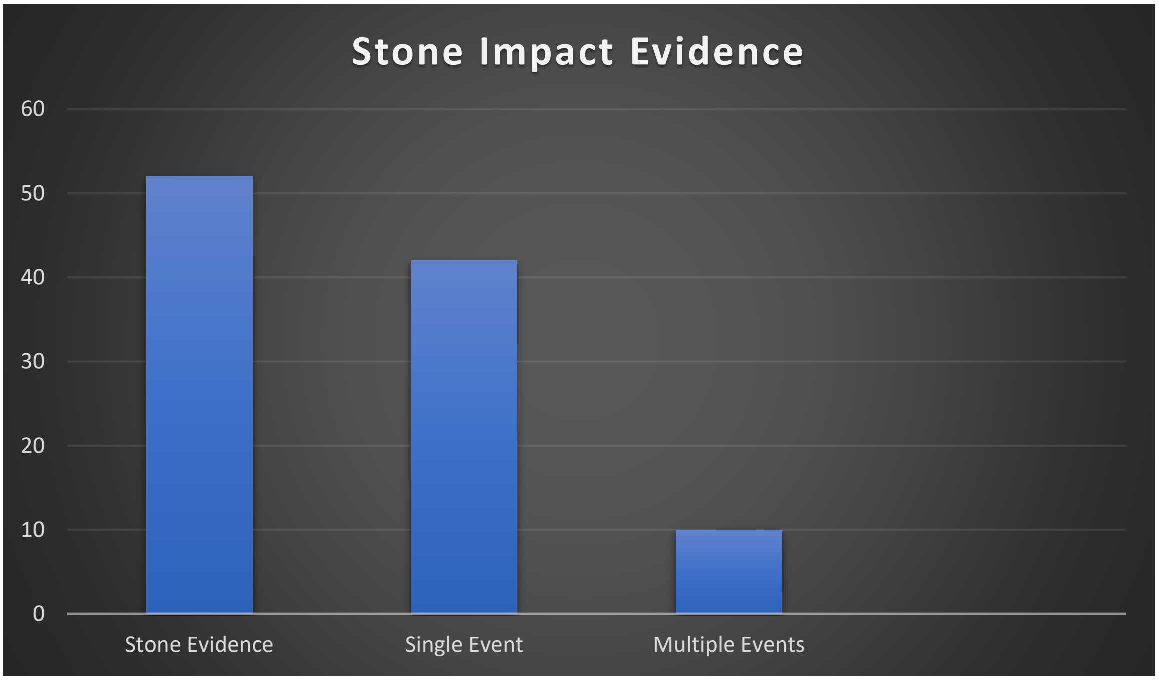

Figure 8.8: Stone impact evidence.

Figure 8.9: Edgehill 2172, spherical bullet showing single stone impact evidence under 10X magnification.

18 bullets display an unknown form of impact evidence, which continues to occur throughout the Edgehill assemblage. This type of evidence, which can be seen in figures 8.10 and 8.11, is termed here as linear rotational impact evidence; although admittedly it is unknown if this evidence came from impacting a surface or is as the result of some form of intentional alteration. The linear rotational impact evidence is in the form of superficial indentations that can run around the circumference of the bullet and can vary in length from bullet to bullet and does not encompass the entire bullet's surface. There are no striations in the indented surface and the linear nature appears uniform on both sides. This differs from stone impact evidence which displays a cleft to one side. Linear rotational impact evidence is similar to that of the mould seam; however, where the mould seam is raised above the surface, this rotational evidence is superficially imbedded into the surface of the bullet. With the spherical distortion level bullets, 11 of the bullets contain a singular linear rotational impact evidence and 7 bullets display multiple linear rotation evidence, wherein the bullet contains at least two of this unknown type of evidence.

Figure 8.10: Edgehill 254, spherical bullet showing linear rotational evidence under 10X magnification.

Figure 8.11: Edgehill 147, spherical bullet showing linear rotational evidence under 10X magnification.

6 bullets display both rotational and stone impact evidence. It is possible that whatever is causing the rotational impact evidence to form is also caused by the ground surface; however, this is only theoretical at this time as no reference from experimental evidence can corroborate this or definitively conclude what causes the rotational impact evidence.

8.1.2 Slight Distortion Level

A total number of 377 out of 803 bullets suffered slight distortion, comprising roughly 47% of the total bullet assemblage, of which 57 bullets have an offset mould seam which caused their distortion level. Most bullets given the slight distortion level are scattered throughout the battlefield; however, there is a main concentration in the core of the battlefield where the infantry action took place, as seen in figure 8.12 below.

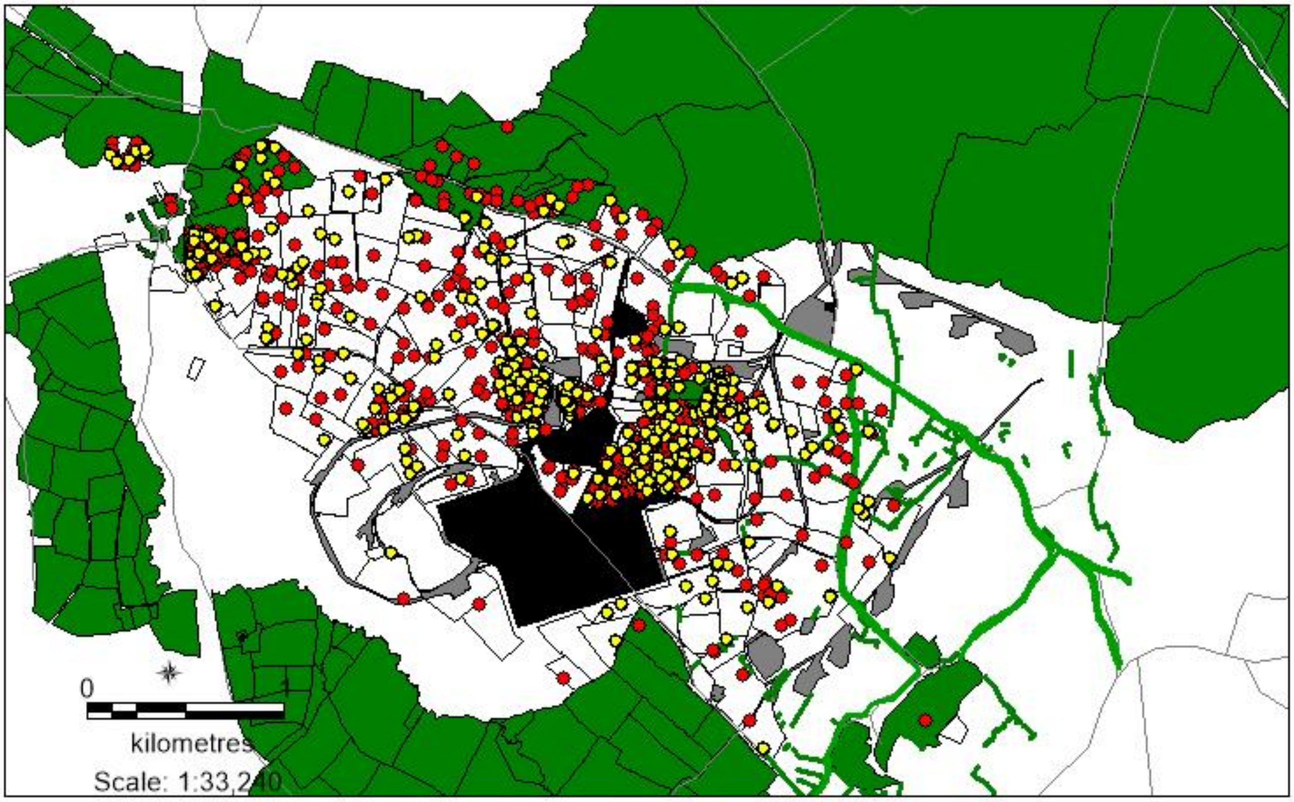

Figure 8.12: All bullets given the slight distortion level are labelled in yellow. The remaining bullets are coloured in red. GIS data courtesy of Glenn Foard.

8.1.2.1 Condition Assessment for Slight Distortion Level

245 bullets were recorded as having a good clean surface in which the transfer of traits was visible. 132 bullets were recorded as having a corroded surface, of which 20 bullets had too much corrosion on the surface which obscured the ability to complete further diagnostic analysis and comparison. This is summed up in figure 8.13.

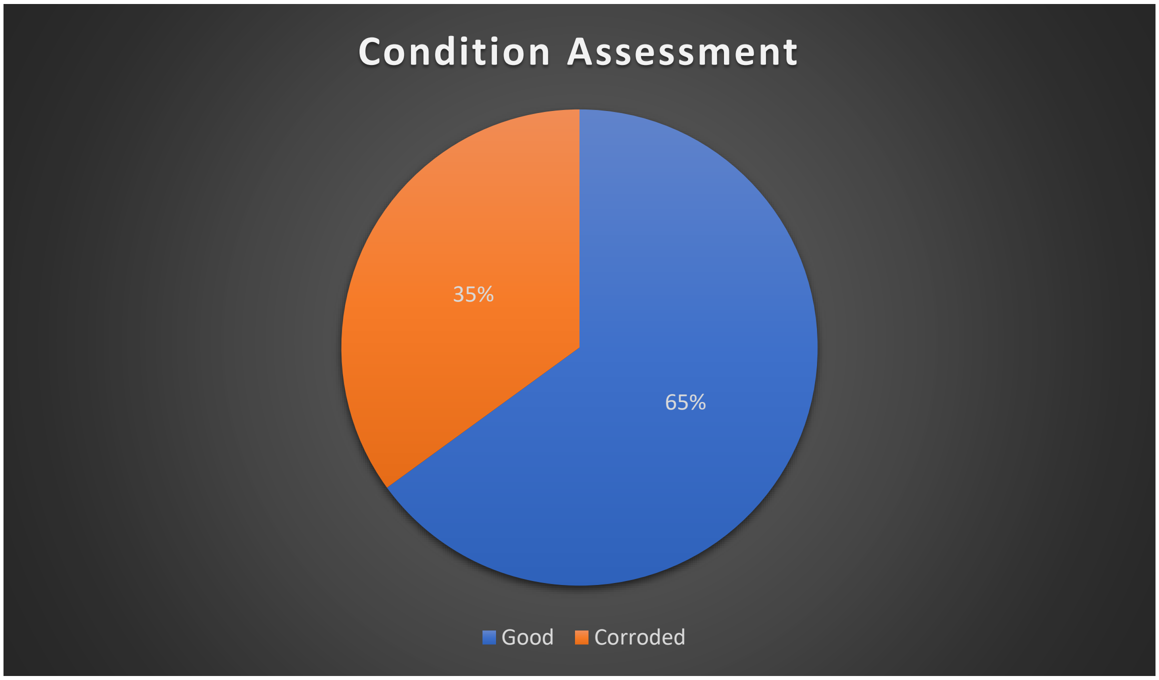

Figure 8.13: Condition assessment.

8.1.2.2 Manufacturing Evidence for Slight Distortion Level

167 bullets show signs of manufacturing evidence, of which 70 bullets contain multiple forms of manufacture evidence and 210 bullets show no signs of manufacture evidence (figure 8.14). These 210 bullets include the 20 bullets with too much corrosion as stated above as well as 17 separate bullets that were chewed thereby obscuring the bullet’s surface. As a result of corrosion and chewing eliminating any diagnostic characteristics on the bullets’ surfaces, these 37 bullets were unable to be analysed for any signs of further definitive evidence or impact damage.

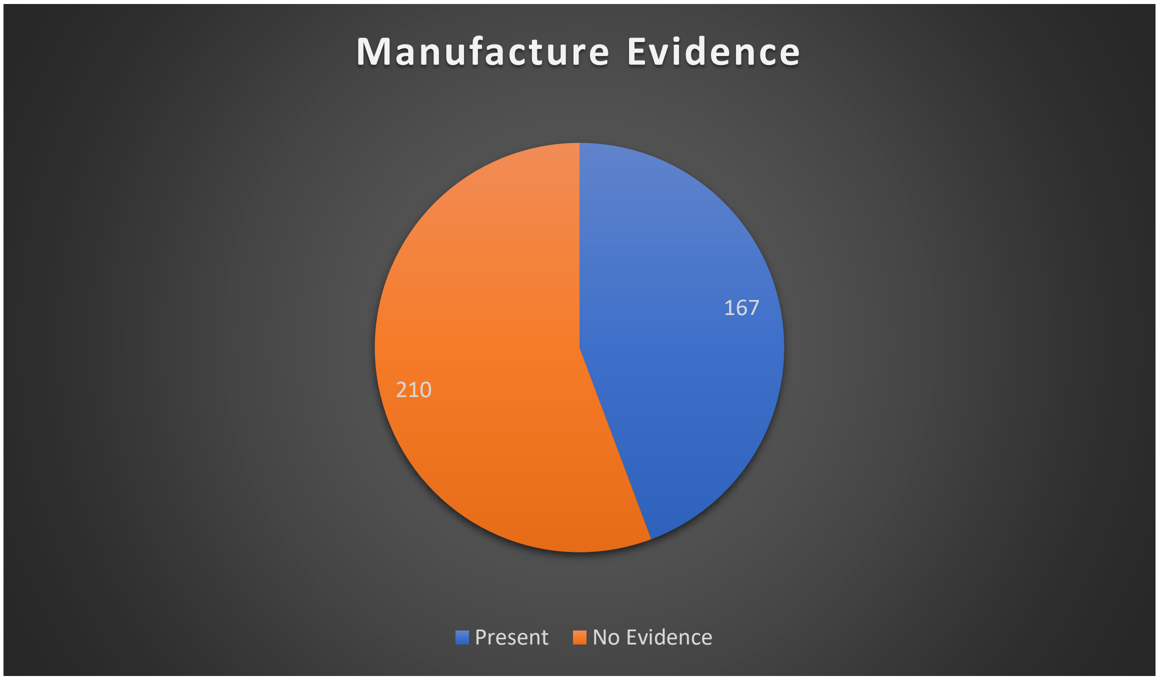

Figure 8.14: Manufacture evidence.

121 bullets display sprue cuts, 2 had an extended sprue and 20 bullets contain a deep sprue cut. The mould seam is still visible on 43 bullets, allowing for the diameter measurements to be taken. It is worth noting; however, that of the 377 bullets listed as slightly distorted that only 11% of those bullets could be measured using digital callipers. 14 bullets also contain flashing around the mould seam; however, only one of those bullets has any signs that the bullet had been fired. 71 casting faults were identified within the slightly distorted bullets. 57 bullets have an offset mould seam of which 12 also show signs of impact damage. 10 bullets show turning lines, 3 bullets contain a void in and around the cut sprue. 2 bullets with casting faults are incomplete fills, neither of which showed signs of firing or impact. A summary of this information can be found in figure 8.15.

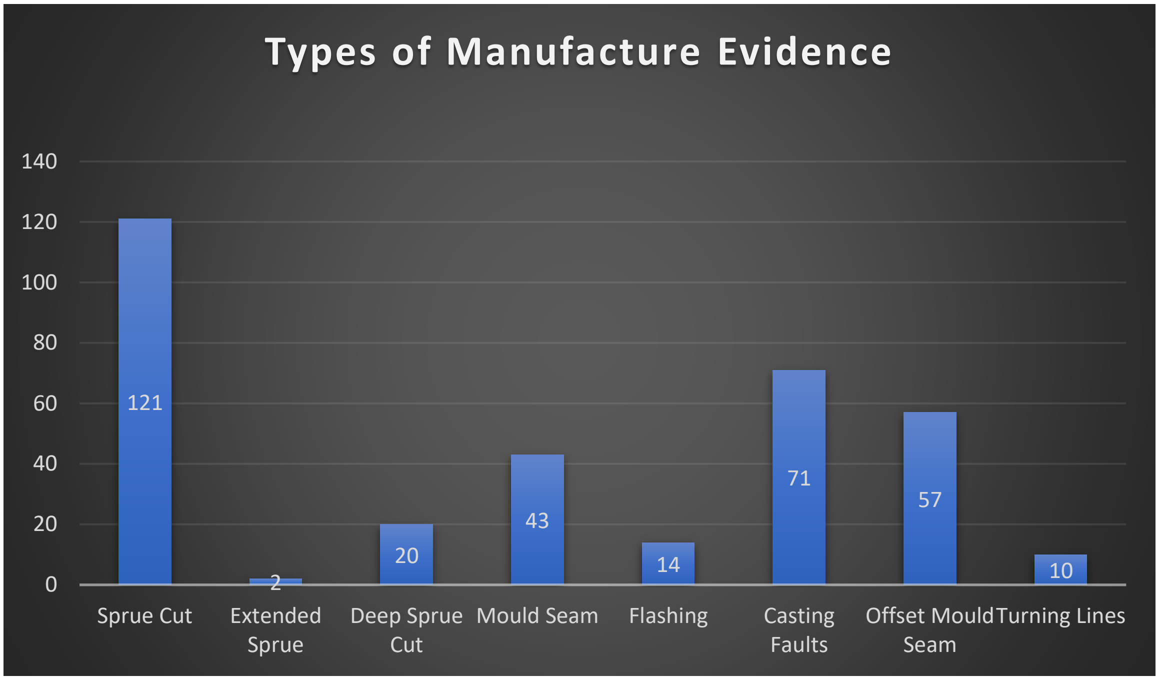

Figure 8.15: Types of manufacture evidence.

8.1.2.3 Loading Evidence for Slight Distortion Level

4 projectiles of buckshot calibre were recorded, and all contain circular depressions on the surface of the bullet suggesting a multiload bullet, such as swan-shot or small buckshot as noted in Chapter One (section 1.3.5.1). It is possible that these bullets are not battle related but are modern buckshot as most of these bullets appear in extremely good condition with little to no corrosion on the surface. These 4 bullets show 3-5 circular depressions on the bullet's surface, as well as compression from firing one of which shows stone impact evidence, see figure 8.16.

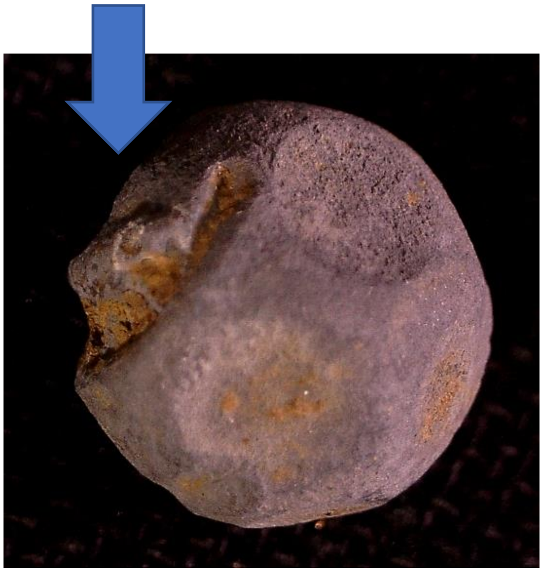

Figure 8.16: Multiload evidence Edgehill 441, note the casting fault in the upper left portion of the bullet.

8.1.2.4 Firing Evidence for Slight Distortion Level

159 of the 377 bullets contain firing evidence. Of which 156 bullets exhibit barrel bands and 34 bullets show signs of melting and powder pitting from firing. 65 of those bullets that show firing evidence also contains impact evidence. 218 of the bullets did not show signs of firing evidence. As previously stated, 20 of these bullets had corrosion on the surface and 17 bullets were heavily chewed rendering evidence obscured. Only one of the 218 bullets that show no firing evidence, contains impact damage. A summary of this information can be found in figure 8.17.

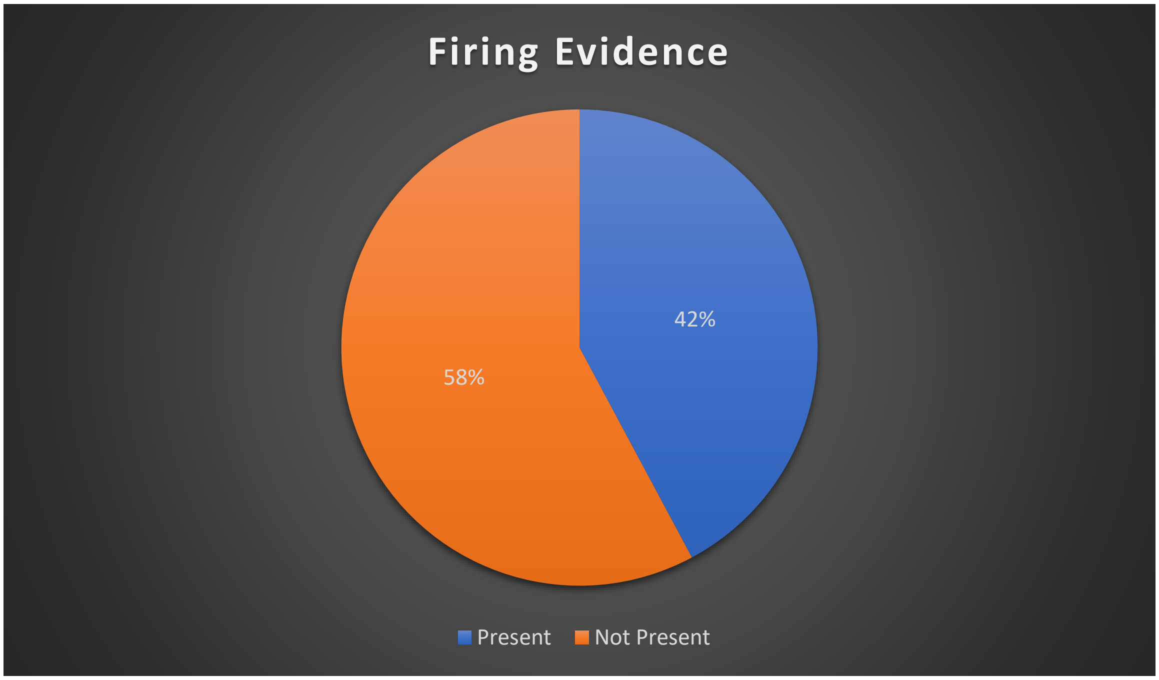

Figure 8.17: Firing evidence.

8.1.2.5 Impact Evidence for Slight Distortion Level

With the other forms of evidence identified and eliminated, the remaining evidence on the bullet's surface can be attributed to either impact evidence or evidence from an unknown source. 177 bullets in the slight distortion category show signs of impact damage and 200 bullets show no signs of impact damage, even though 92 of those 200 bullets display firing evidence (figure 8.18). This large proportion of bullets showing firing evidence, but no impact evidence reinforces the need for further experimentation. As noted by Foard, there are conditions wherein a bullet can be fired and impact the ground without showing impact damage (Foard 2012: 158).

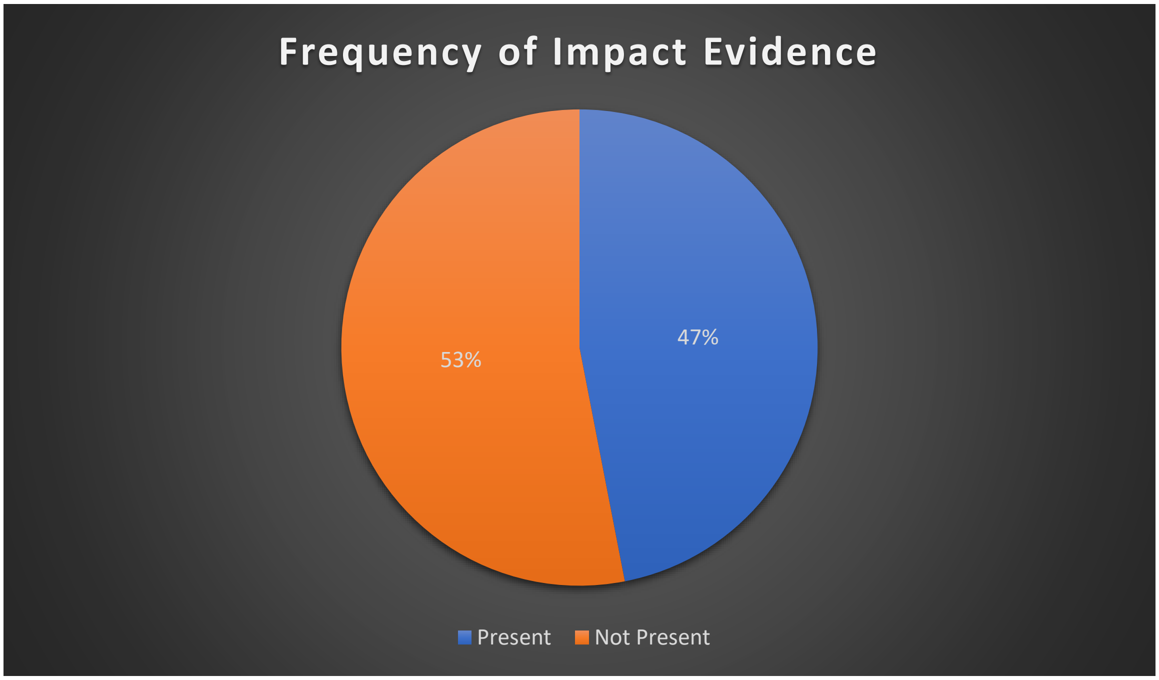

Figure 8.18: Frequency of impact evidence.

Of the 177 bullets exhibiting impact evidence, multiple types of impact evidence are noted, and some bullets contain multiple forms of impact evidence. The experimental reference collection was used to assist in determining and categorising the impact evidence and a summary of the types of impact evidence can be found in figure 8.19.

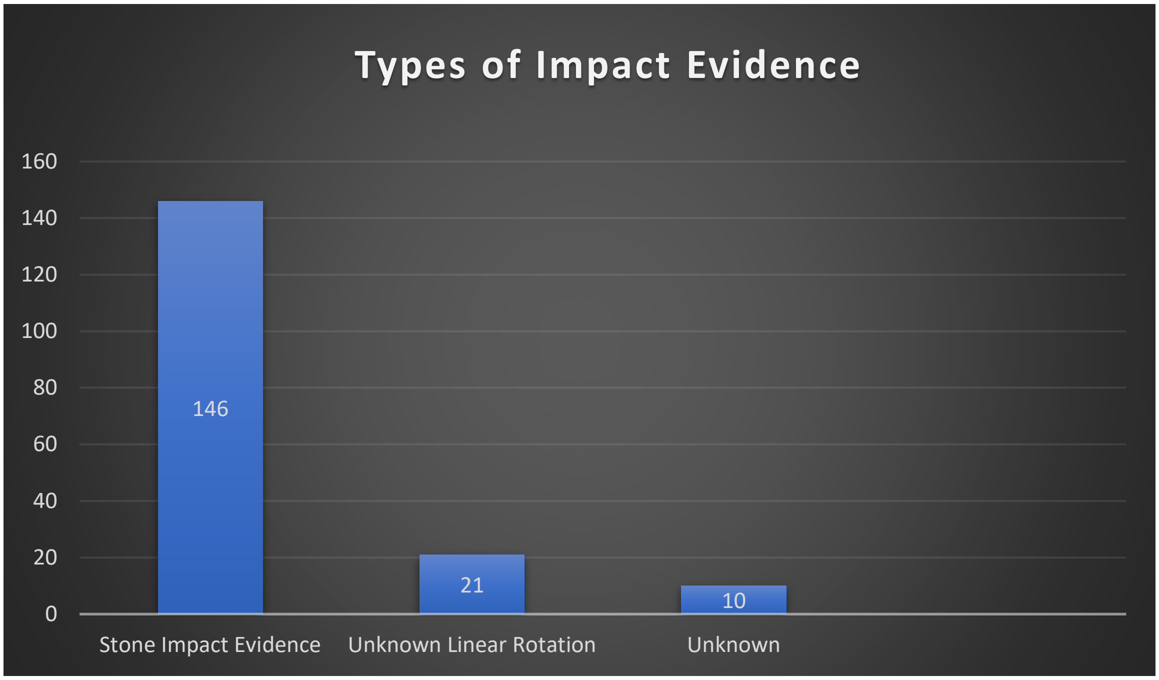

Figure 8.19: Types of impact evidence.

146 total bullets show a variety of fine tight linear striations, gouges and clefts that are consistent with impacting stones within the soil. 100 bullets display impact evidence consistent with single stone impacts, through either a direct single impact or abrasion from bounce and roll across the ground surface. The other 46 bullets show multiple stone impact events from impacting multiple stones during the process of bounce and roll after ground impact. It was not possible to determine firing distance using the computer modelling program as too many variables were unaccounted for and it is not possible to determine the size of the stone that the bullet impacted as previously advised. In some instances, it is possible to determine the series of impacts based on how the striations crossed the surface of the bullet or crossed other sections of impact evidence. For example, a cleft or gouge caused by one stone impact may interrupt the striations of a previous impact event, as seen in figure 8.20 below. Figures 8.21 and 8.22 show evidence of single stone impact events and figure 8.23 demonstrates multiple stone impact events. While figure 8.24 below, shows a single stone impact event with stone inclusion in the impact surface.

Figure 8.20: Edgehill 2330, slightly distorted bullet showing a single stone impact event that interrupted a previous rotational impact event, under 10X magnification.

Figure 8.21: Edgehill 133, slightly distorted bullet showing single stone impact evidence, under 10X magnification.

Figure 8.22: Edgehill 144, slightly distorted bullet showing single stone impact evidence, under 10X magnification.

Figure 8.23: Edgehill 1398, slightly distorted bullet showing evidence of multiple stone impacts, under 10X magnification.

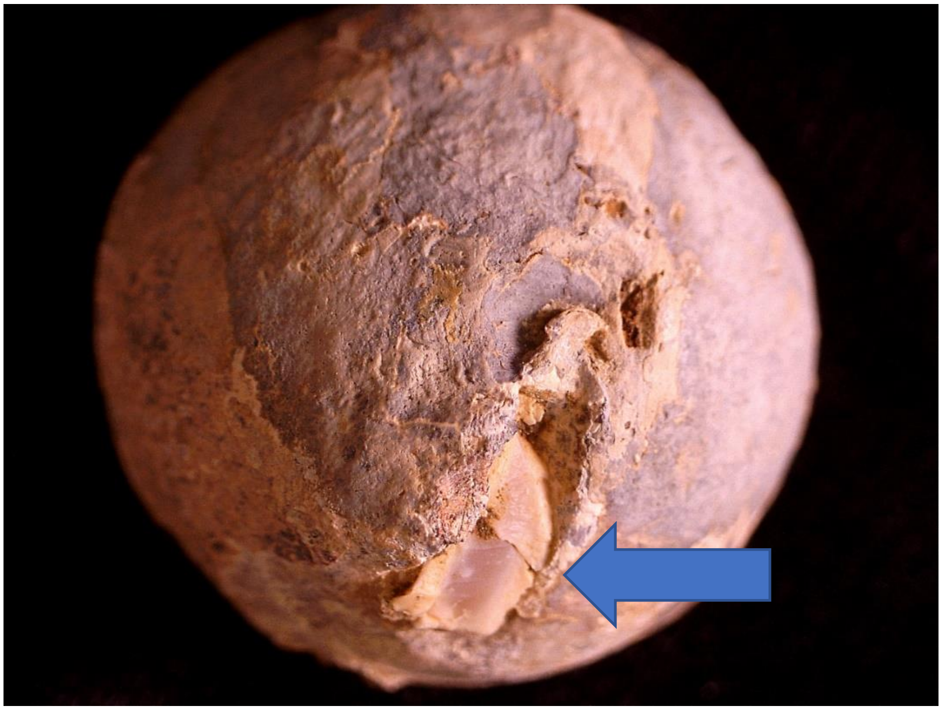

Figure 8.24: Edgehill 1189, slightly distorted bullet showing stone impact evidence with stone inclusion, under 10X magnification.

43 bullets exhibit the unknown linear rotational impact damage as discussed above in the spherical distortion level. 23 bullets show singular rotational evidence, while an additional 20 bullets display multiple rotational markers, an example can be seen in figure 8.25.

Figure 8.25: Edgehill 2082, slightly distorted bullet showing rotational impact evidence, under 10X magnification.

22 bullets display both linear rotational and stone impact evidence. The implication from this could be that both sets of evidence on the bullets' surfaces are being caused by the ground surface, possibly during bounce and roll or potentially something the bullet is impacting before it impacts the ground.

Wood impact evidence is more difficult to locate within the archaeological record than within the experimentally fired bullets. As noted in Chapter Seven, wood grain impression can be quite faint and sometimes only visible under 10X magnification. Concern was noted that corrosion would easily obfuscate or eliminate the wood grain impressions rendering it difficult to confirm as wood impact evidence. 4 bullets are listed as possible wood impacts, and 2 of the 4 could be stone impacts. However, these 4 bullets are ultimately unknown impact evidence, because, without the characteristic traits present, only the appearance of the surface of the bullets are similar to wood impact evidence, this is demonstrated in figures 8.26 and 8.27 below. This is because these two bullets have no central point of impact as is a common indicator of wood impact evidence as seen in the experimental reference collection in Chapter Seven. It is also difficult to examine the specific striations within the impact surface due to corrosion. The striations themselves would help determine whether this impact damage was due to wood, stone or an unknown impact surface.

Figure 8.26: Edgehill 879, slightly distorted bullet showing unknown impact evidence, under 10X magnification.

Figure 8.27: Edgehill 2080, slightly distorted bullet showing unknown impact evidence, under 10X magnification.

5 bullets contain unknown impact evidence, which consists of deep circular facets as seen in figure 8.28. These deep circular facets are not consistent with any known impact or intentional alteration known to the author. This evidence requires further analysis and comparison to future experimentally fired bullets not explored in this thesis. Future experimental firing trials with varying targets are necessary to expand the current experimental reference collection of known impact evidence to help identify these remaining unknowns.

Figure 8.28: Edgehill 2155, slightly distorted bullet showing unknown impact evidence with corrosion in the impact surface, under 10X magnification.

8.1.3 Moderate Distortion Level

77 of the 803 bullets were categorised as moderately distorted, which encompasses 10% of the total assemblage. Most of the bullets categorised as moderately distorted can be found in the core of the infantry action as seen in figure 8.29 below.

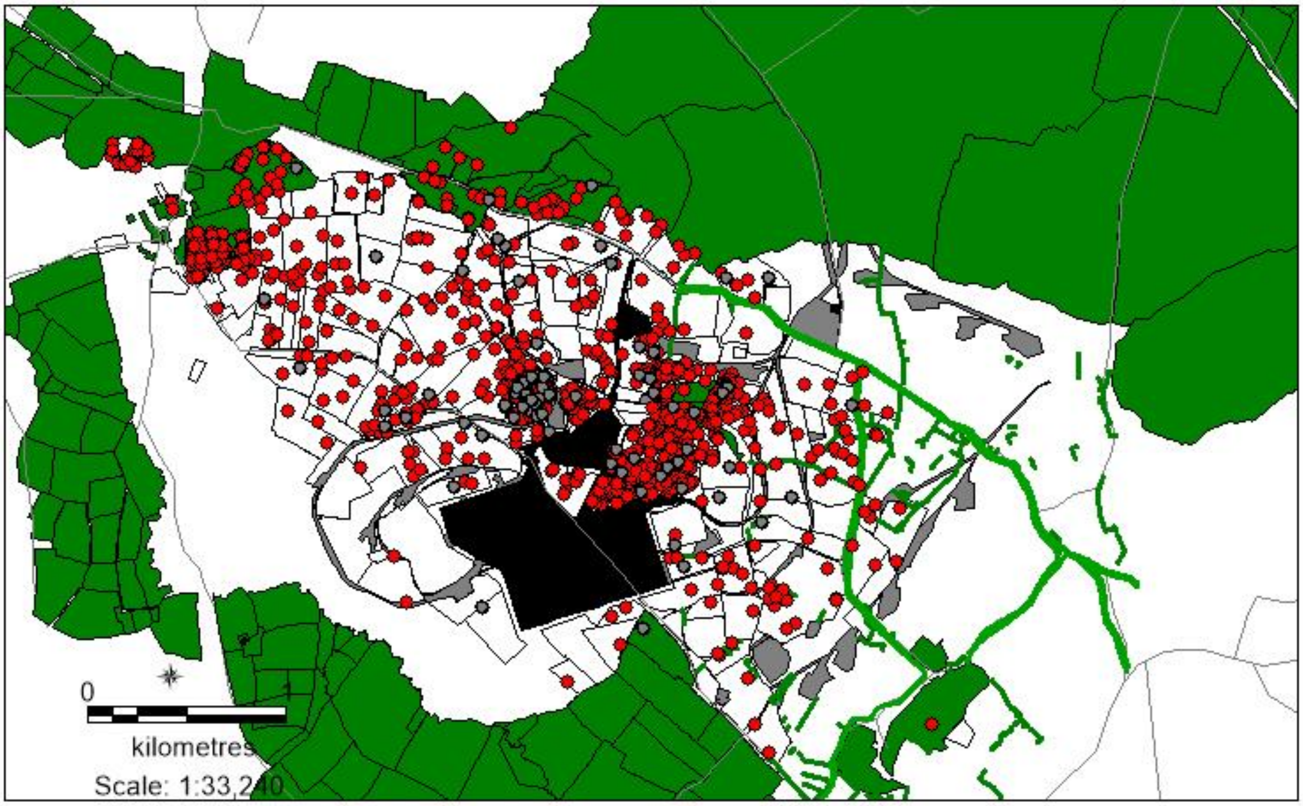

Figure 8.29: All bullets given the moderate distortion level are labelled in grey. The remaining bullets are coloured in red. GIS data courtesy of Glenn Foard.

8.1.3.1 Condition Assessment for Moderate Distortion Level

The condition assessment for the bullets classified as moderately distorted show 58 bullets listed as being in good condition, and 19 bullets as corroded. 9 of the 19 corroded bullets are listed as having so much corrosion that renders the bullet's surface impossible to interpret (figure 8.30).

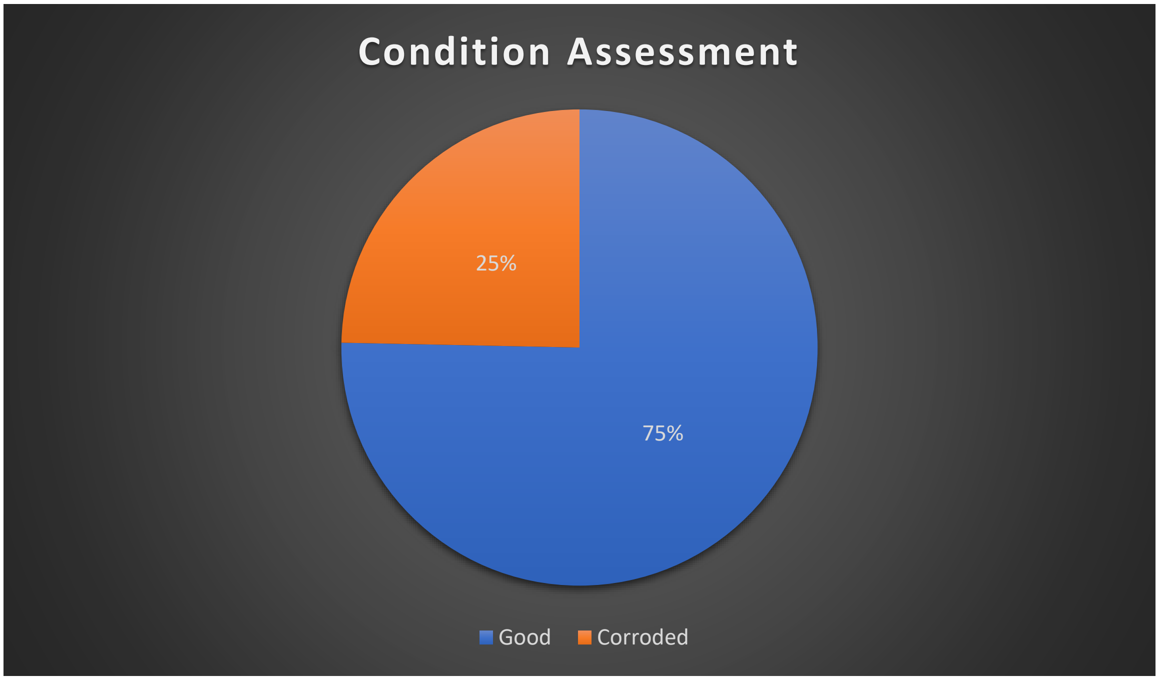

Figure 8.30: Condition assessment.

8.1.3.2 Manufacturing Evidence for Moderate Distortion Level

Of the 77 bullets listed as moderately distorted, only 8 bullets show signs of manufacturing evidence, whereas 69 bullets do not show any signs of manufacture evidence. No bullets at this distortion level show multiple signs of manufacturing evidence. 3 bullets have a sprue cut, one bullet has an extended sprue and one bullet shows a deep sprue cut. This lack of manufacturing evidence seems to coincide with the increase in distortion level, as seen in figure 8.31.

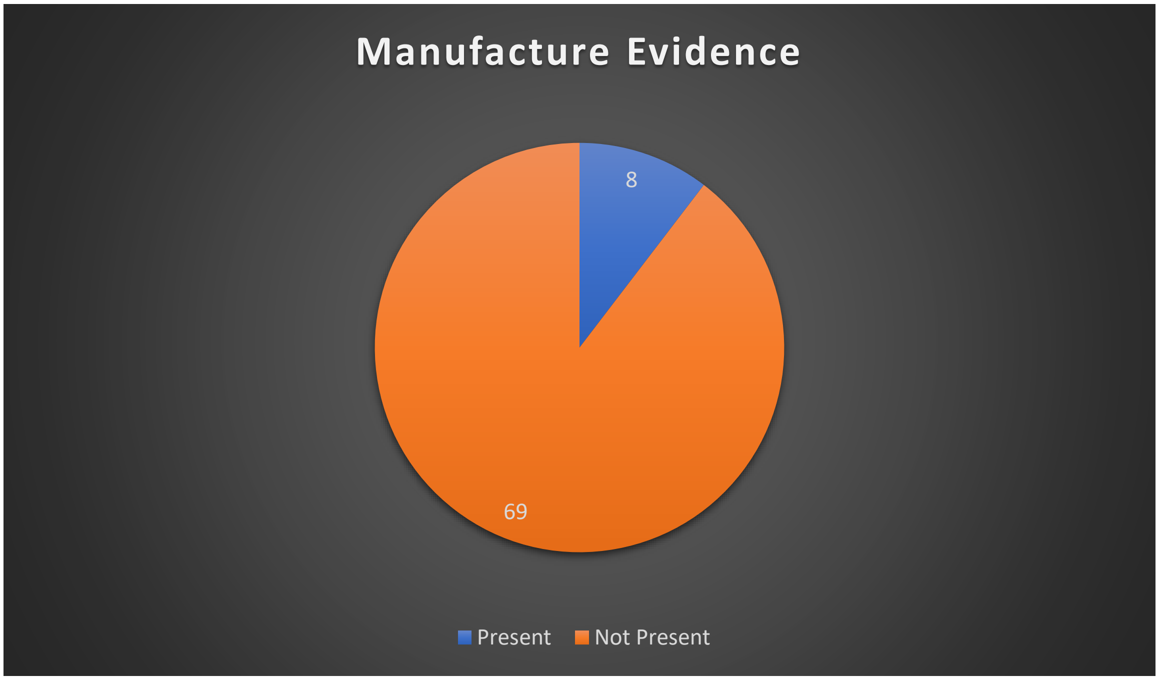

Figure 8.31: Manufacture evidence.

5 casting faults were identified within the moderately distorted bullets. 3 bullets are incomplete fills all of which show either firing or impact evidence and 2 bullets have an offset mould seam, neither of which show firing or impact evidence. Figure 8.32 illustrates the different types of manufacture evidence.

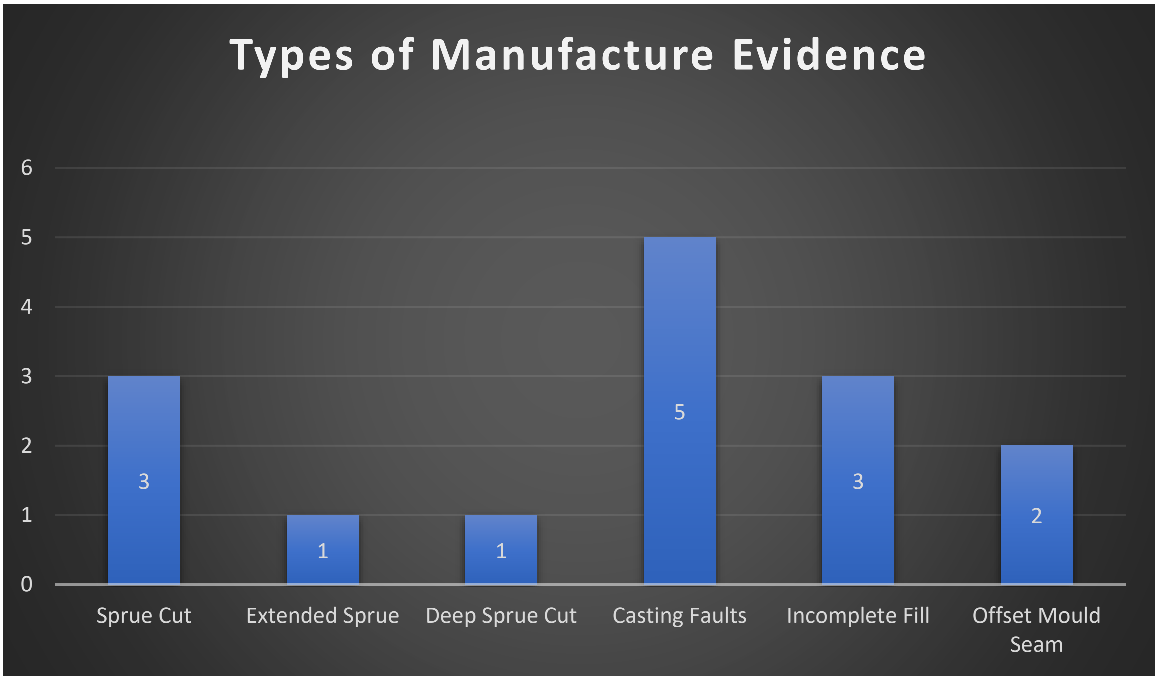

Figure 8.32: Types of manufacture evidence.

8.1.3.3 Loading Evidence for Moderate Distortion Level

3 bullets of buckshot calibre were recorded; these bullets contain circular depression on the surface of the bullet suggesting a multiload bullet, such as swan shot or buckshot. These bullets all contain at least 4 circular depressions on their surfaces, as well as compression from firing and, all 3 bullets show evidence of firing and impact. As previously stated, it is possible that these bullets are modern buckshot as the bullets are in excellent condition and show very little corrosion.

8.1.3.4 Firing Evidence for Moderate Distortion Level

22 of the 77 bullets categorised as moderately distorted exhibit firing evidence. 22 bullets show barrel bands, and 2 show powder pitting and melting on the surface from firing. 20 of the 22

bullets display impact evidence as well (figure 8.33).

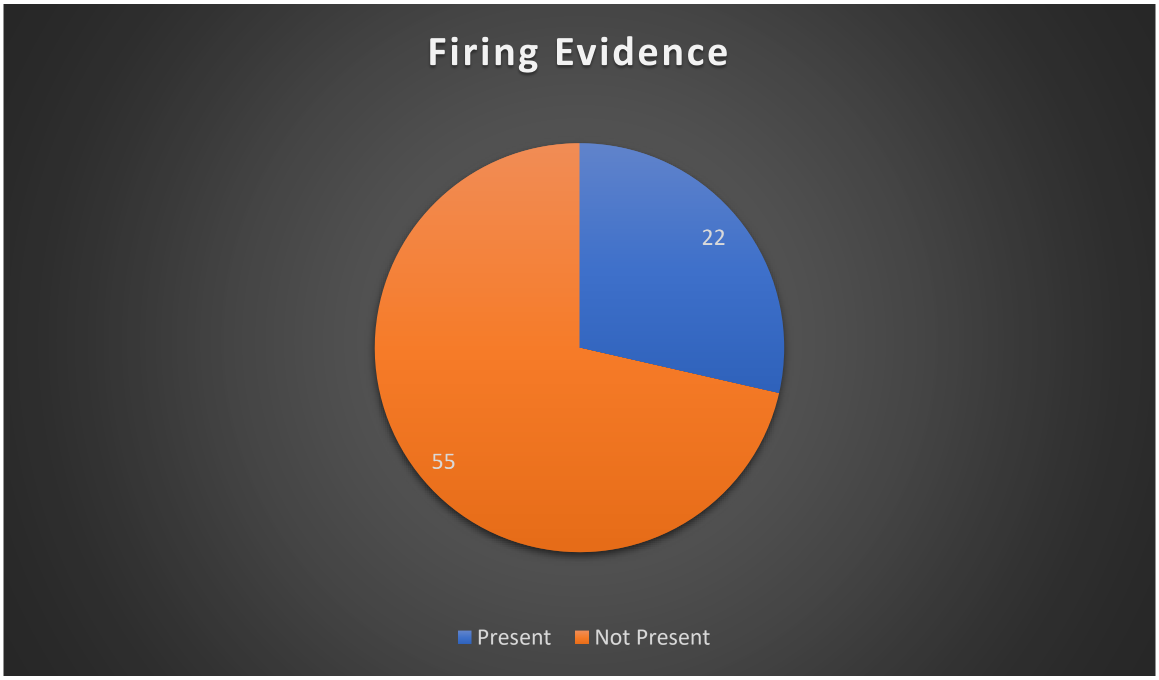

Figure 8.33: Firing evidence.

8.1.3.5 Impact Evidence for Moderate Distortion Level

With the other forms of bullet evidence taken into consideration, the remaining evidence on the bullet can be attributed to either impact evidence or evidence of an unknown origin. 66 bullets show signs of impact damage, while only 20 of those bullets show signs of firing evidence. Of the 11 bullets that do not exhibit impact evidence, 2 are heavily chewed and 9 bullets were too corroded to determine any kind of surface characteristics. The frequency of impact evidence for the moderate distortion level is illustrated in figure 8.34. Figure 8.35 demonstrates the different types of impact evidence noted on these bullets.

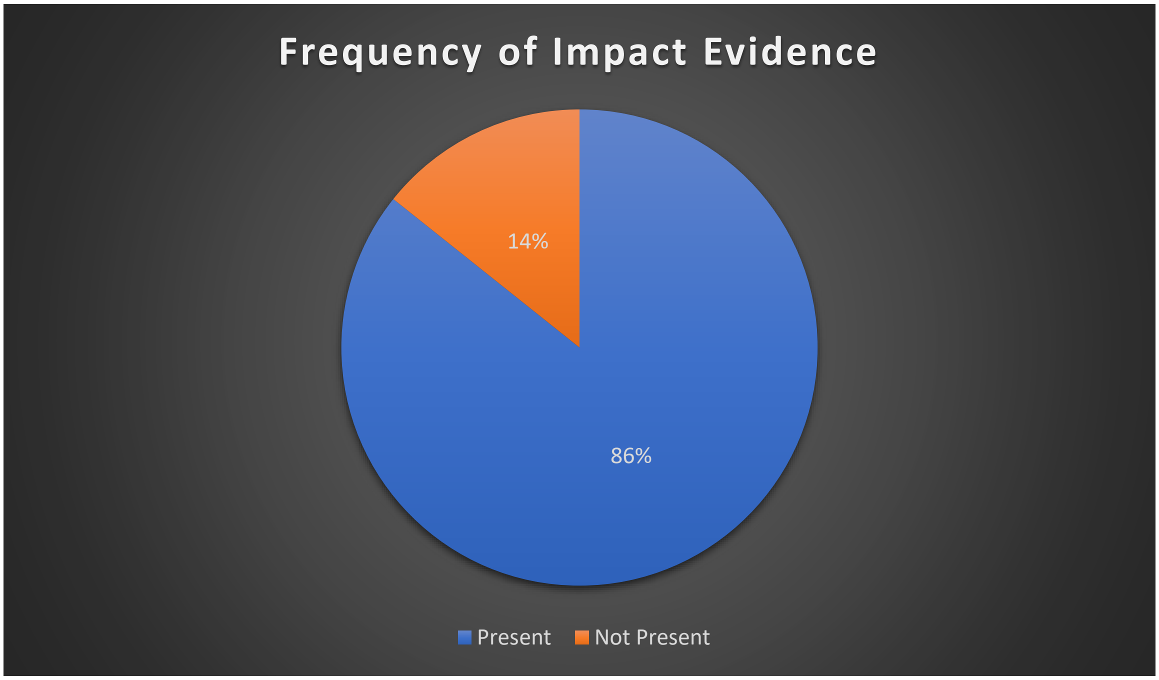

Figure 8.34: Frequency of impact evidence.

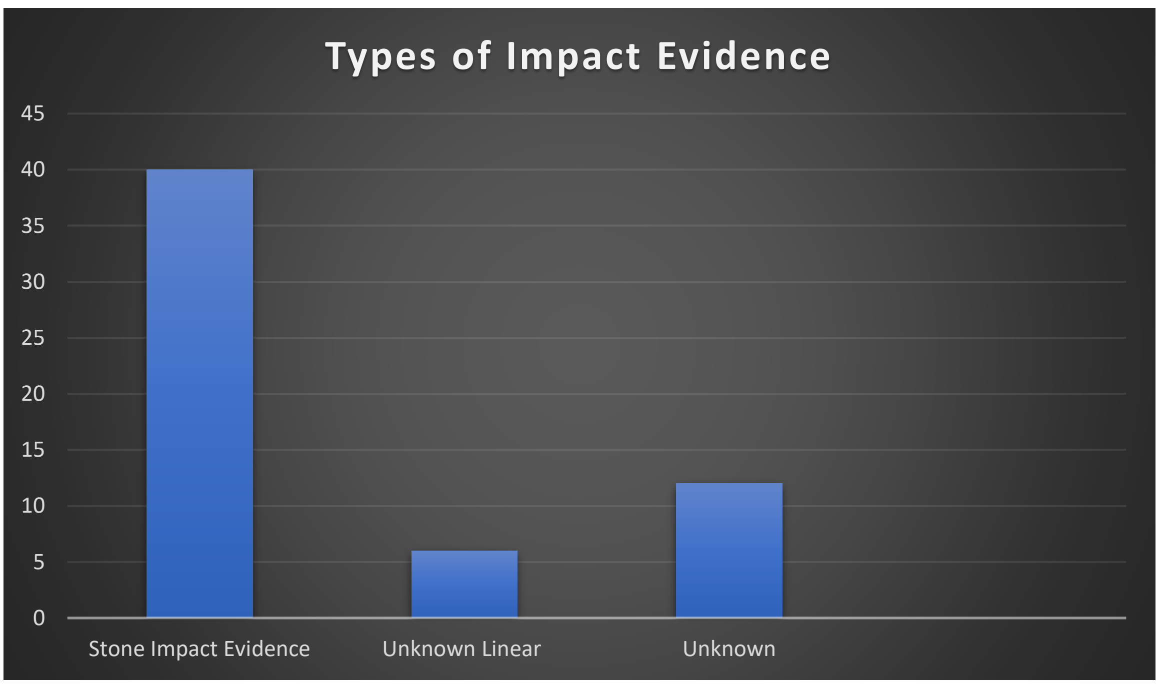

Figure 8.35: Types of impact evidence.

40 of the 66 bullets display fine tight linear striations, gouges and clefts which are consistent with stone impact evidence. 17 of those bullets show singular stone impacts and 23 exhibit

multiple stone impact events on the bullets’ surfaces. The transfer of characteristic traits is a result of the bullet bouncing and rolling across the field after ground impact. Figures 8.36 and 8.37 demonstrate multiple stone impact events, and figure 8.38 shows a single stone impact event.

Figure 8.36: Edgehill 154, moderately distorted bullet showing multiple stone impact evidence, under 10X magnification.

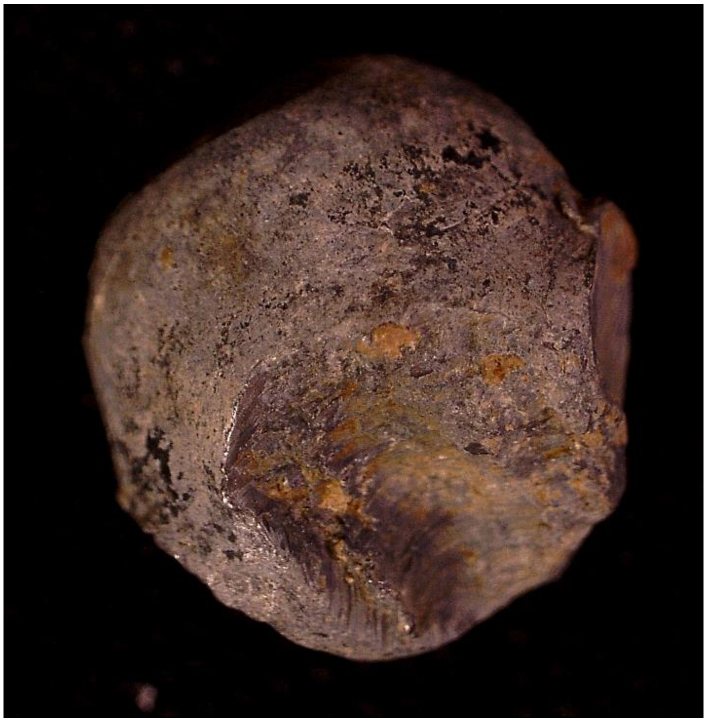

Figure 8.37: Edgehill 2305, moderately distorted bullet showing multiple stone impact evidence, under 10X magnification.

Figure 8.38: Edgehill 2348, moderately distorted bullet showing single stone impact evidence, under 10X magnification.

2 bullets display the unknown multiple linear rotational impact markers, and 4 bullets exhibit both impact evidence consistent with stone and rotational damage.

One bullet exhibits a fabric impression, although it is not possible to determine if this was from impacting clothing or from being fired from a cartridge as both are a possibility as seen in Chapter One (section 1.3.5.7). Further experimental firing is necessary to investigate fabric impressions on bullets as this was unexplored in this study.

12 bullets can be attributed to potential wood impacts, although this is based solely on the appearance of the bullet. These bullets are in a semi-hemispherical shape which is also consistent with wood impacts, although the central point of impact could not be located on the bullets' surfaces. 4 additional bullets could either be attributed to impacting wood or a stone. These 4 bullets contain linear striations consistent with both types of impact evidence, although corrosion has affected the bullets' surfaces making it difficult to determine specifics. Figures 8.39 and 8.41 below could be potential evidence of wood impacts, although without the striations present this cannot be confirmed. Figure 8.40 has almost the same appearance as one of the experimentally fired bullets (B60-Chapter Seven, section 7.5) from the experimental firing trials; a bullet that impacted two different branches while exiting a mock hedge. The impact left that bullet with a central ridge between the impact points. However, without the wood grain impressions to verify that hypothesis, figure 8.40 is relegated to unknown impact evidence. As mentioned above, the appearance of the bullet is not enough to classify the impact evidence as wood and without the transfer of characteristic traits from the impact surface, this type of evidence must be relegated to unknown impact evidence.

Figure 8.39: Edgehill 22, moderately distorted bullet showing unknown impact evidence, under 10X magnification.

Figure 8.40: Edgehill 2251, moderately distorted bullet showing unknown impact evidence, under 10X magnification.

Figure 8.41: Edgehill 2679, moderately distorted bullet showing unknown impact evidence, under 10X magnification.

15 bullets have various unknown impact evidence on their surfaces. It was not possible to categorise each individual bullet as the impact evidence varied between each bullet. The figures 8.42 and 8.43 below show the bullets in more detail.

Figure 8.42: Edgehill 3050, unknown evidence, under 10X magnification.

Figure 8.43: Edgehill 884, moderately distorted bullet with unknown impact evidence, under 10X magnification. Note the raised lip around the perimeter of the bullet.

8.1.4 Heavy Distortion Level

Out of the total of 803 bullets, 10 bullets are listed as heavily distorted, comprising 1% of the total assemblage. Those bullets are located within the centre of the infantry action as noted in figure 8.44.

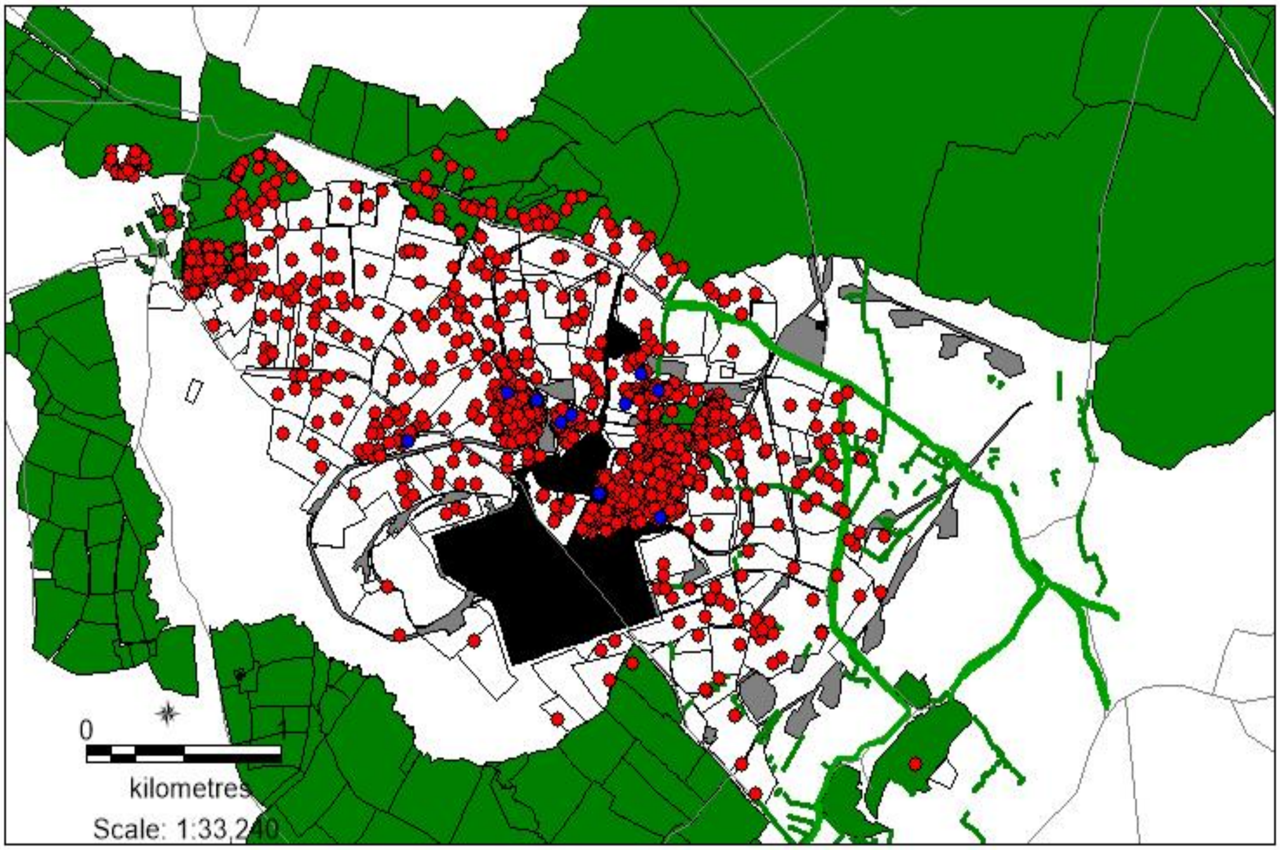

Figure 8.44: All bullets given the heavy distortion level are labelled in blue. The remaining bullets are coloured in red. GIS data courtesy of Glenn Foard.

8.1.4.1 Condition Assessment for Heavy Distortion Level

The condition assessment for the bullets categorised as heavily distorted shows that 9 bullets are in good condition and one is categorised as corroded.

8.1.4.2 Manufacturing Evidence for Heavy Distortion Level

Only one bullet from this category shows manufacturing evidence, the remaining 9 bullets do not. The sprue cut, and the mould seam are visible on the one bullet.

8.1.4.3 Firing Evidence for Heavy Distortion Level

3 bullets show evidence of being fired, all 3 contain banding evidence and one shows both banding and powder pitting from firing. The three bullets also show signs of impact.

8.1.4.4 Impact Evidence for Heavy Distortion Level

9 bullets from the heavy distortion level exhibit impact evidence, one bullet does not because it is heavily chewed. Only 3 of these nine bullets also display firing evidence.

6 bullets exhibit impact evidence that is consistent with the fine linear striations expected from stone impacts. 5 of those bullets show single stone impacts and one bullet shows multiple stone impact points. Figure 8.45 below shows evidence of a single stone impact.

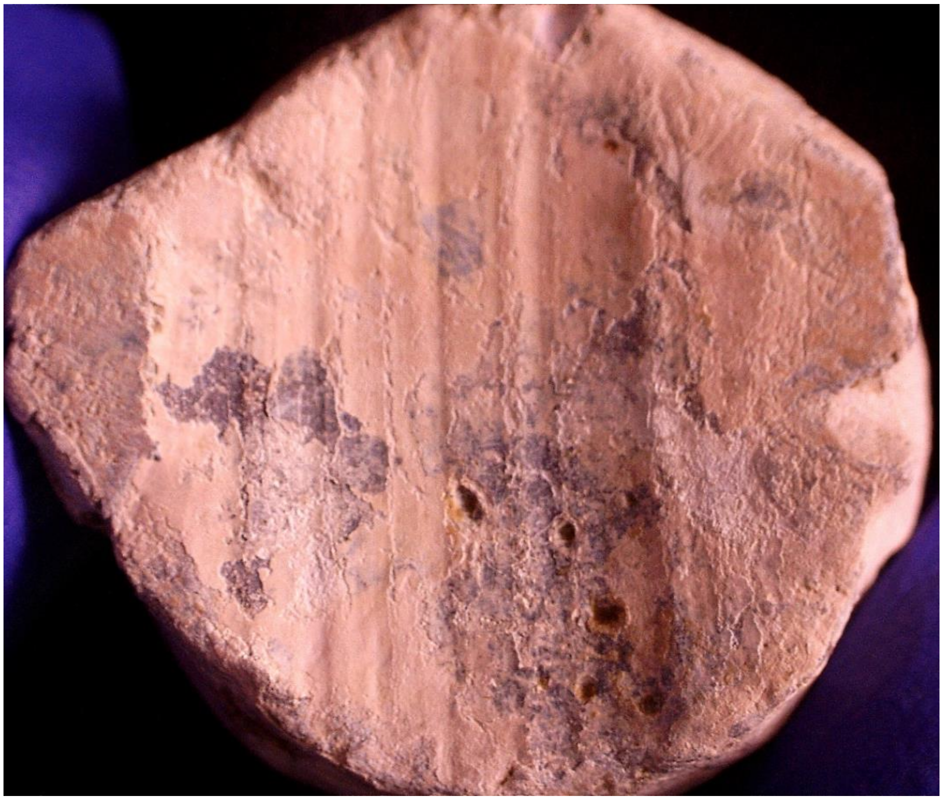

Figure 8.45: Edgehill 1792, heavily distorted bullet showing stone impact evidence, under 10X magnification. Note the tiny pockmarks in the impact surface which is similar to direct contact with pebbles in the soil as seen in Chapter Seven.

Only one bullet displays the unknown multiple linear rotational impact evidence on its surface. 3 bullets were determined to contain potential wood impact evidence, although it is difficult to determine with certainty as the thick linear striations are difficult to identify with the corrosion layer on the bullets' surfaces. One of these bullets could have impact damage either from stone or wood, as the corrosion makes it difficult to determine the type of linear striations on the impact surface of the bullet (figure 8.46). However, as noted above without those linear striations, this thesis could not confirm that the bullet impacted a wooden target and was therefore relegated to unknown impact evidence.

Figure 8.46: Edgehill 2220, heavily distorted bullet. Either a potential wood impact or from stone impact. The lack of evidence in the impact surface made definitive determination impossible.

8.1.5 Irregular shaped Distortion Level

40 bullets were categorised as irregularly distorted, comprising 5% of the total bullet assemblage. 2 of these bullets were of an alternate bullet type known as quartered bullets, and 16 were heavily chewed. The remaining 22 bullets were irregular from impact. Bullets categorised as irregular in shape are found distributed across the battlefield as seen in figure 8.47 below.

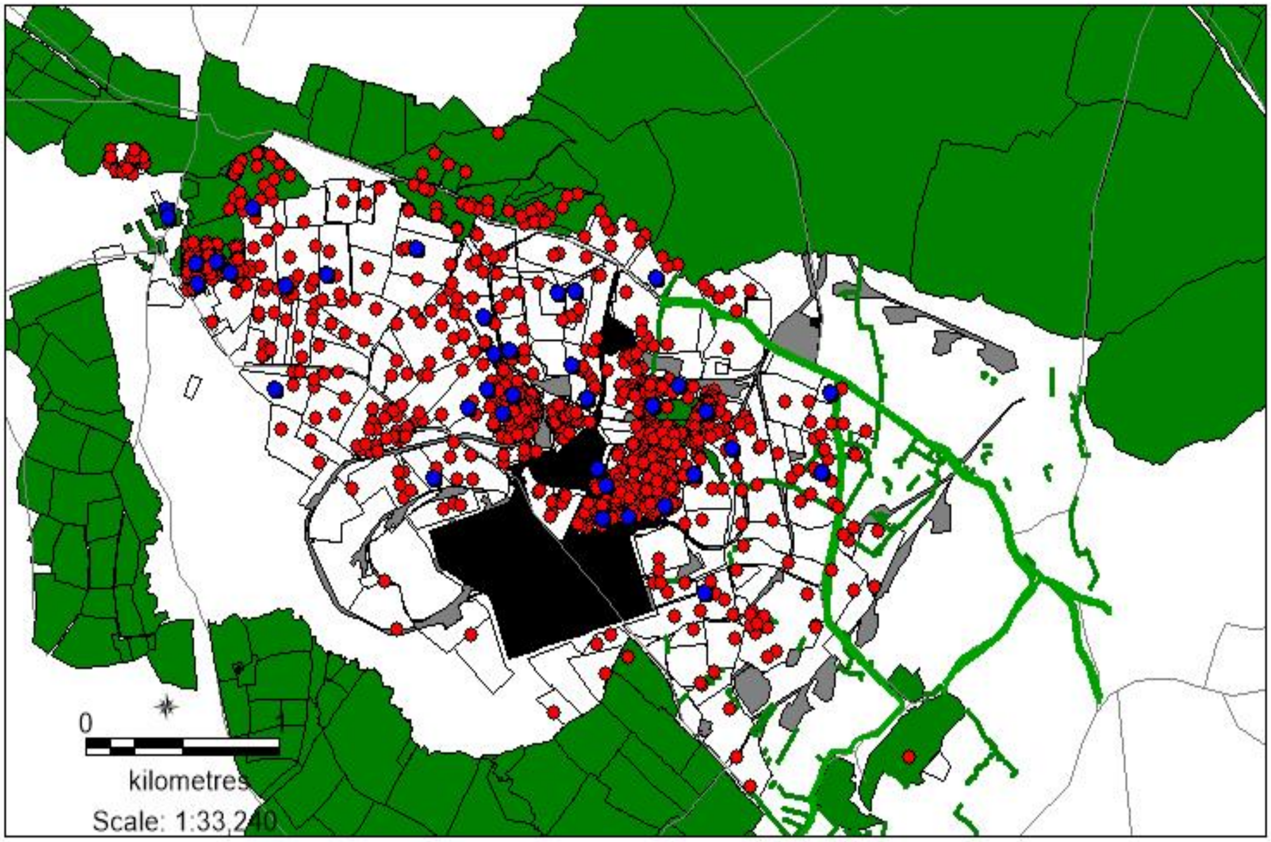

Figure 8.47: All bullets given the irregular distortion level are labelled in blue. The remaining bullets are coloured in red. GIS data courtesy of Glenn Foard.

8.1.5.1 Condition Assessment for Irregular Distortion Level

The condition assessment for the bullets categorised as irregular in shape show that 35 of the irregular bullets are in good condition, while only 5 are recorded as corroded, this is illustrated in figure 8.48.

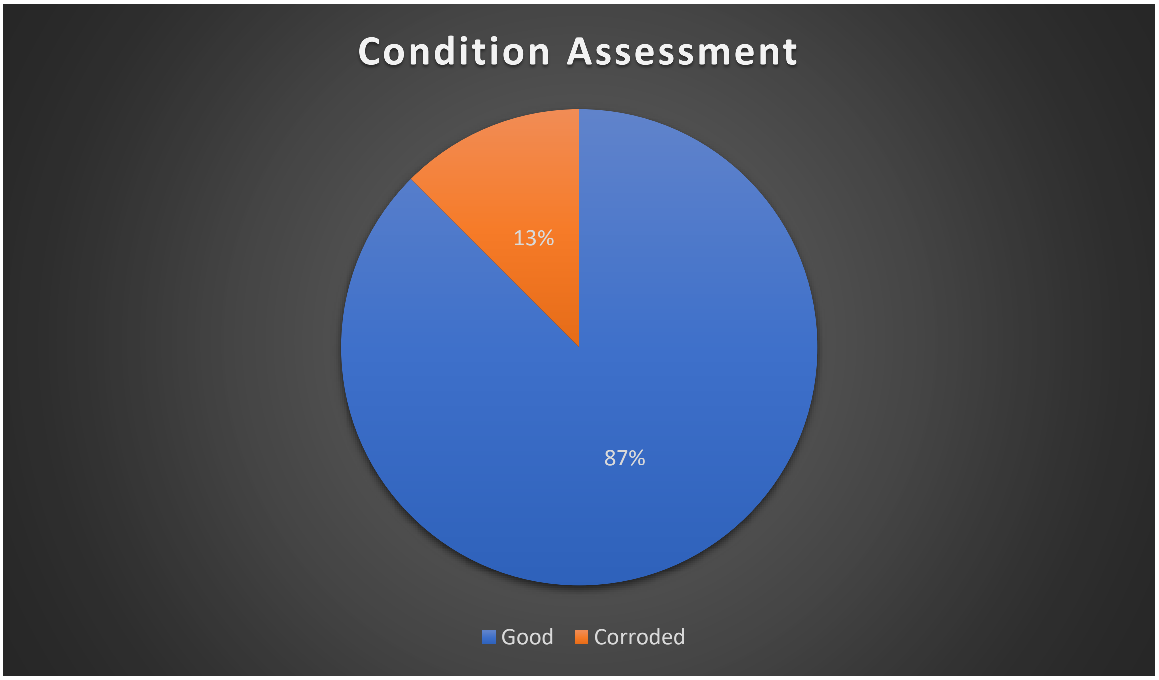

Figure 8.48: Condition assessment.

8.1.5.2 Manufacturing Evidence for Irregular Distortion Level

6 bullets show manufacturing evidence while the remaining 34 do not (figure 8.49). All 6 bullets have casting faults, 4 containing voids in the bullet, including one bullet that was quartered. 2 bullets were incomplete mould fills.

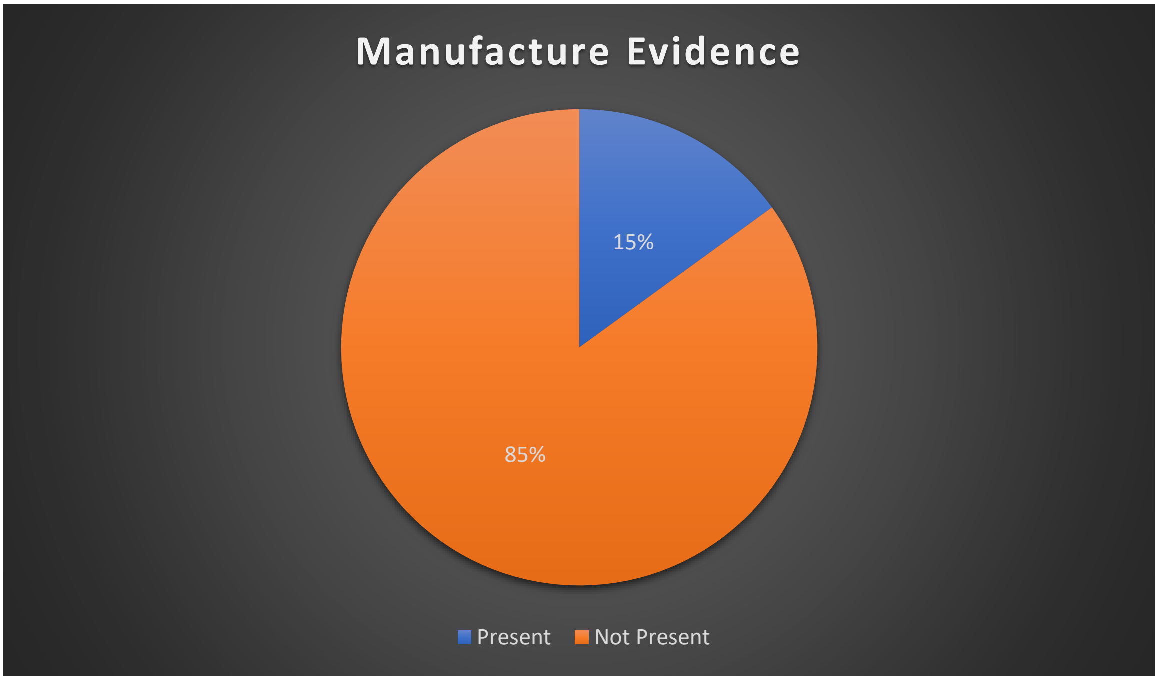

Figure 8.49: Manufacture evidence.

8.1.5.3 Firing Evidence for Irregular Distortion Level

Only 7 of the 40 bullets categorised as irregular in shape show firing evidence. 2 bullets show powder pitting, and one bullet displays banding evidence. The remaining 4 are the quartered bullets which are broken apart into their respective 4 individual pieces. The 3 bullets that exhibit powder pitting and banding also show impact damage (figure 8.50).

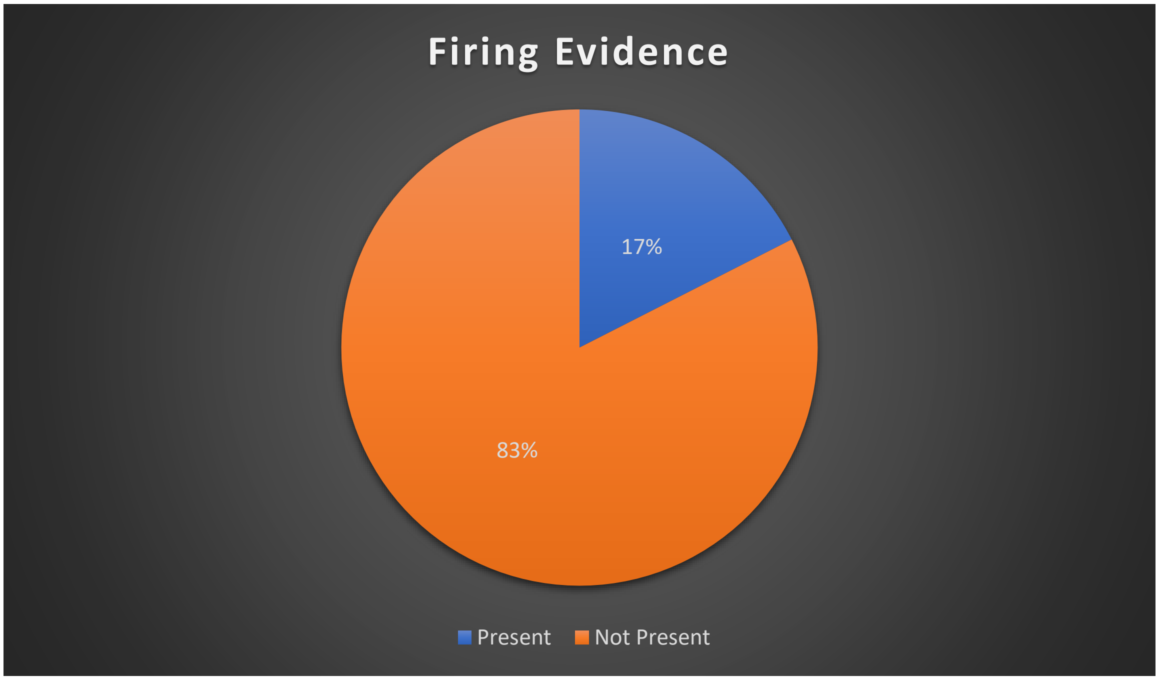

Figure 8.50: Firing evidence.

8.1.5.4 Impact Evidence for Irregular Distortion Level

15 of the 40 bullets show impact evidence and of the 15 impacted bullets, only 3 bullets show evidence of firing. Of the 25 bullets that do not show impact evidence, 16 bullets are heavily chewed, 5 bullets contain casting faults and one bullet was quartered. A summary of the types of impact evidence can be found in figure 8.51.

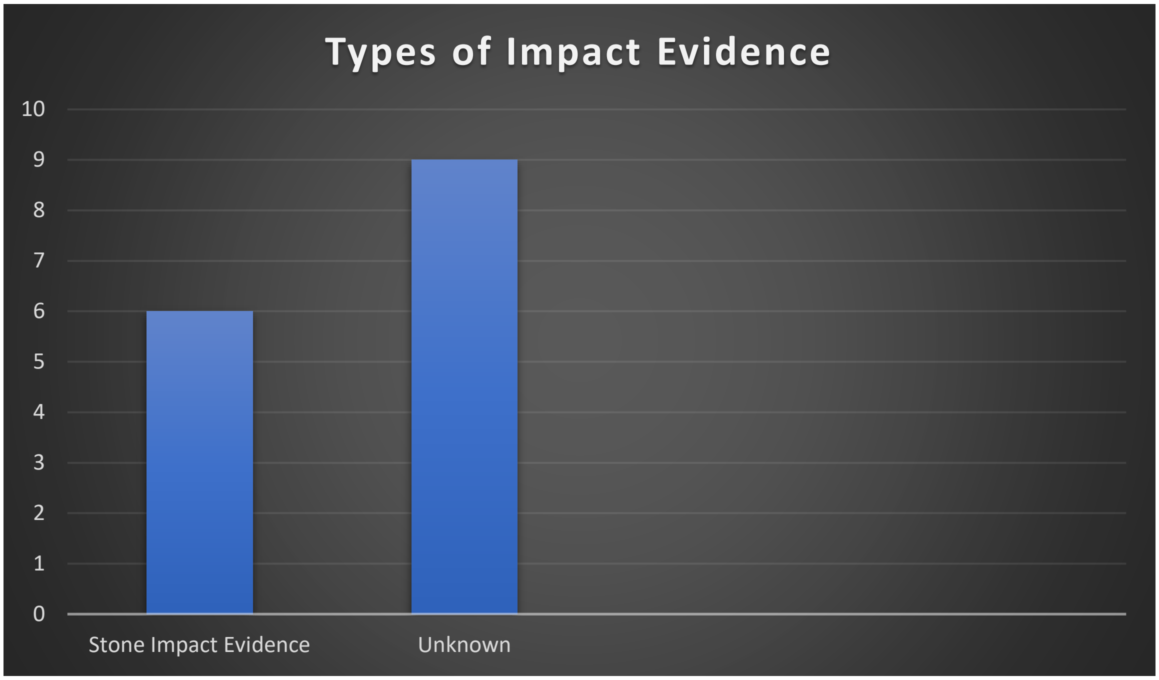

Figure 8.51: Types of impact evidence.

When compared to the experimental reference collection, 6 of the 15 bullets definitively exhibit impact evidence consistent with stone impacts. These bullets display fine tight linear striations, gouges and clefts, 5 of which can be attributed to single stone impacts due to only one impact impression and the remaining one bullet exhibits multiple stone impact events; this is illustrated in figures 8.52 and 8.53.

Figure 8.52: Edgehill 1470, irregular bullet showing stone impact evidence.

Figure 8.53: Edgehill 1378, irregular bullet showing stone impact evidence.

6 bullets display potential wood impact evidence, although the presence of a central point of impact is still missing from the archaeologically recovered bullets. The evidence that remains is

the semi-hemispherical shape, although as noted above shape is not enough to definitively determine what the bullet impacted. These bullets can be seen in figures 8.54 and 8.55 below. Admittedly, 4 of those 6 bullets could be stone impact evidence as the linear striations are difficult to interpret due to corrosion in the impact surface. This is apparent in figures 8.56 and 8.57 below.

Figure 8.54: Edgehill 2021, irregular bullet showing unknown impact evidence.

Figure 8.55: Edgehill 2048, irregular bullet showing unknown impact evidence, under 10X magnification.

Figure 8.56: Edgehill 2976, irregular bullet showing potential wood impact or stone impact evidence, under 10X magnification.

Figure 8.57: Edgehill 2979, irregular bullet showing potential wood impact or stone impact evidence, under 10X magnification.

3 bullets contain an unknown form of impact evidence which can be seen in figures 8.58 and 8.59 below.

Figure 8.58: Edgehill 151, irregular bullet showing unknown evidence, under 10X magnification.

Figure 8.59: Edgehill 648, irregular bullet showing unknown evidence, under 10X magnification.

8.1.6 Edgehill Bullet Assemblage Discussion

803 total bullets were analysed from the Edgehill bullet assemblage using the bullet analysis methodology laid out in Chapter One, section 1.5, for each individual bullet. Each bullet was first assigned a distortion level based on its percentage of distortion from the ideal shape of a spherical bullet. The percentages for the total assemblage can be seen in figure 8.60 below.

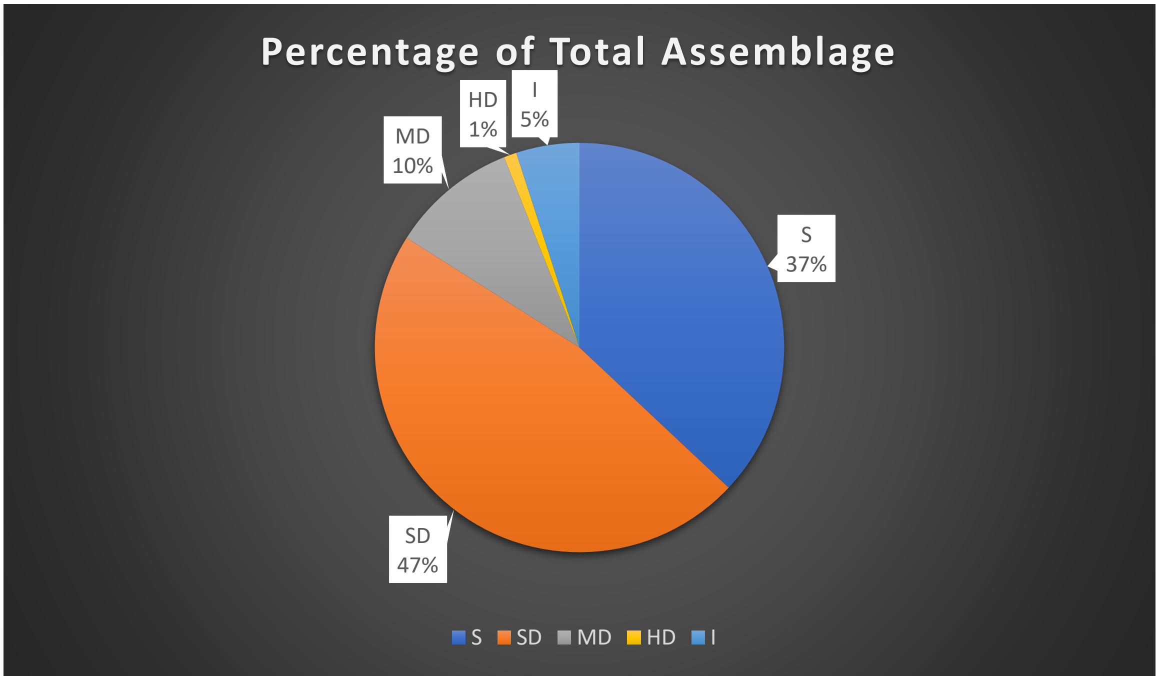

Figure 8.60: Distortion level per percentage of total assemblage.

299 bullets are listed a spherical in shape and 377 bullets are recorded as slightly distorted, comprising 37% and 47% of the total assemblage respectively. The final 16% is allocated to bullets from the distortion levels of moderate, heavy and irregular. While 84% of the bullets from this assemblage are close to their ideal shape, this does not mean that those bullets were unfired or did not impact a target as will be seen in further detail below.

8.1.6.1 Overall Impact Evidence

41% of the bullets from the Edgehill bullet assemblage show impact evidence. Out of the 803 total bullets in this assemblage, 331 bullets show impact evidence, while 472 do not. The experimental reference collection created in the experimental firing trials in Chapter Seven of this thesis was instrumental in advancing our understanding of the impact evidence recorded on the Edgehill bullets. While many forms of impact evidence remain unidentified and therefore prevent a complete understanding of all impact evidence present on the bullets' surfaces, this thesis proves the concept that experimentally fired bullets can enable an advanced understanding of the impact evidence present on archaeologically recovered bullets.

Of the 331 bullets that show impact evidence, the type of impact evidence on 290 bullets were identified. This means that 88% of the impact evidence on the bullets from the Edgehill assemblage matched the impact evidence from the reference collection of known bullet impacts. 254 bullets exhibit fine tight linear striations, gouges and/or clefts that are consistent with stone impact events during the bounce and roll process after the bullets’ trajectory decayed and the bullet impacted the ground. 173 of these bullets show evidence of a single stone impact event, while an additional 81 bullets contain evidence of multiple stone impact events.

Figure 8.61 below shows the distribution of all bullets in the Edgehill assemblage that impacted stone. Most of these bullets are in the core section of the battlefield where the infantry action took place. Drawing back to the reconstructed historic terrain in Chapter Five (section 5.2), this section of the battlefield was either pasture or arable land. As the experimental firing of bullets into pasture field conditions was not completed, no definitive conclusion can be drawn about the state of the field conditions during the battle from the impacted bullets in the reference collection at this time.

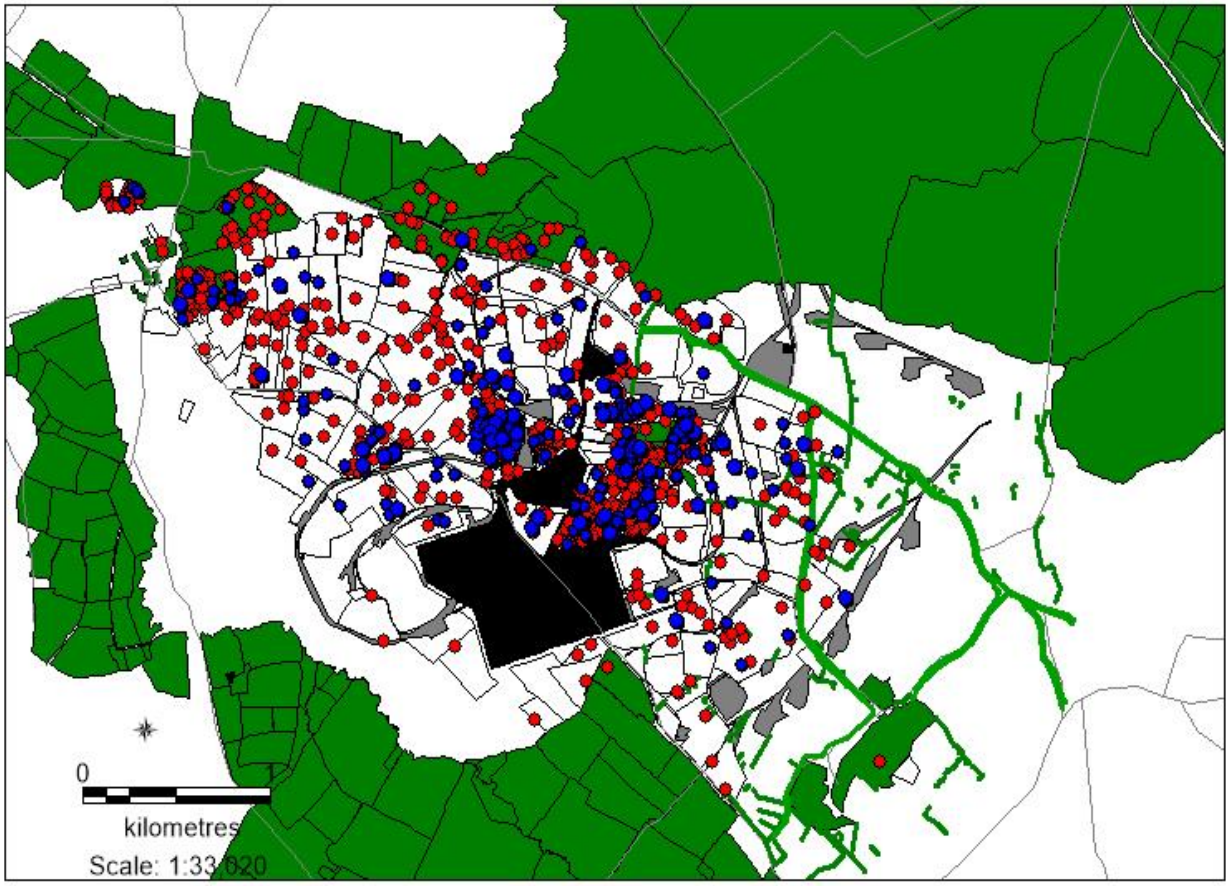

Figure 8.61: All bullets exhibiting stone impact evidence are labelled in blue. The remaining bullets are coloured in red. GIS data courtesy of Glenn Foard.

63 bullets contain an unknown linear rotational impact evidence in the form of superficial indentations of various lengths that could be found across the surface of the bullet. No indentations contained striations of any kind. 33 of these bullets display a single rotational marker, while an additional 30 bullets exhibit multiple rotational markers. Figure 8.62 below shows the locations of the bullets exhibiting the rotational evidence. A further 32 bullets show evidence from both stone impacts and from the unknown linear rotational markers across the surface of the bullet.

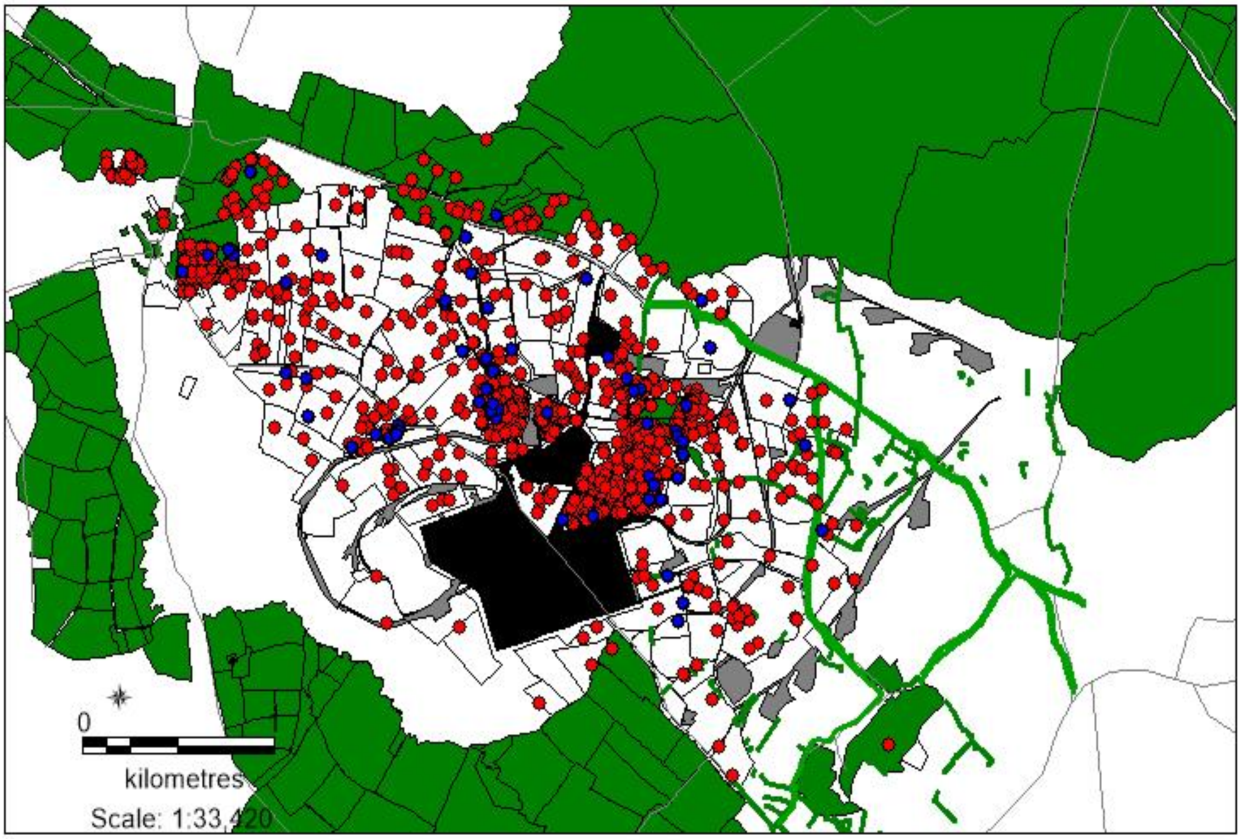

Figure 8.62: All bullets exhibiting rotational or multiple rotational impact evidence are labelled in blue. The remaining bullets are coloured in red. GIS data courtesy of Glenn Foard.

25 bullets exhibit distortion level and shape changes that appear to be consistent with wood impact evidence, although not one bullet displays the central point of impact with adhering wood grain impressions that were common during the experimental firing trials. It is theorised that due to the faint nature of the wood grain impressions that both time and corrosion can lead to obfuscation and overall elimination of this evidence. This could be why the finer detail and wood grain impressions are less pronounced and almost non-existent in the archaeological assemblage. To further complicate the matter, 11 additional bullets exhibit linear striations that were difficult to determine whether they were attributed to stone or wood impacts due to corrosion. Due to the lack of clear evidence in the impact surface, these bullets were initially labelled as potential wood impact evidence; however, upon further review, all these bullets have been listed as unknown impact evidence. Figure 8.63 below shows the distribution of all bullets that were

initially categorised as potential wood impact evidence. Note that the majority of the bullets are not found within the enclosures as would be expected from bullets impacting a wooden target. There are two potential reasons for this explanation; one, that there are additional wooden targets on the battlefield landscape that have not been noted within the primary accounts or two, these bullets are not actual evidence of wood impacts but rather originate from an unknown source that this thesis has not investigated. The second point demonstrates the strong reasoning for the further creation and development of the experimental reference collection, so this problem can be resolved.

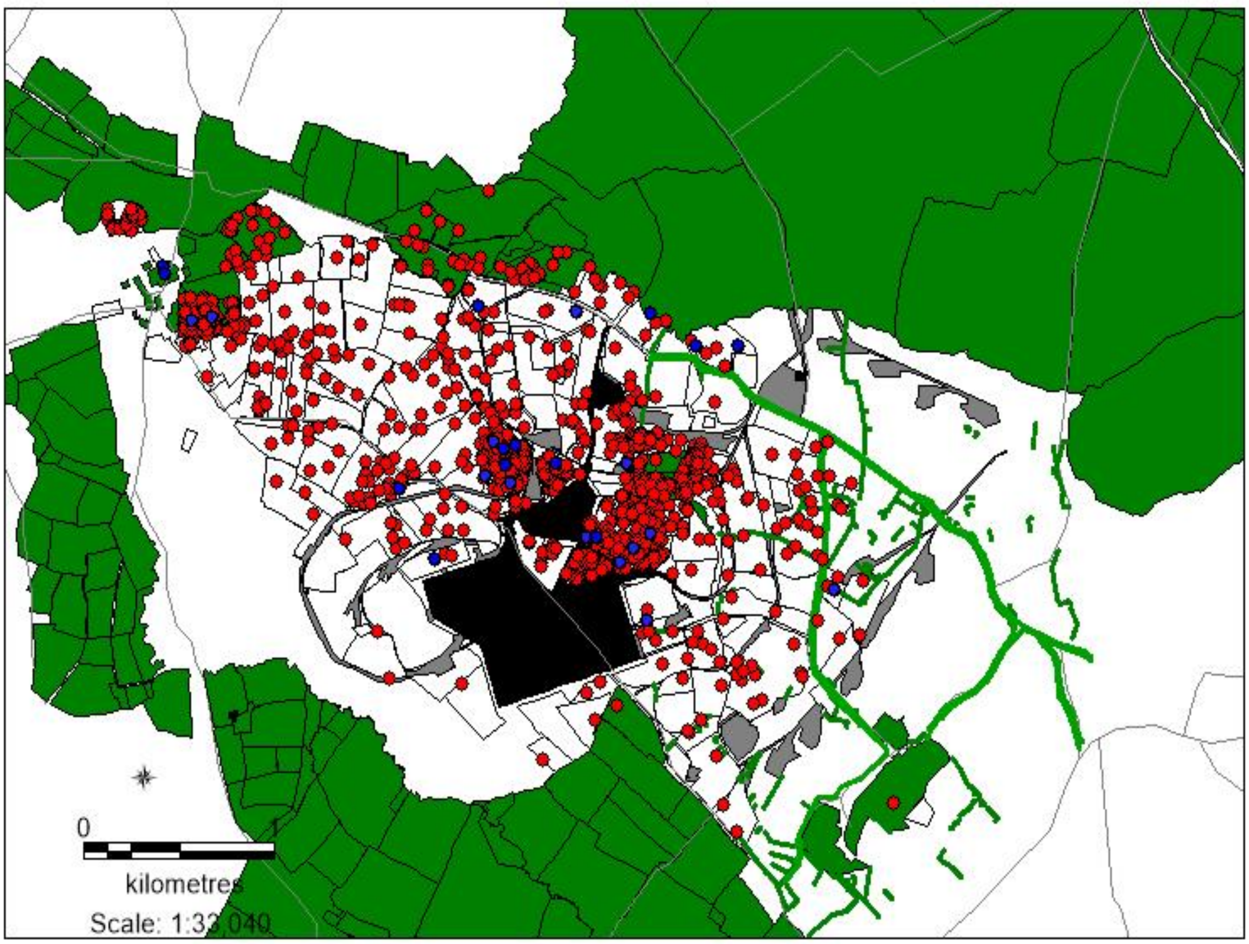

Figure 8.63: All bullets exhibiting potential wood impact evidence are labelled in blue. The remaining bullets are coloured in red. GIS data courtesy of Glenn Foard.

Finally, 23 bullets remain as unknown impact evidence or evidence with an unknown origin. The forms of impact evidence on the surface of those bullets are varied and further experimental firing needs to be carried out to expand the reference collection and assist on revealing further and different impact evidence seen on those bullets. Figure 8.64 illustrates the distribution of the unknown evidence and can be seen on the map below.

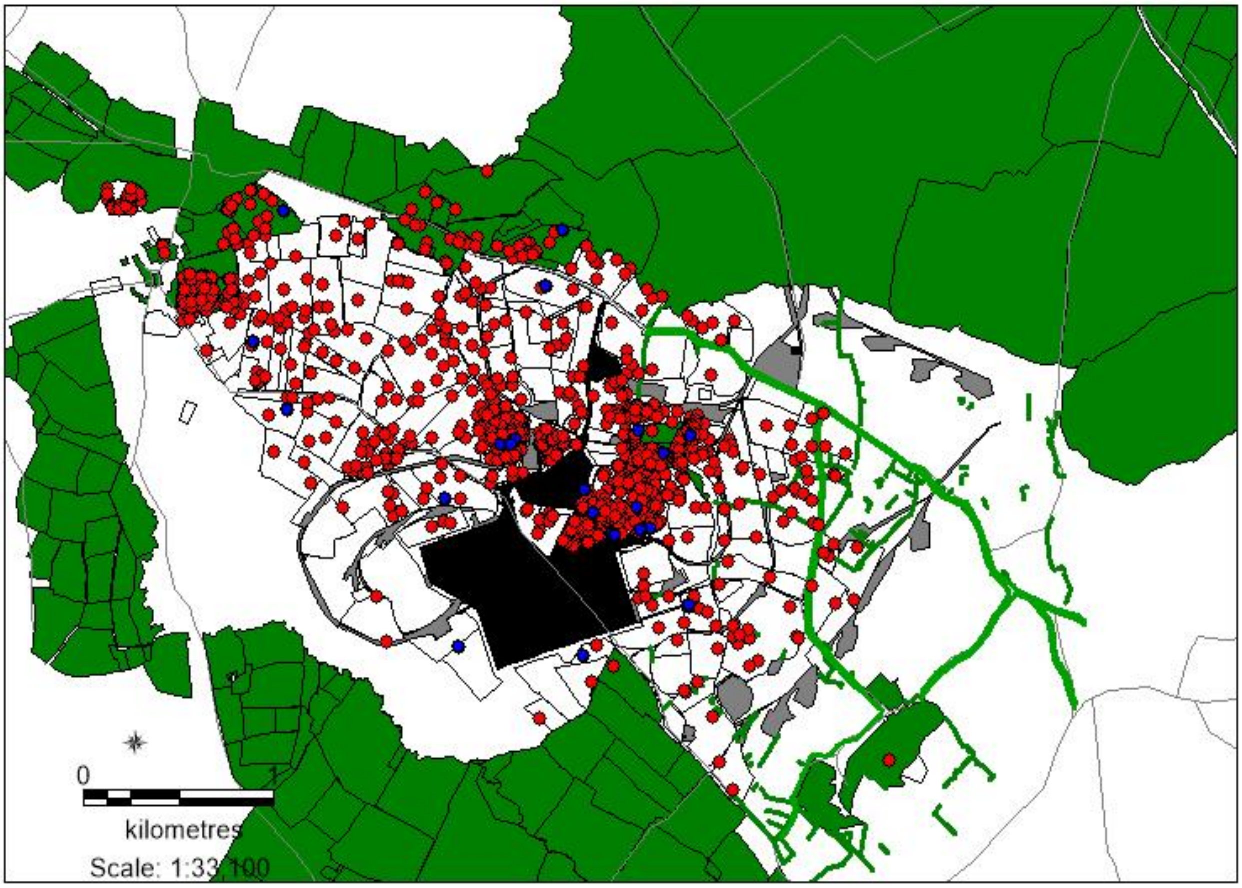

Figure 8.64: All bullets exhibiting unknown evidence are labelled in blue. The remaining bullets are coloured in red. GIS data courtesy of Glenn Foard.

8.2 Oudenaarde Bullet Assemblage

The Oudenaarde bullet assemblage analysed in this thesis came from the archaeological survey of the Oudenaarde battlefield, Belgium, which was supervised by Dr Glenn Foard and conducted mainly by Amanda Wynne and Colin Parkman from September to November 2011 (Foard *et al.* 2012: 47-48). The survey focused on the core area of the battlefield and expanded outwards as the limited time allowed. A total of 761 artefacts were recovered during the archaeological investigation, although not all finds were battle related. 363 of the finds were bullets from the early modern period and were originally analysed by Amanda Wynne (Foard *et al.* 2012: 64, 74). Slugs and case shot from artillery recovered were purposefully excluded from the analysis by this thesis, reducing the number of bullets analysed to a total of 351. The calibre graphs and bullet distribution maps for the original bullet analysis can be found in Foard et al 2012, along with detailed discussions (Foard *et al.* 2012: 75, 79). It is not the intent of this thesis to challenge the interpretations of the analysis completed by Wynne, but to test the ability of both the reference collection and the bullet analysis methodology to enable an advanced interpretation of the bullet impact evidence within the Oudenaarde bullet assemblage.

All 351 bullets from the Oudenaarde assemblage were examined using the methodology created in Chapter One, section 1.5, in conjunction with the reference collection of known bullet impact evidence created in the experimental firing trials in Chapter Seven. Figure 8.65 shows the final stages of the battle, along with the core of the fighting in the enclosed landscape. Most of the bullets recovered from the survey focused on this section of the battlefield. The bullet distribution map (figure 8.66) below shows the locations of all the bullets recovered during the 2011 archaeological survey. Most of the battlefield was fought between and through enclosures as previously discussed in Chapter Five (section 5.3).

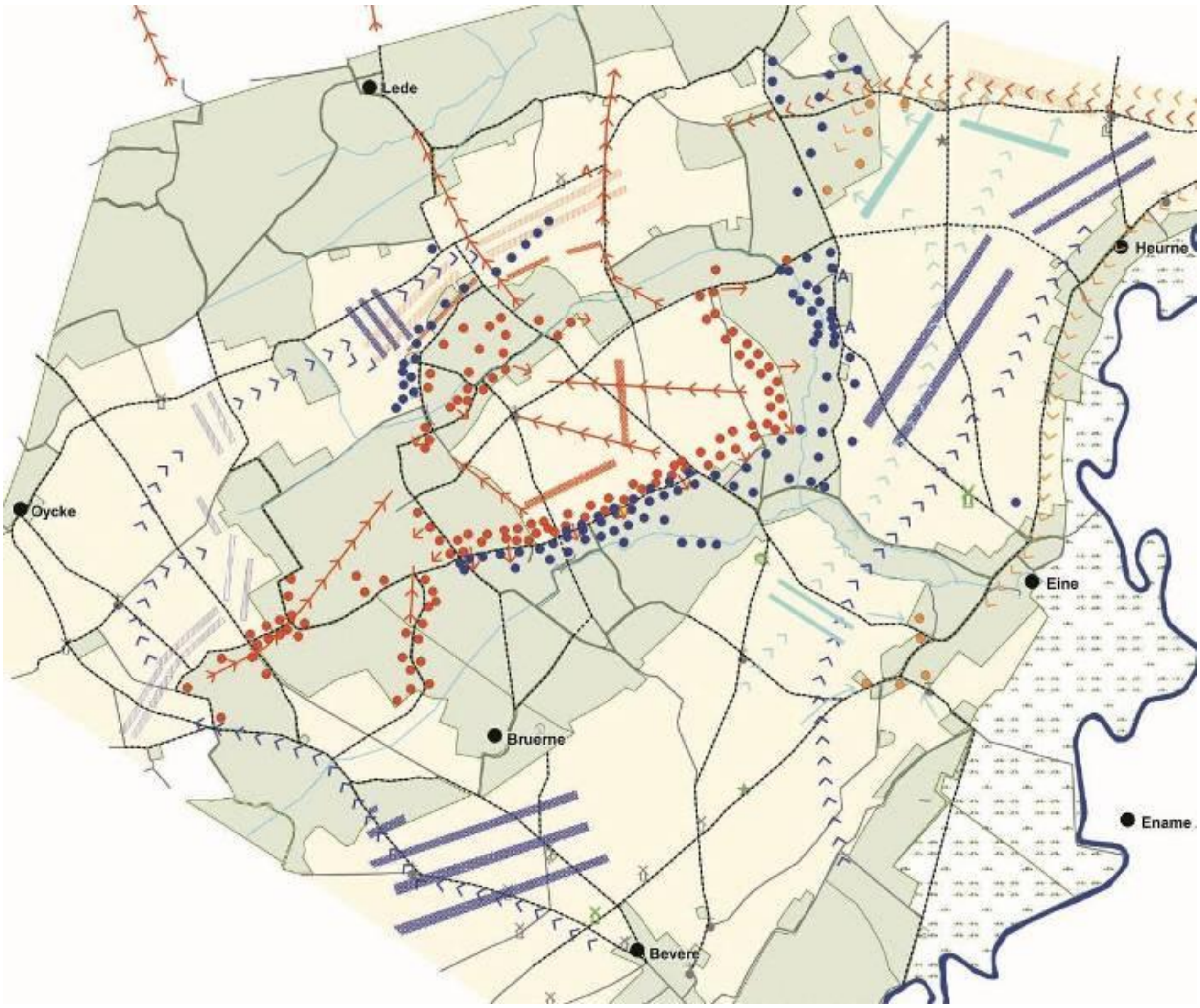

Figure 8.65: The core of the fighting in the enclosed landscape from Tindal map, Foard et al 2012: 46, completed by Tracey Partida, courtesy of Glenn Foard.

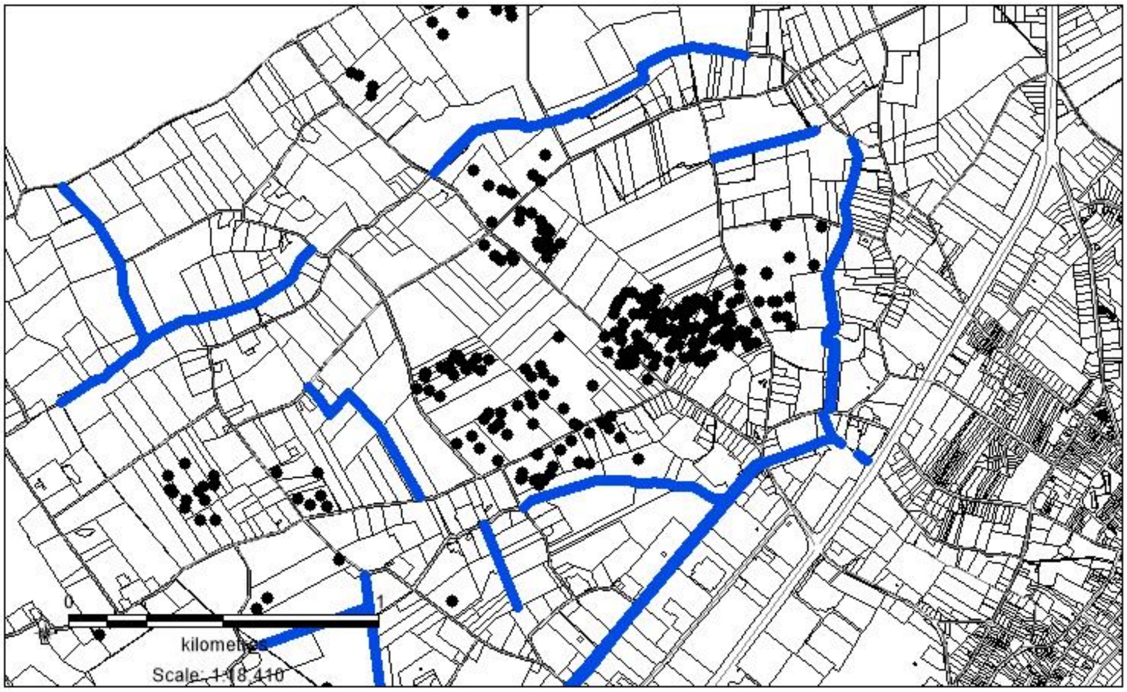

Figure 8.66: All bullets recovered during the Oudenaarde archaeological survey. GIS data courtesy of Glenn Foard.

8.2.1 Spherical Distortion Level

85 of the 351 bullets that make up the Oudenaarde bullet assemblage were determined to be spherical in shape. This comprises 24% of the total assemblage. Figure 8.67 below shows all bullets determined to be of a spherical shape.

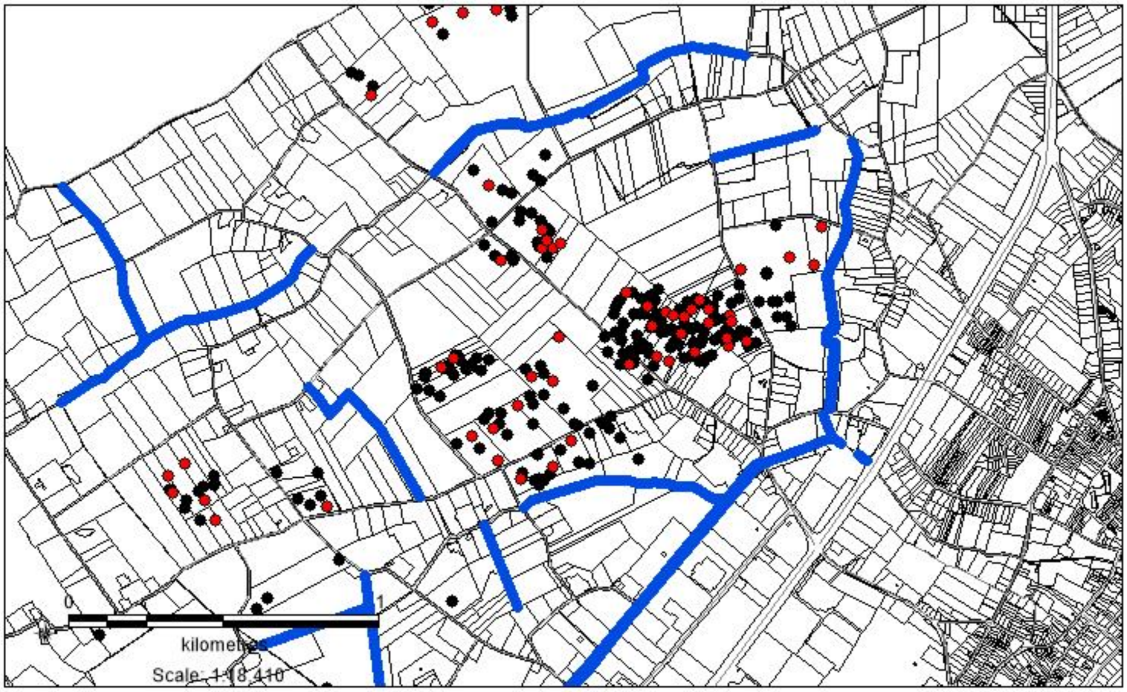

Figure 8.67: All bullets given the spherical distortion level are labelled in red. The remaining bullets are coloured in black. GIS data courtesy of Glenn Foard.

8.2.1.1 Condition Assessment for Spherical Distortion Level

Of the 85 bullets categorised with the spherical distortion level, 6 bullets are recorded as in good condition and 79 were determined to be corroded, of which 19 were too corroded to determine any kind of diagnostic characteristics, a summary of this can be seen in figure 8.68.

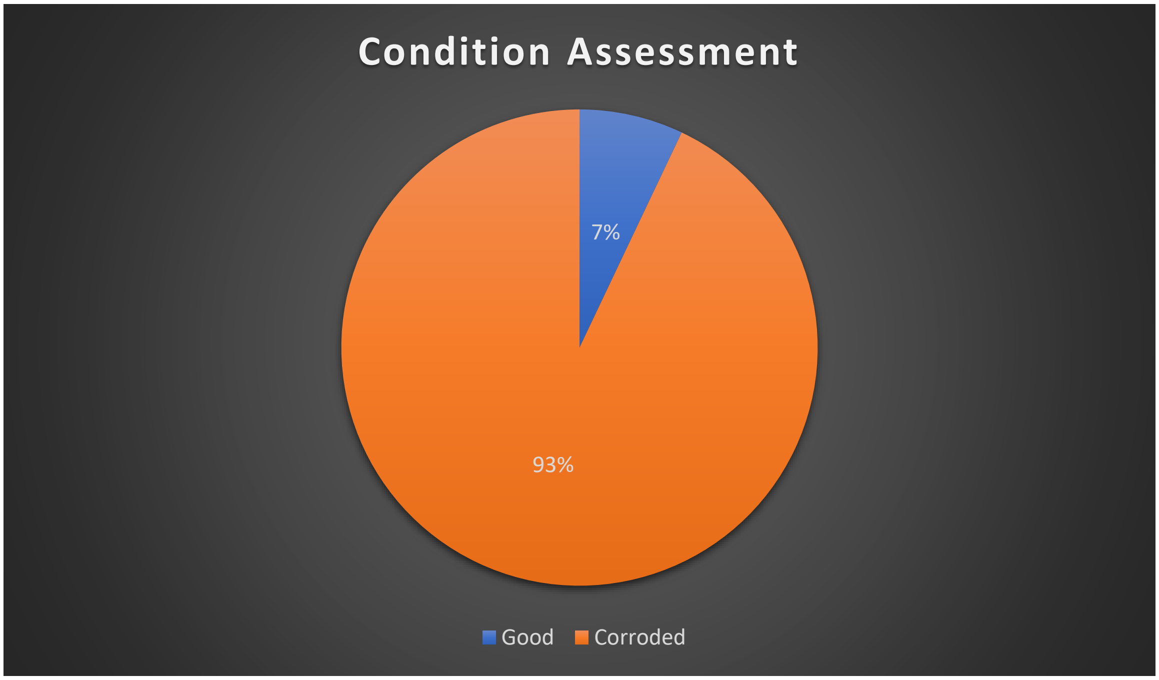

Figure 8.68: Condition assessment.

8.2.1.2 Manufacturing Evidence for Spherical Distortion Level

Only 9 bullets display manufacturing evidence, while 76 bullets do not (figure 8.69). Of these 9 bullets, 6 exhibit sprue cuts, and one bullet has a deep sprue cut. Two casting faults are recorded amongst the 9 bullets. One bullet contains turning lines from the bullet mould and one bullet has an offset mould seam.

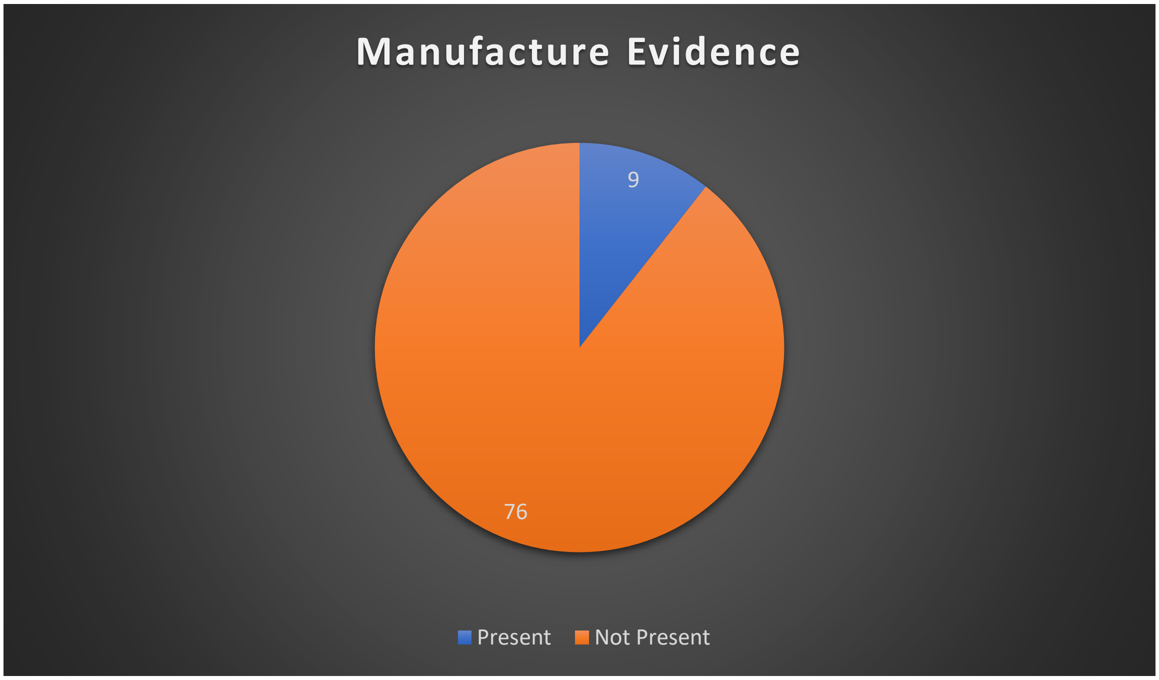

Figure 8.69: Manufacture evidence.

8.2.1.3 Firing Evidence for Spherical Distortion Level

Only 3 of the 85 bullets exhibits firing evidence. All 3 bullets show banding and one shows barrel wall characteristics from the firearm used. Of the three bullets; none show impact damage. This is illustrated in figure 8.70.

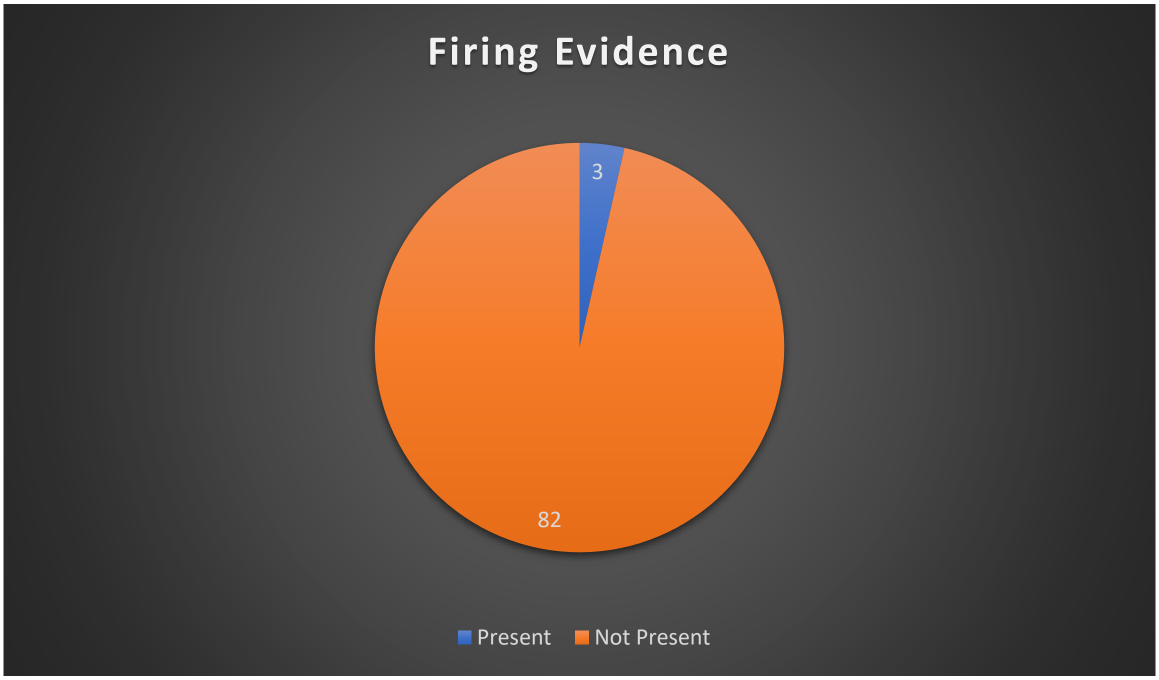

Figure 8.70: Firing evidence.

8.2.1.4 Impact Evidence for Spherical Distortion Level

With the other forms of bullet evidence identified on the spherical distortion level, the investigation of impact evidence is clearer. 47 of the 85 bullets listed as spherical in shape exhibit impact evidence. However, of these 47 bullets, none show any firing evidence. Figure 8.71 below shows the frequency of impact evidence for this distortion level, while figure 8.72 illustrates the different types of impact evidence.

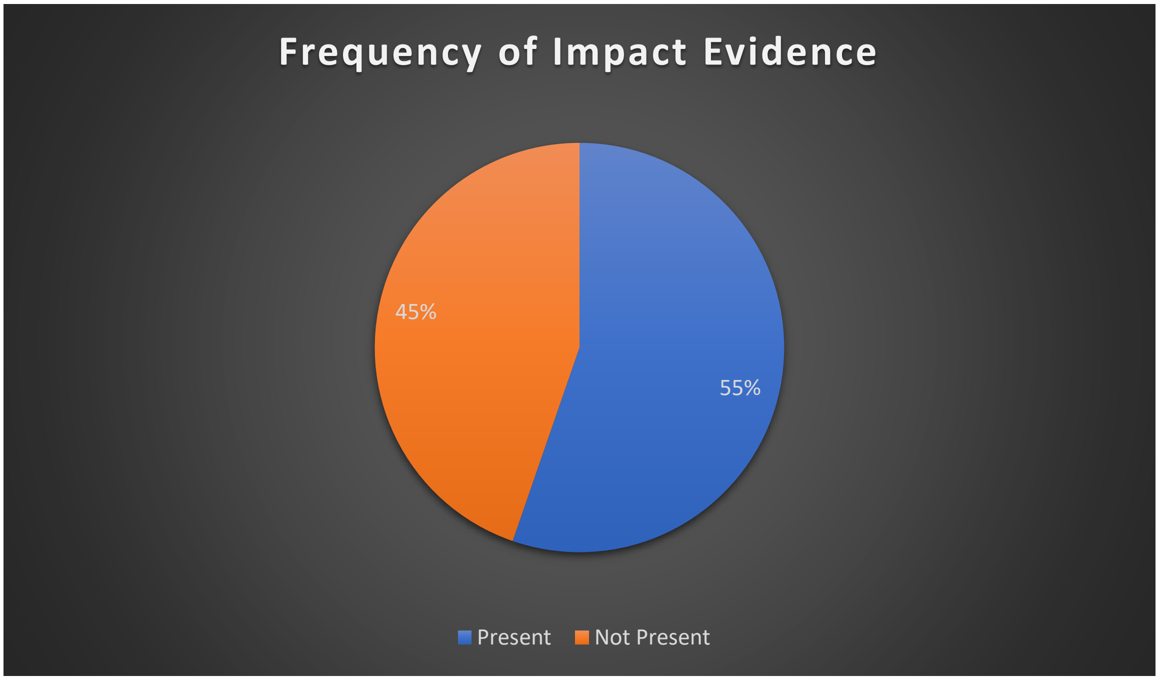

Figure 8.71: Frequency of impact evidence.

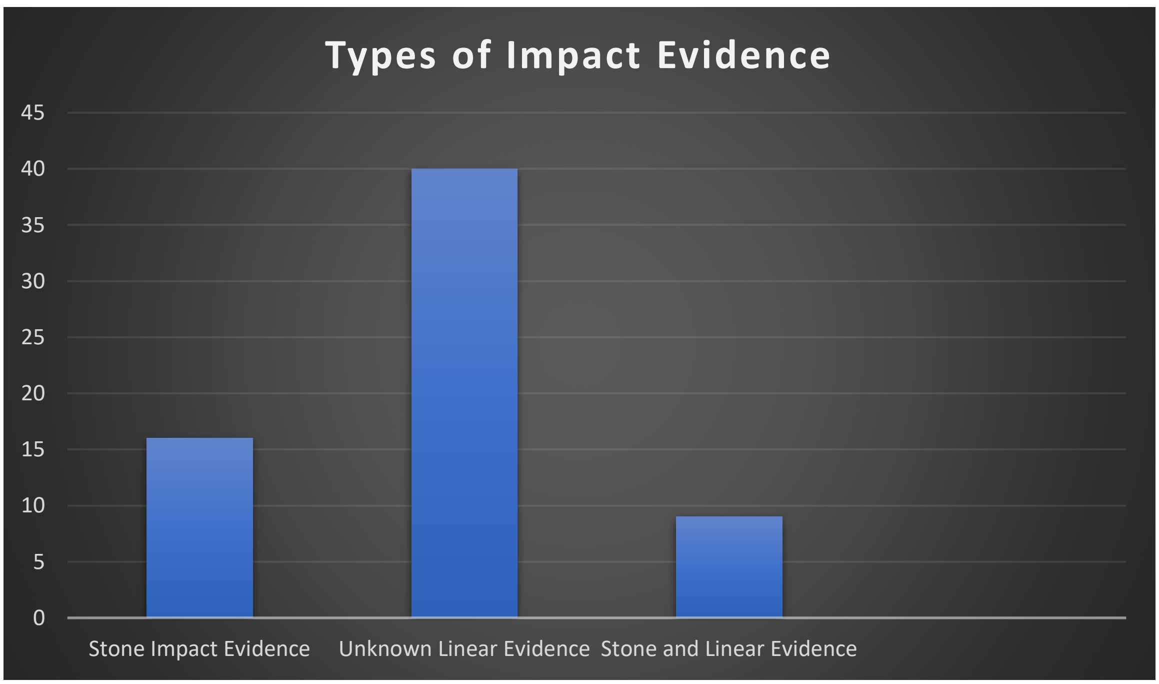

Figure 8.72: Types of impact evidence.

16 bullets exhibit fine tight linear striations, along with clefts and gouges which are consistent with stone impact evidence. 7 bullets display evidence of single stone impact events, while 9 additional bullets exhibit multiple stone impact events.

40 bullets exhibit the same unknown linear rotational impact evidence as seen in the Edgehill assemblage. 2 bullets display evidence of singular rotational evidence (figure 8.73), while 38 bullets show evidence of multiple rotational impressions.

Figure 8.73: Oudenaarde 367, spherical bullet showing linear rotational evidence under 10X magnification.

9 bullets have impact evidence that is consistent with both multiple stone impacts and multiple rotation impacts.

8.2.2 Slight Distortion Level

A total number of 158 out of the 351 bullets were classified as having a slight distortion level.

This comprises 45% of the total assemblage. Figure 8.74 below shows the finds location for all bullets categorised as having a slight distortion level.

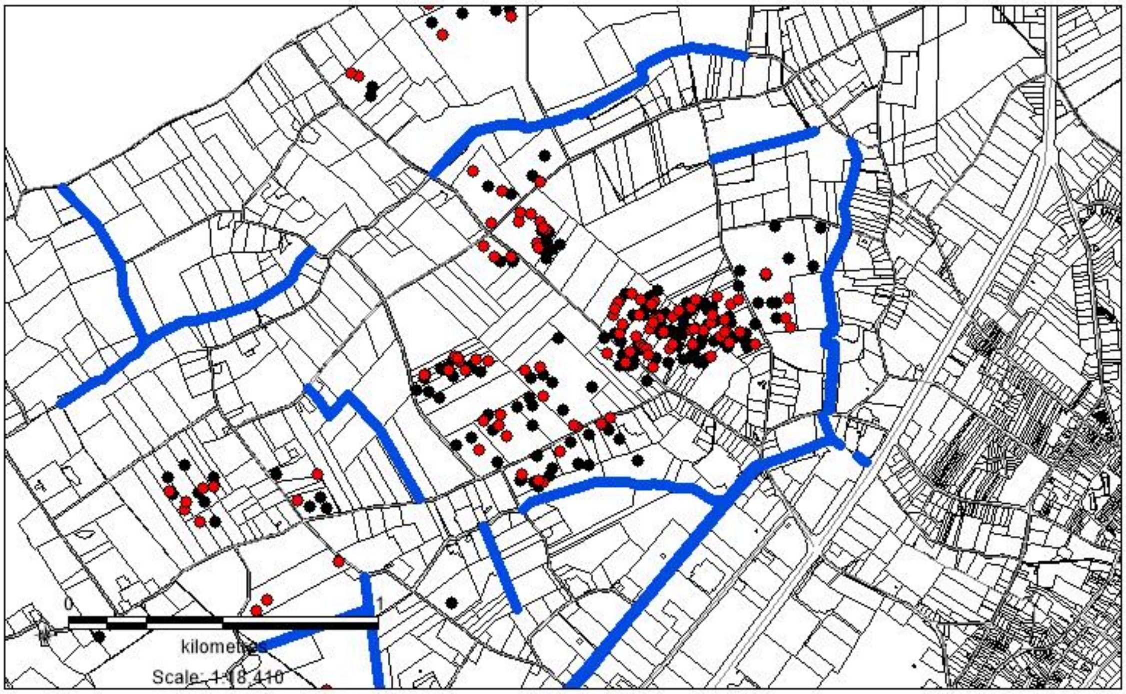

Figure 8.74: All bullets given the slight distortion level are labelled in red. The remaining bullets are coloured in black. GIS data courtesy of Glenn Foard.

8.2.2.1 Condition Assessment for Slight Distortion Level

Only 7 of the 158 bullets are in good condition, while 151 are recorded as corroded (figure 8.75). 18 of the 151 corroded bullets are too corroded for surface examination. 2 bullets are heavily chewed and unable to be examined for any diagnostic traits.

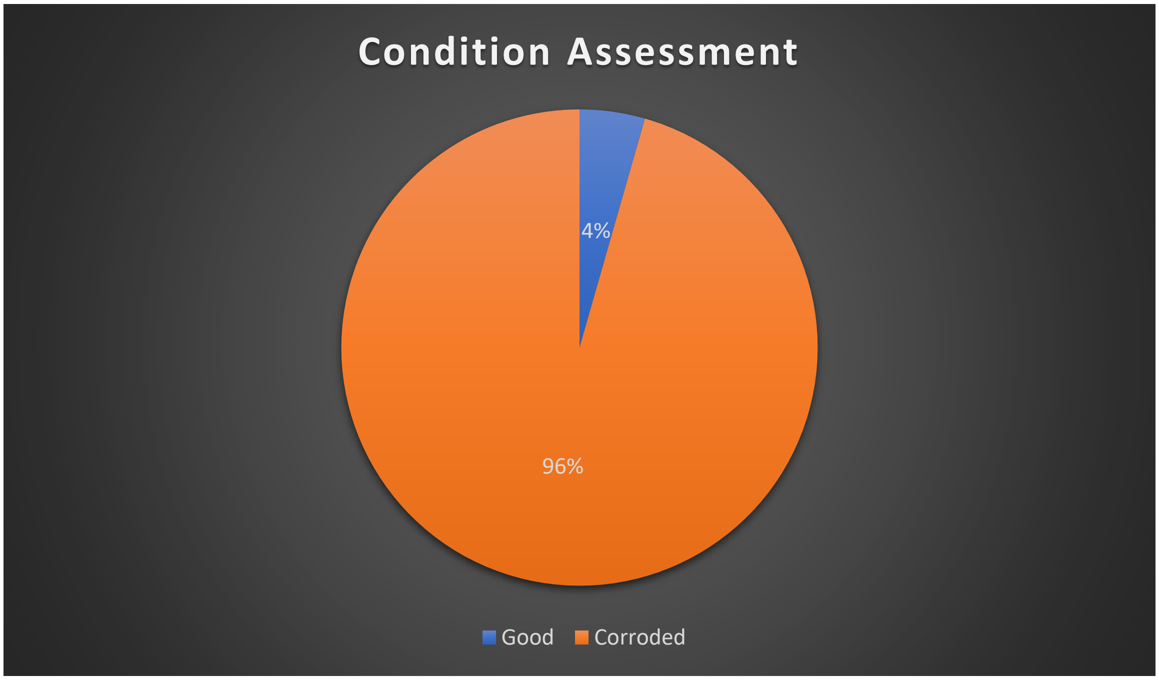

Figure 8.75: Condition assessment.

8.2.2.2 Manufacturing Evidence for Slight Distortion Level

21 bullets show manufacturing evidence, whereas 137 do not (figure 8.76). Of the 21 bullets, 10 bullets display sprue cuts, 5 of which are deep sprue cuts. 8 bullets exhibit casting faults ranging from 5 offset bullets, 2 potlids, and one void in a bullet near the sprue cut.

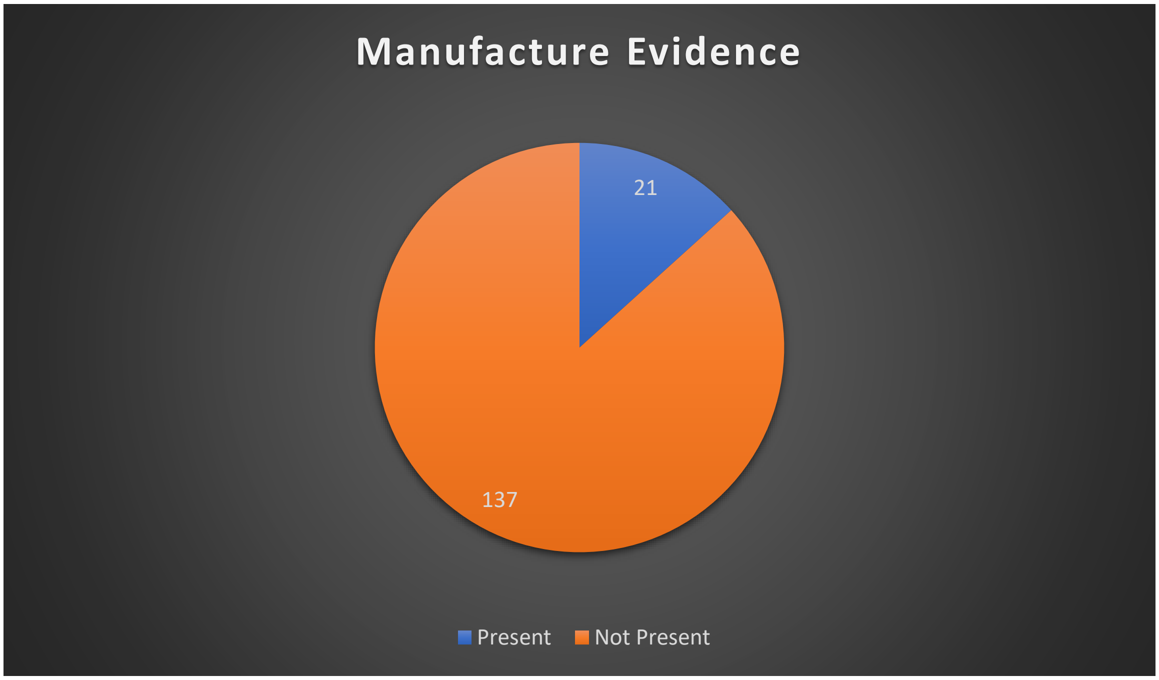

Figure 8.76: Manufacture evidence.

8.2.2.3 Firing Evidence for Slight Distortion Level

29 of the 158 bullets exhibits firing evidence, while 129 bullets did not. 12 of the 29 bullets display firing evidence but show no signs of impact damage, whereas 17 of the 29 do show impact evidence. Of the 29 bullets that exhibit firing evidence, all 29 of those bullets contained banding evidence. A summary of this can be found in figure 8.77.

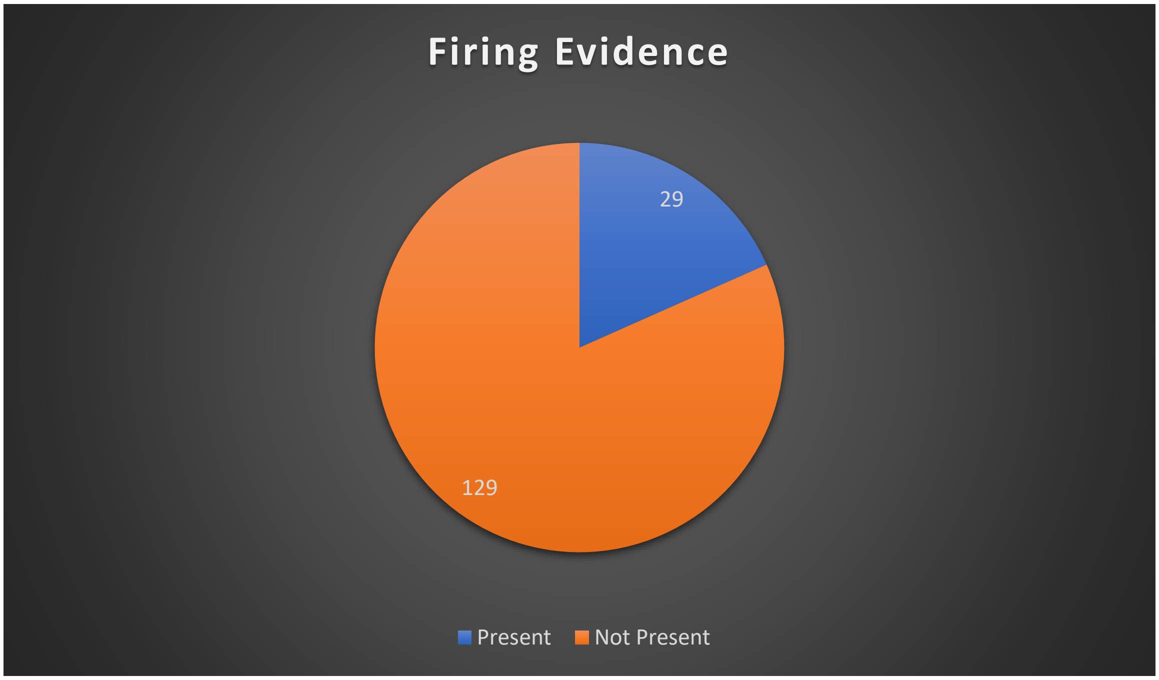

Figure 8.77: Firing evidence.

8.2.2.4 Impact Evidence for Slight Distortion Level

132 of the 158 bullets show impact evidence, of which 17 also show firing evidence. 26 bullets show no impact evidence. The frequency of impact evidence for the slight distortion level can be found in figure 8.78, while the types of impact evidence can be found in figure 8.79.

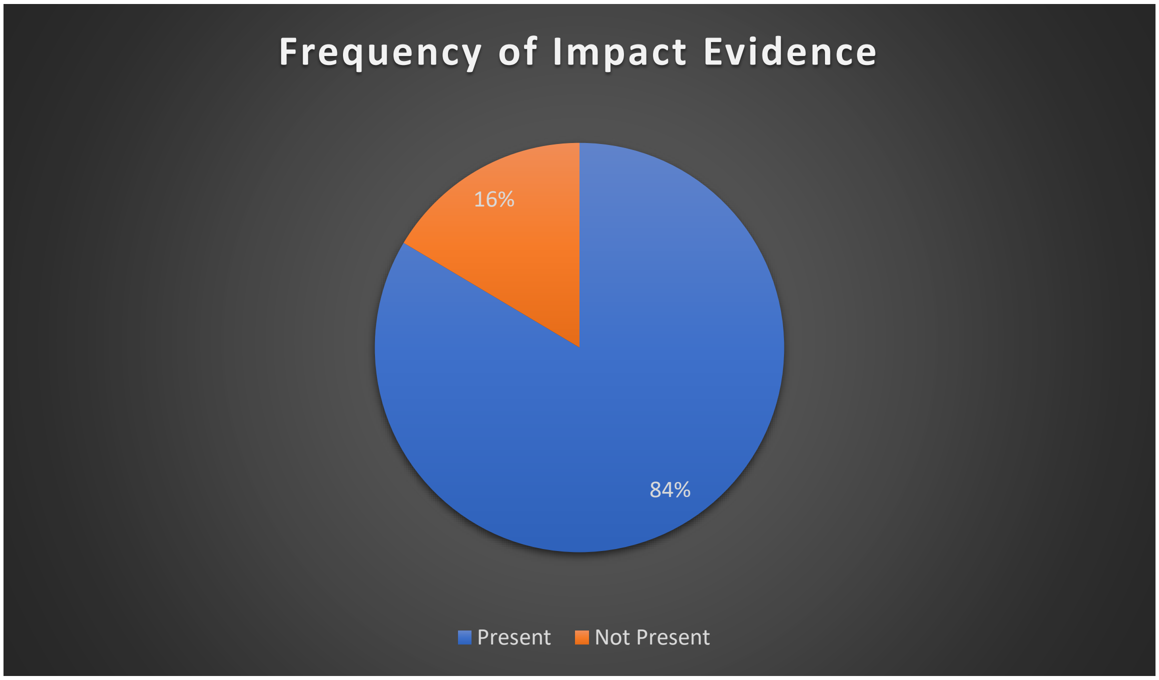

Figure 8.78: Frequency of impact evidence.

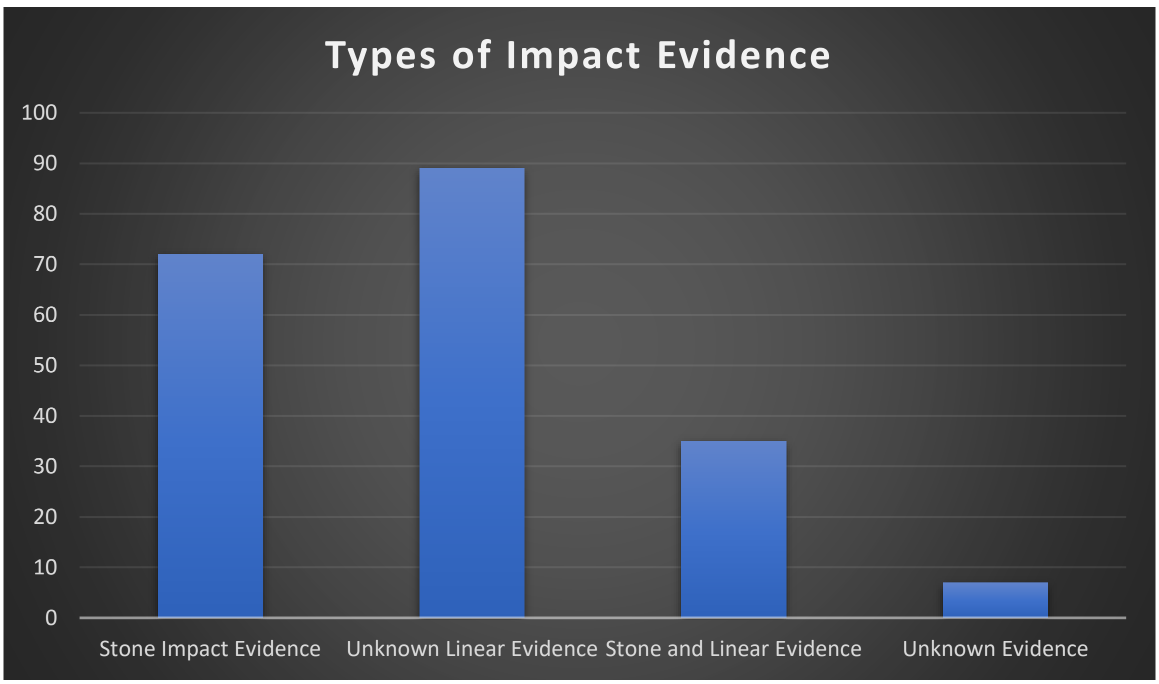

Figure 8.79 Types of impact evidence.

72 total bullets have a variety of fine tight linear striations, gouges and clefts that are consistent with impacting stones within the soil. 24 bullets display impact evidence consistent with single stone impacts, through either direct impact or abrasion from bounce and roll across the ground surface, as can be seen in figure 8.80. An additional 48 bullets show multiple stone impact events from impacting multiple stones during the process of bounce and roll after ground impact, as demonstrated in figure 8.81.

Figure 8.80: Oudenaarde 687, slightly distorted bullet showing single stone impact evidence, under 10X magnification.

Figure 8.81: Oudenaarde 477, slightly distorted bullet showing multiple stone impact events, under 10X magnification.

89 bullets exhibit the unknown linear rotational impact damage as discussed above. 3 bullets have singular rotational evidence, while an additional 86 display multiple rotational markers, as seen in figure 8.82. 35 bullets display both linear rotational and stone impact evidence, which is illustrated in figures 8.83 and 8.84 below.

Figure 8.82: Oudenaarde 179, slightly distorted bullet showing multi-rotational evidence.

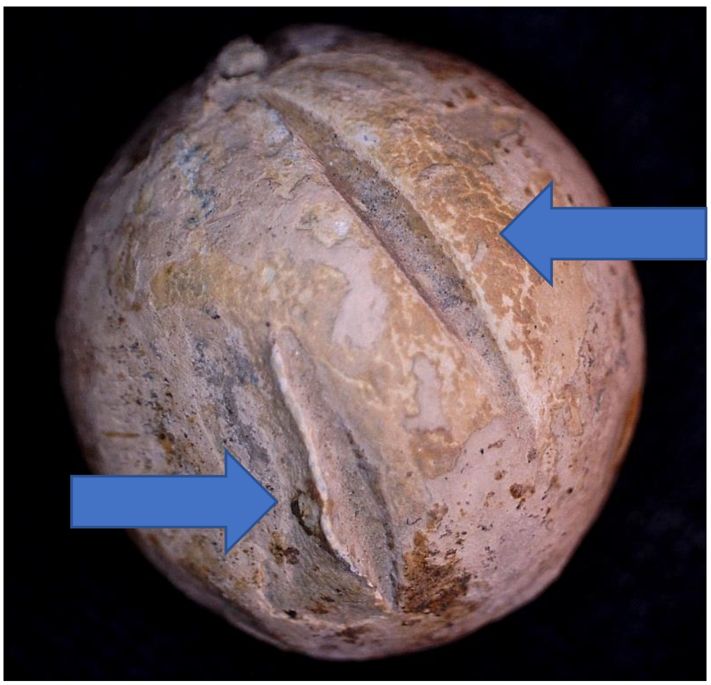

Figure 8.83: Oudenaarde 188, slightly distorted bullet showing rotational (upper hemisphere) and stone impact evidence (lower hemisphere of the bullet), under 10X magnification.

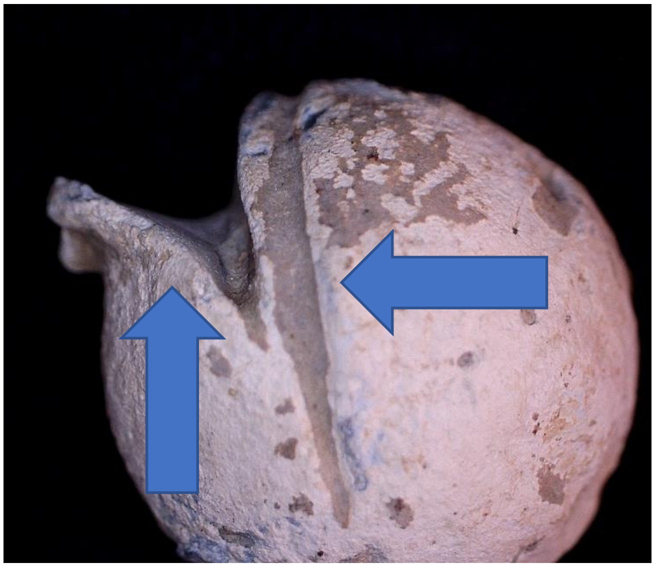

Figure 8.84: Oudenaarde 422, slightly distorted bullet showing rotational (right) and stone impact (left) evidence, under 10X magnification.

7 bullets show a variety of unknown impact evidence which can be seen in figures 8.85 below, of which 3 bullets contain too much corrosion on the impact surface to properly identify the evidence.

Figure 8.85: Oudenaarde 106, slightly distorted bullet showing unknown evidence, under 10X magnification.

8.2.3 Moderate Distortion Level

A total number of 64 out of the 351 bullets were determined to be moderately distorted, which comprises 18% of the total assemblage. Figure 8.86 below shows the finds location of the moderately distorted bullets.

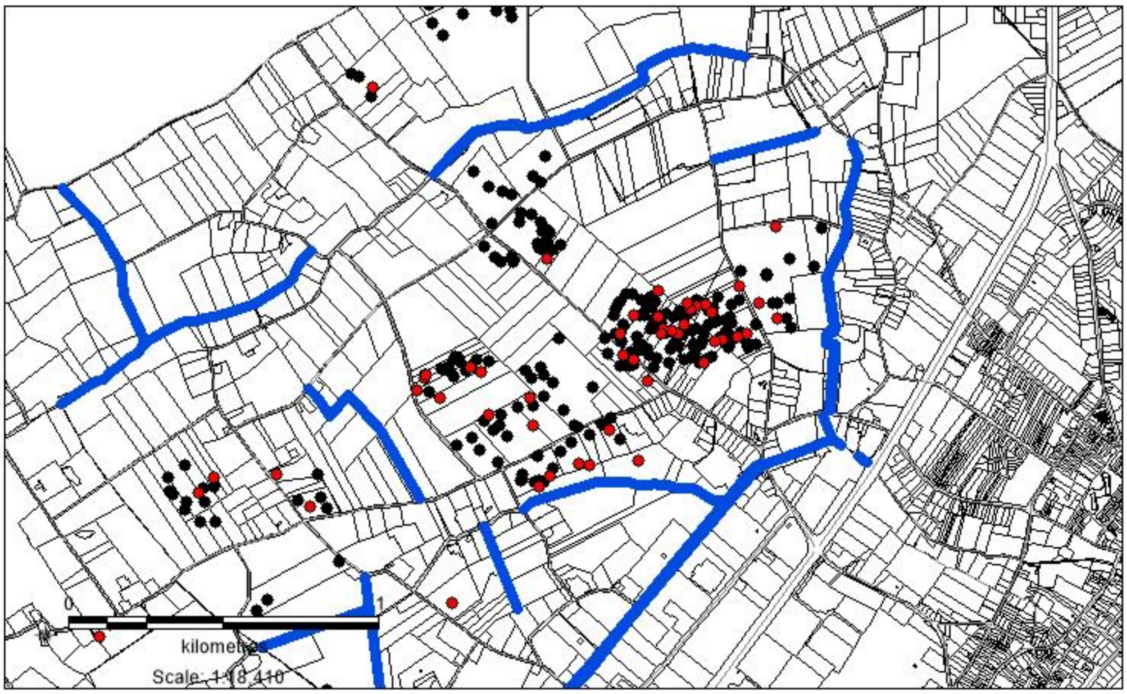

Figure 8.86: All bullets given the moderate distortion level are labelled in red. The remaining bullets are coloured in black. GIS data courtesy of Glenn Foard.

8.2.3.1 Condition Assessment for Moderate Distortion Level

Only one bullet was categorised as being in good condition and 63 bullets were listed as corroded, of which 36 are determined to have too much corrosion to properly identify any diagnostic surface evidence; this is demonstrated in figure 8.87.

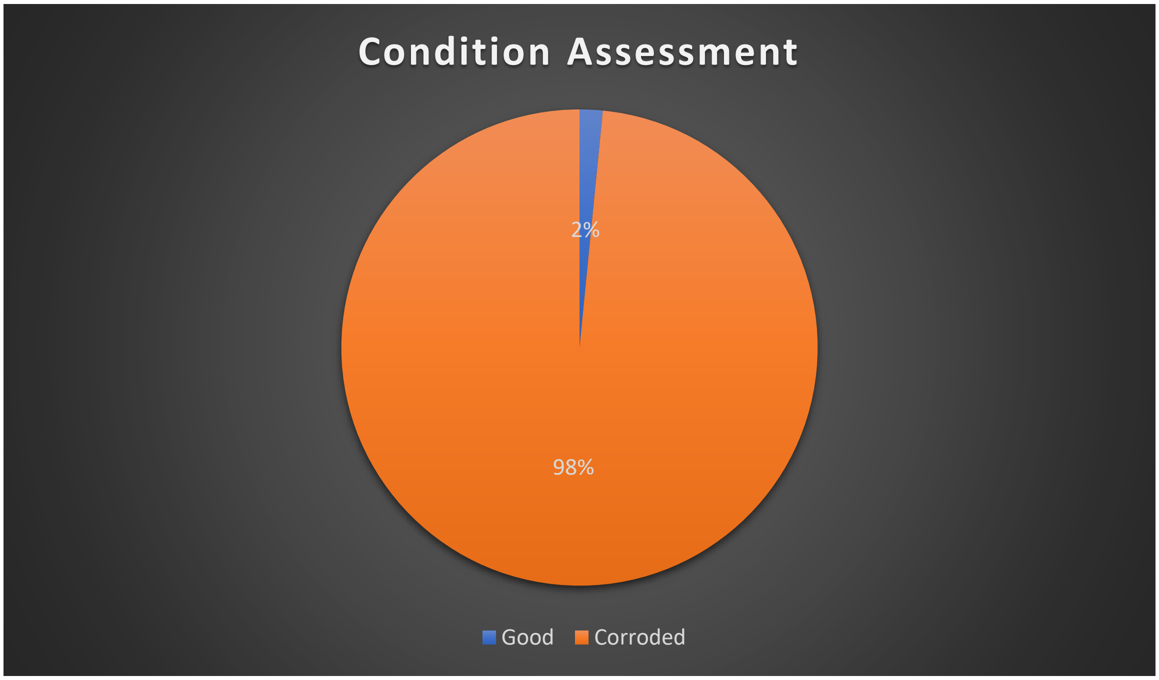

Figure 8.87: Condition assessment.

8.2.3.2 Manufacturing Evidence for Moderate Distortion Level

3 of the 64 bullets contain manufacturing evidence and 61 bullets do not. Of the 3 bullets that exhibit manufacturing evidence, 2 bullets have a mould seam, one has flashing around the mould seam, and one bullet exhibits a sprue cut; this is illustrated in figure 8.88.

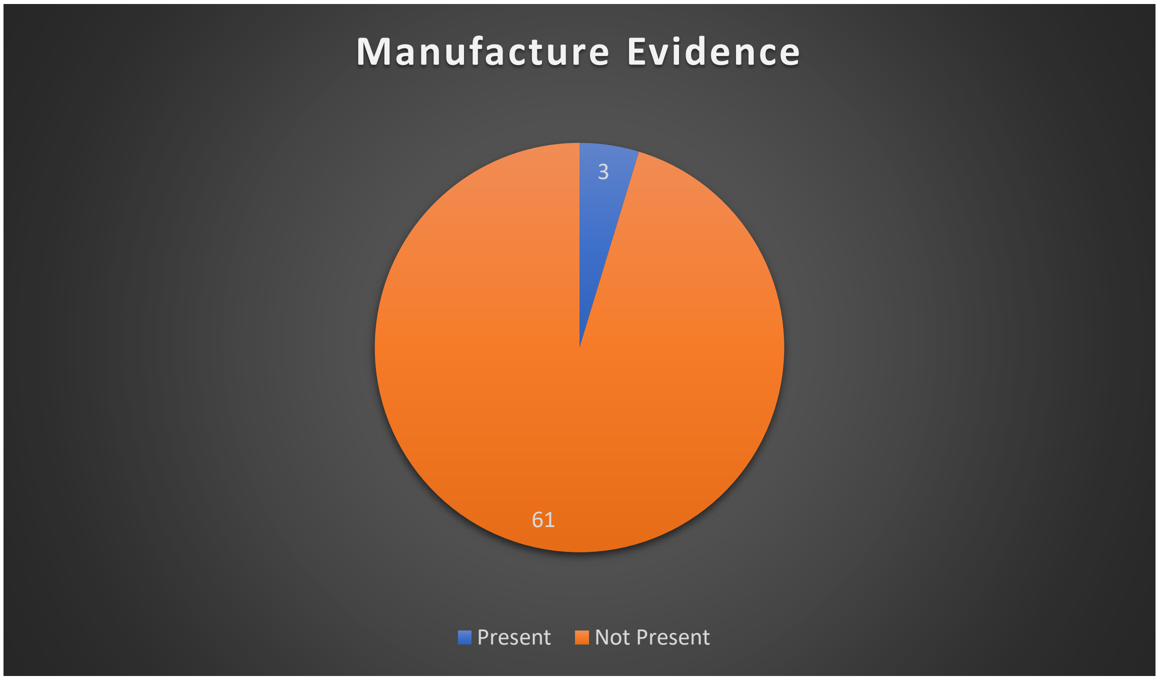

Figure 8.88: Manufacture evidence.

8.2.3.3 Firing Evidence for Moderate Distortion Level

Of the 64 bullets categorised as moderately distorted, 7 bullets show firing evidence, all of which show evidence of banding. The 7 bullets that show firing evidence also exhibit impact evidence, as seen in figure 8.89.

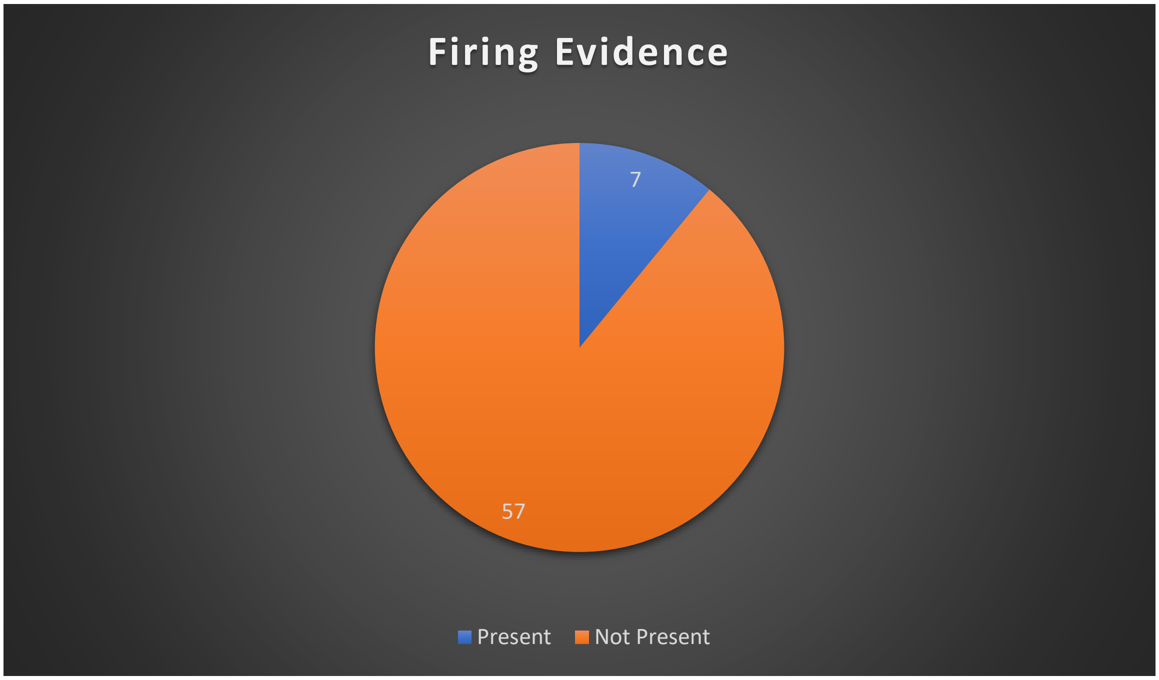

Figure 8.89: Firing evidence.

8.2.3.4 Impact Evidence for Moderate Distortion Level

59 of the 64 bullets categorised as moderately distorted exhibit impact damage and 5 do not. As previously noted, only 7 of the impacted bullets also show firing evidence, this information is summarised in figure 8.90. Figure 8.91 illustrates the different types of impact evidence recorded in the moderate distortion level.

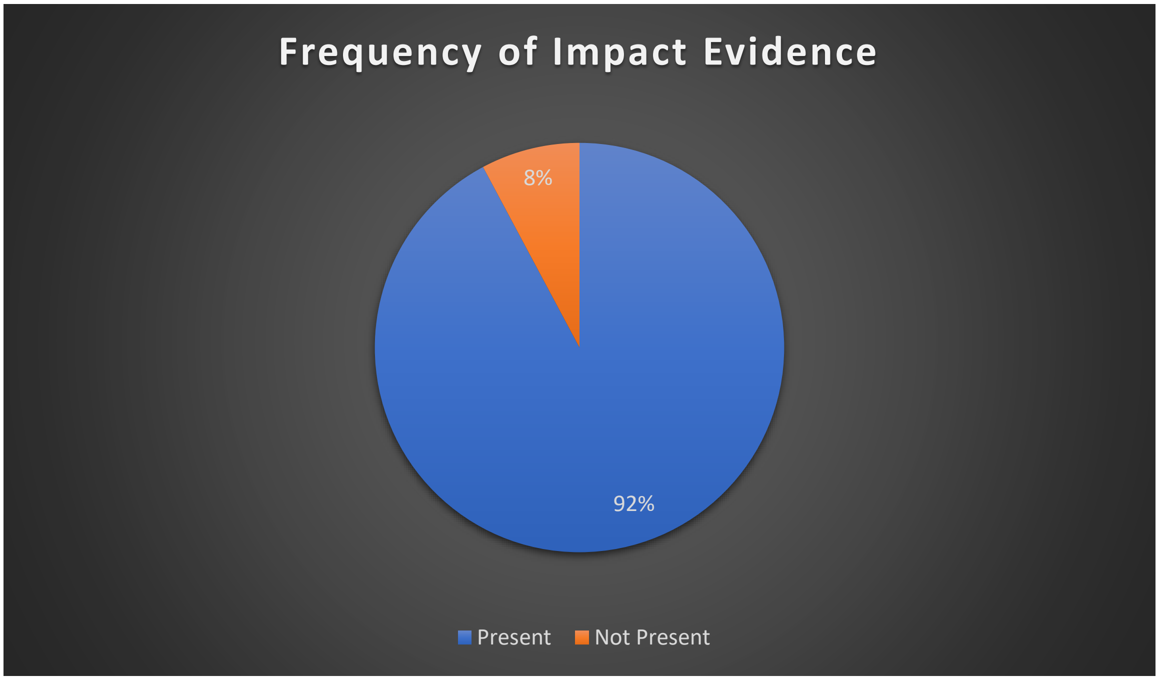

Figure 8.90: Frequency of impact evidence.

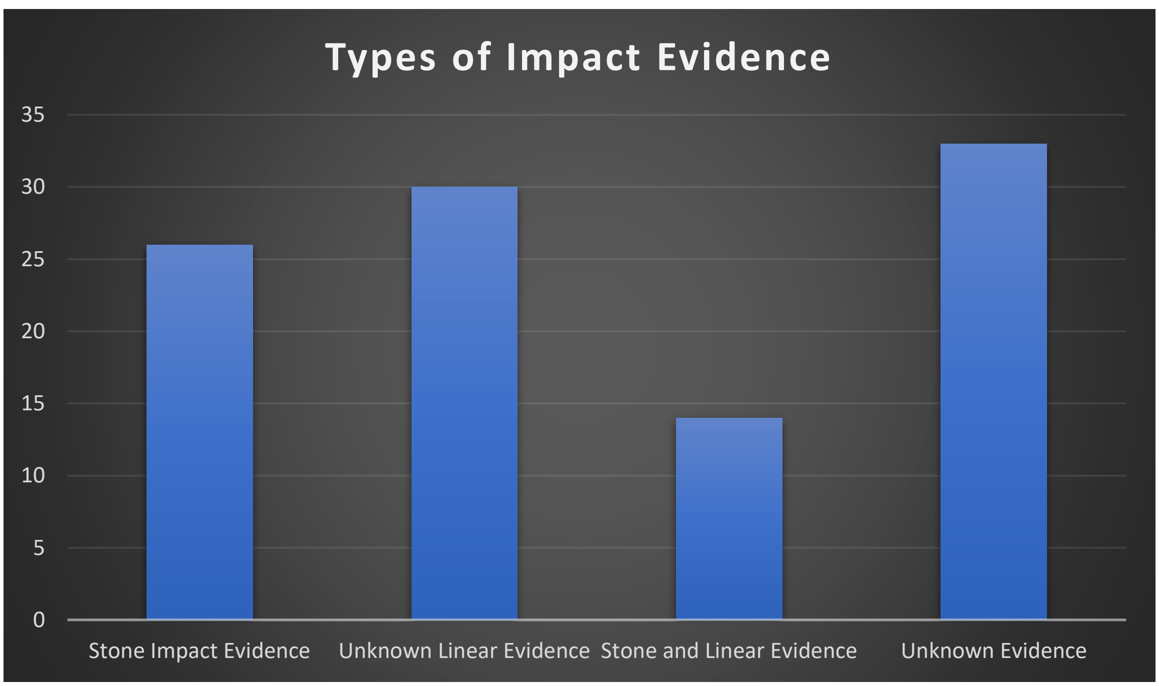

Figure 8.91: Types of impact evidence.

26 bullets display fine tight linear striations within the gouges and or clefts caused by stone impact events. 10 bullets exhibit single stone impact events and 16 bullets show multiple stone

impact events. An additional 14 bullets display evidence of both the unknown linear rotational impressions and stone impacts. Figure 8.92 below, demonstrates single stone impact evidence.

Figure 8.92: Oudenaarde 207, moderately distorted bullet showing single stone impact evidence, under 10X magnification.

30 bullets exhibit the unknown linear rotational impact evince (figure 8.93). One bullet shows singular rotational evidence, whereas 29 bullets show multiple linear rotational markers.

Figure 8.93: Oudenaarde 190, moderately distorted bullet showing rotational evidence, under 10X magnification.

29 Bullets were semi-hemispherical in shape; however, there are no noticeable linear striations on the surface of the bullets due to heavy corrosion. It is tempting to categorise these bullets as potential wood impacts due to the semi-hemispherical nature of the impact itself, but no definitive conclusion can be drawn due to the obfuscation of the impact surface from corrosion. An additional 4 bullets exhibit various forms of unknown impact evidence.

8.2.4 Heavy Distortion Level

36 out of the 351 bullets were categorised as heavily distorted, which comprises 10% of the total assemblage. All bullets categorised as heavily distorted can be seen in figure 8.94 below.

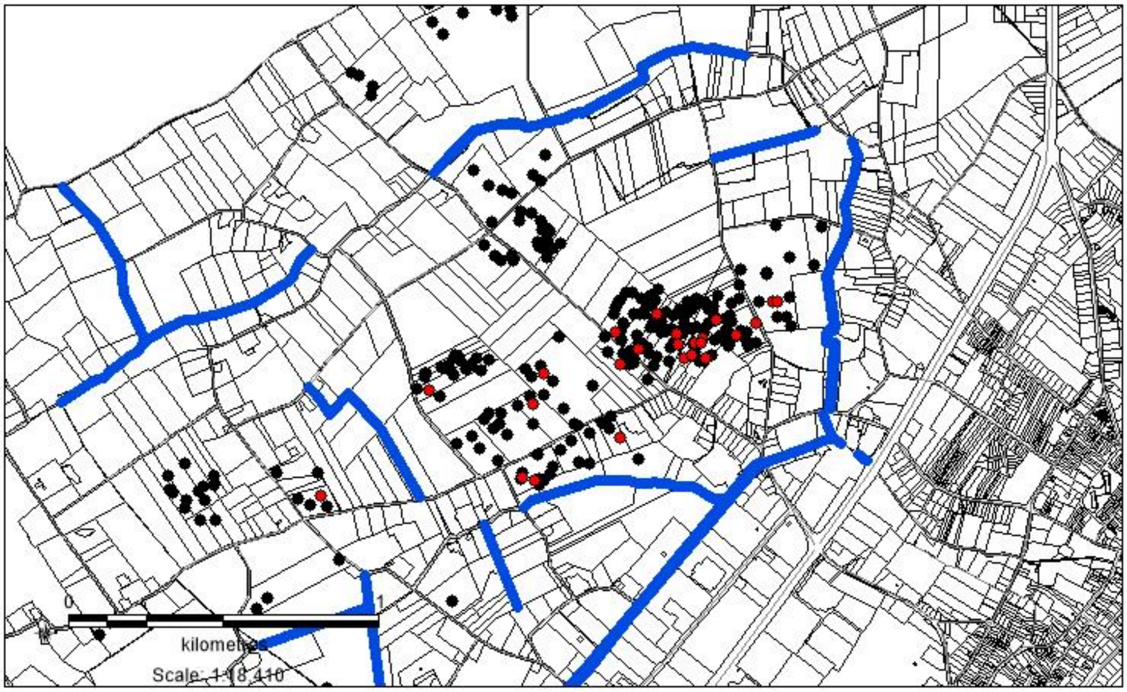

Figure 8.94: All bullets given the heavy distortion level are labelled in red. The remaining bullets are coloured in black. GIS data courtesy of Glenn Foard.

8.2.4.1 Condition Assessment for Heavy Distortion Level

Of the 36 bullets categorised as heavily distorted all of them are recorded as having a corroded surface. 22 of these bullets are too corroded to determine any form of surface characteristics; this can be seen in figure 8.95.

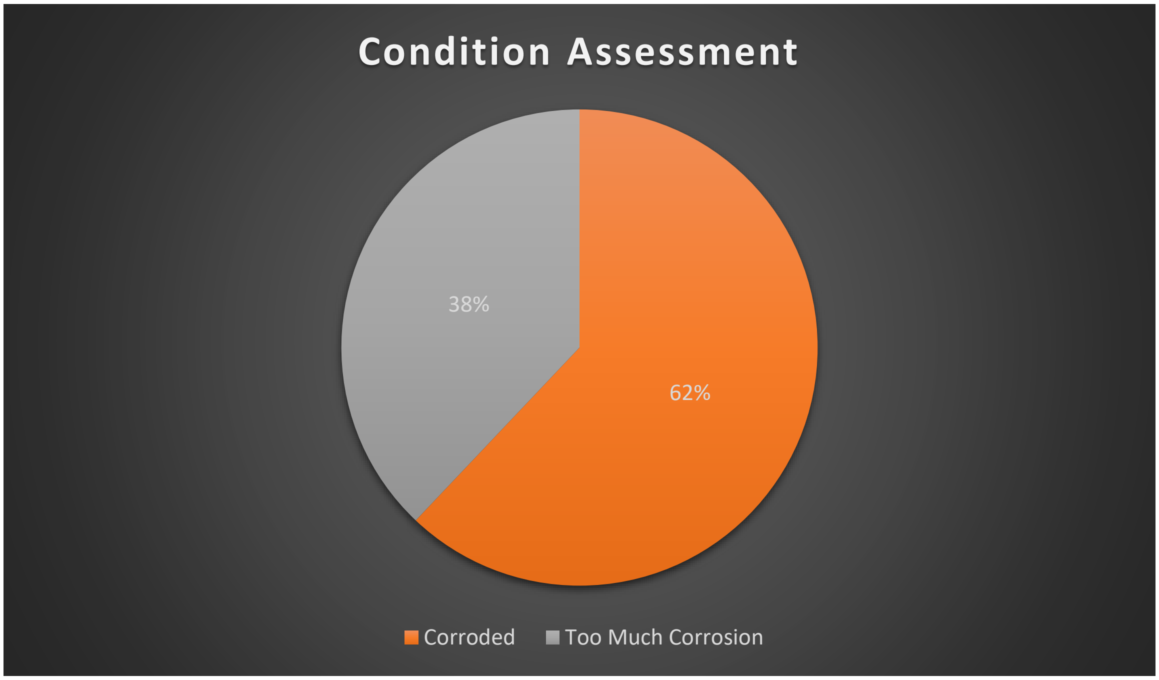

Figure 8.95: Condition assessment.

8.2.4.2 Manufacturing Evidence for Heavy Distortion Level

Only one bullet shows manufacturing evidence which is a mould seam and a sprue cut. The remaining 35 bullets have no signs of manufacturing evidence.

8.2.4.3 Firing Evidence for Heavy Distortion Level

Only one bullet shows firing evidence, which is in the form of banding. This bullet also displays impact evidence. The remaining 35 bullets have no signs of firing evidence, but 33 show evidence of impact and 2 bullets are heavily chewed. This information is summarised in figure 8.96.

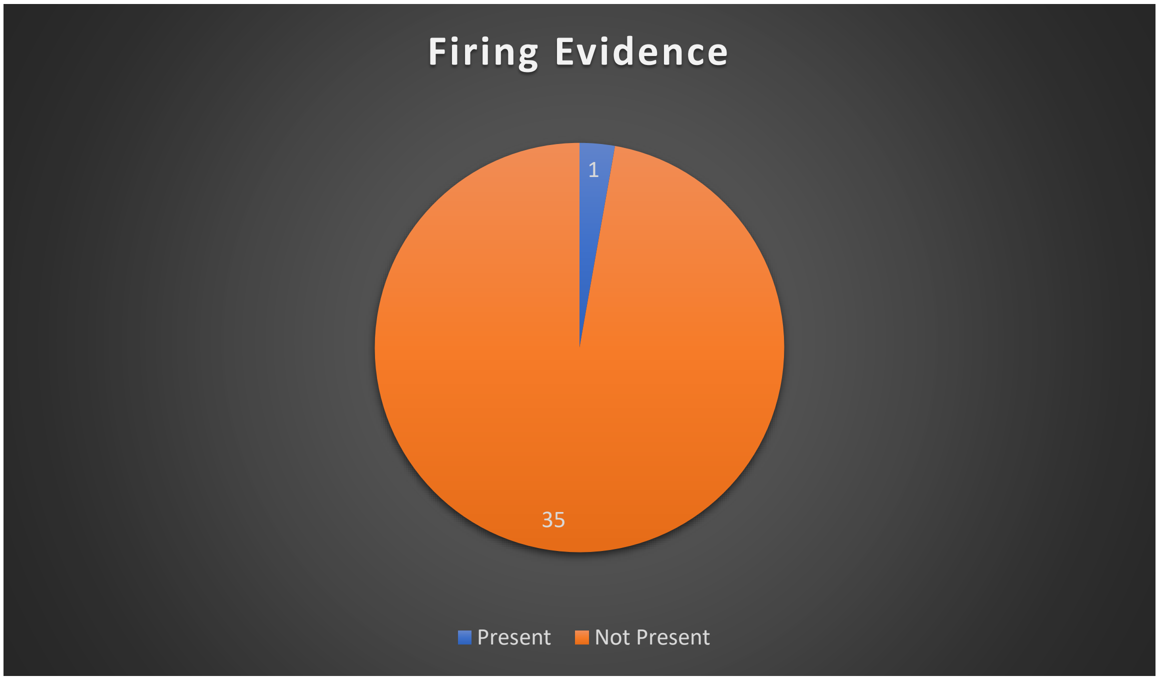

Figure 8.96: Firing evidence.

8.2.4.4 Impact Evidence for Heavy Distortion Level

32 of the 36 bullets exhibit impact evidence. Of the 4 bullets that have no impact evidence, 2 are heavily chewed, and one bullet is an alternate bullet type known as a quartered bullet. One bullet contains too much corrosion within the impact surface to properly identify any evidence. Figure 8.97 below shows the frequency of impact evidence for the heavy distortion level, while figure 8.98 illustrates the different types of impact evidence.

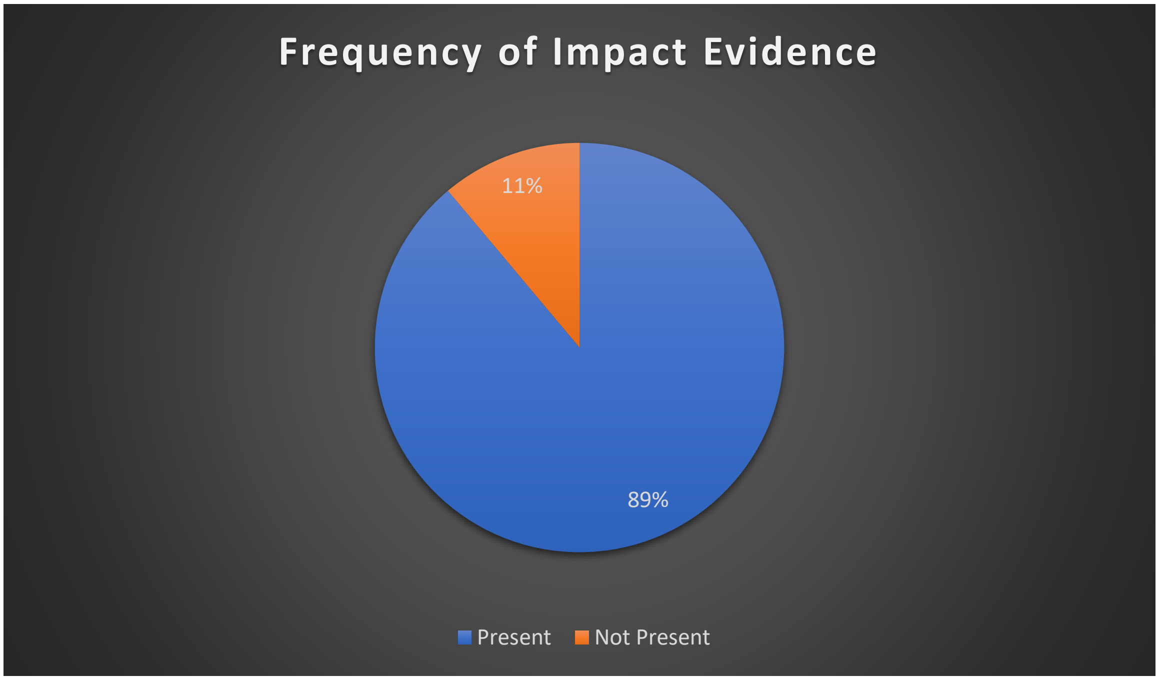

Figure 8.97: Frequency of impact evidence.

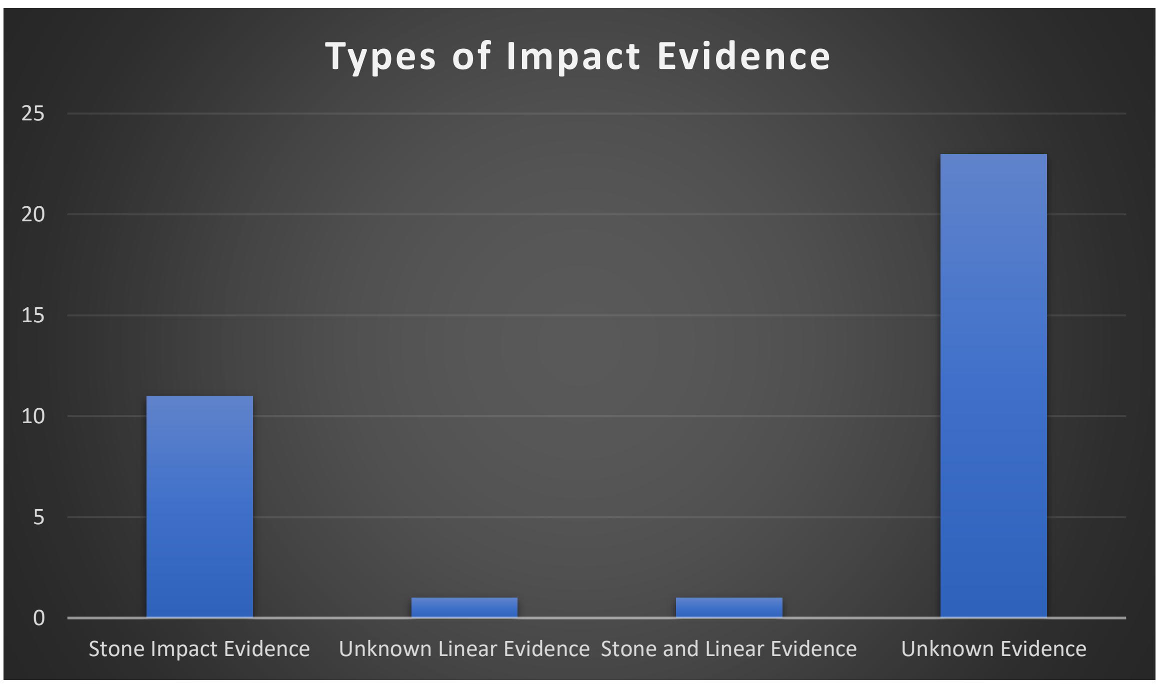

Figure 8.98: Types of impact evidence.

11 total bullets exhibit impact evidence consistent with stone impacts. 6 bullets display singular stone impact evidence and an additional 5 bullets exhibit multiple stone impact events. Figure

8.99 shows a bullet with stone impact evidence and stone inclusion in the impact surface. Figures 8.100 and 8.101 demonstrate heavily distorted bullets due to stone impact evidence.

Figure 8.99: Oudenaarde 193, heavily distorted bullet showing stone impact evidence with stone inclusion, under10X magnification.

Figure 8.100: Oudenaarde 537, heavily distorted bullet showing stone impact evidence, under 10X magnification.

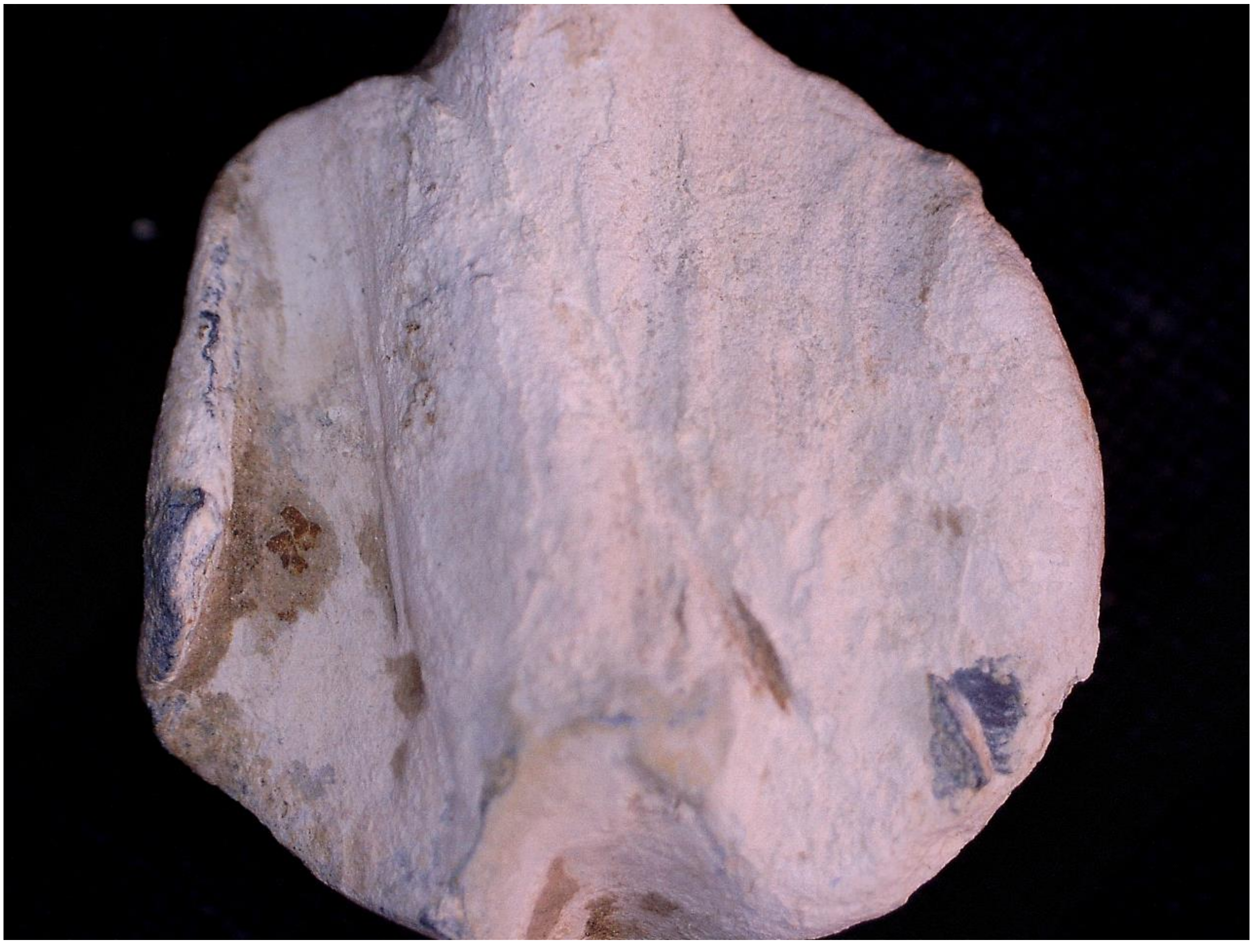

Figure 8.101: Oudenaarde 578, heavily distorted bullet showing stone impact evidence, under 10X magnification.

Of the 32 bullets that have impact evidence, only one bullet displays the unknown multiple rotational impact evidence as well as multiple points of stone impact evidence.

14 bullets were semi-hemispherical in shape and were initially listed as potential wood impact evidence, but without linear striations or a central point of impact, it is possible they could also be considered stone impacts (figure 8.102). The corrosion on the surface of the bullets makes a definitive conclusion impossible, and due to this, all 14 bullets were categorised as unknown impact evidence.

Figure 8.102: Oudenaarde 674, heavily distorted bullet showing unknown impact evidence, under 10X magnification.

9 bullets show unknown impact damage, of which 6 bullets are pancaked, but corrosion prevented a positive identification of the impact surface.

8.2.5 Irregular Distortion Level

Only 8 out of 351 bullets were determined to be irregular, which comprises 3% of the total assemblage. The bullets listed as irregular in shape are seen in figure 8.103 below.

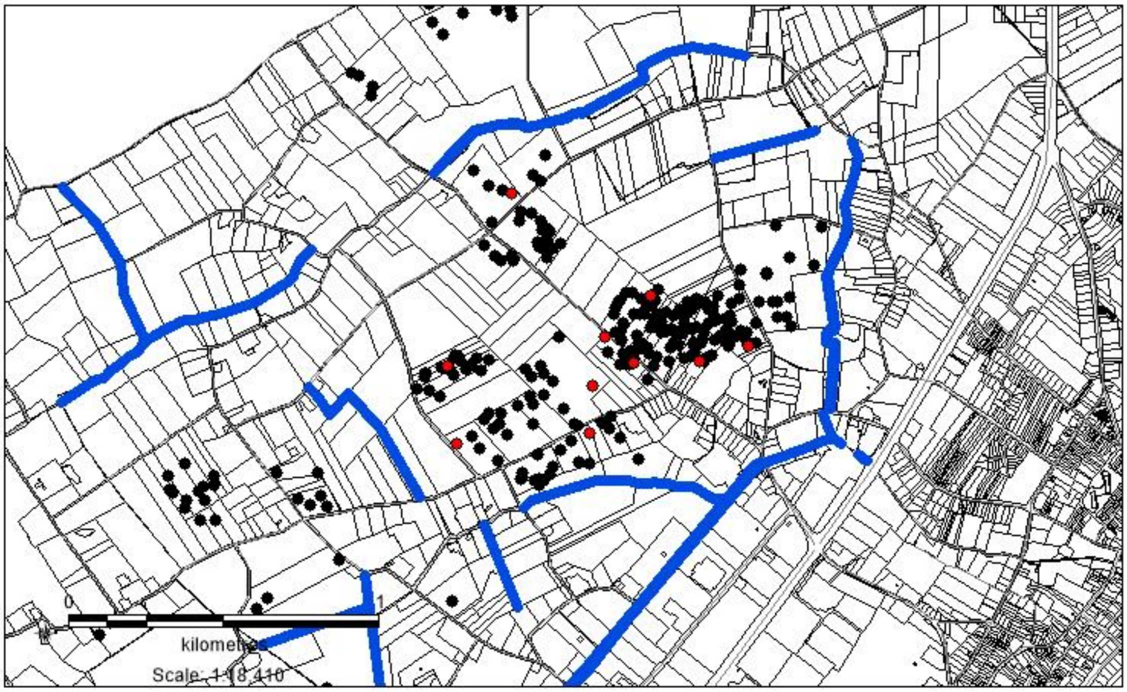

Figure 8.103: All bullets given the irregular distortion level are labelled in red. The remaining bullets are coloured in black. GIS data courtesy of Glenn Foard.

8.2.5.1 Condition Assessment for Irregular Distortion Level

All 8 bullets were determined to have a corroded surface which makes identifying diagnostic evidence difficult. 4 of the 8 have too much corrosion on the surface to determine any surface traits.

8.2.5.2 Manufacturing Evidence for Irregular Distortion Level

No manufacturing evidence is visible on any of the 8 bullets.

8.2.5.3 Firing Evidence for Irregular Distortion Level

No firing evidence is visible on any of the 8 bullets categorised as irregular in shape, but 7 of the 8 bullets show impact damage.

8.2.5.4 Impact Evidence for Irregular Distortion Level

7 bullets show impact damage, 4 of which contain too much corrosion on the impact surface to definitively determine the specific type of impact evidence. One bullet is heavily chewed and unable to be analysed further.

Two bullets contain clefts and gouges consistent with stone impacts, as seen in figures 8.104 and 8.105. The 4 corroded bullets are also pancaked, but due to corrosion eliminating any diagnostic features, it is impossible to determine what caused this pancaked impact damage. This can be seen in figures 8.106 and 8.107.

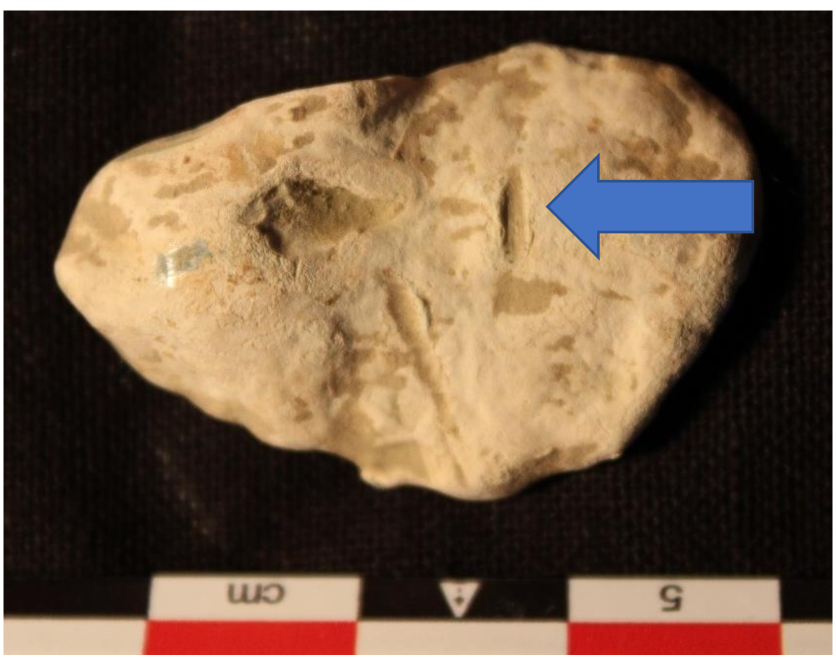

Figure 8.104: Oudenaarde 197, irregular bullet showing stone impact evidence.

Figure 8.105: Oudenaarde 346, irregular bullet showing multiple stone impact evidence, under 10X magnification.

Figure 8.106: Oudenaarde 504, irregular bullet showing unknown evidence.

Figure 8.107: Oudenaarde 506, irregular bullet showing unknown impact evidence, under 10X magnification.

8.2.6 Oudenaarde Bullet Assemblage Discussion

351 total bullets were analysed from the Oudenaarde bullet assemblage. The bullet analysis methodology laid out in Chapter One was used to examine every bullet from the assemblage. As per the bullet analysis methodology, each bullet was first allotted a distortion level based on their percentage of distortion from their ideal spherical shape. The percentage of the total assemblage can be found below in figure 8.108.

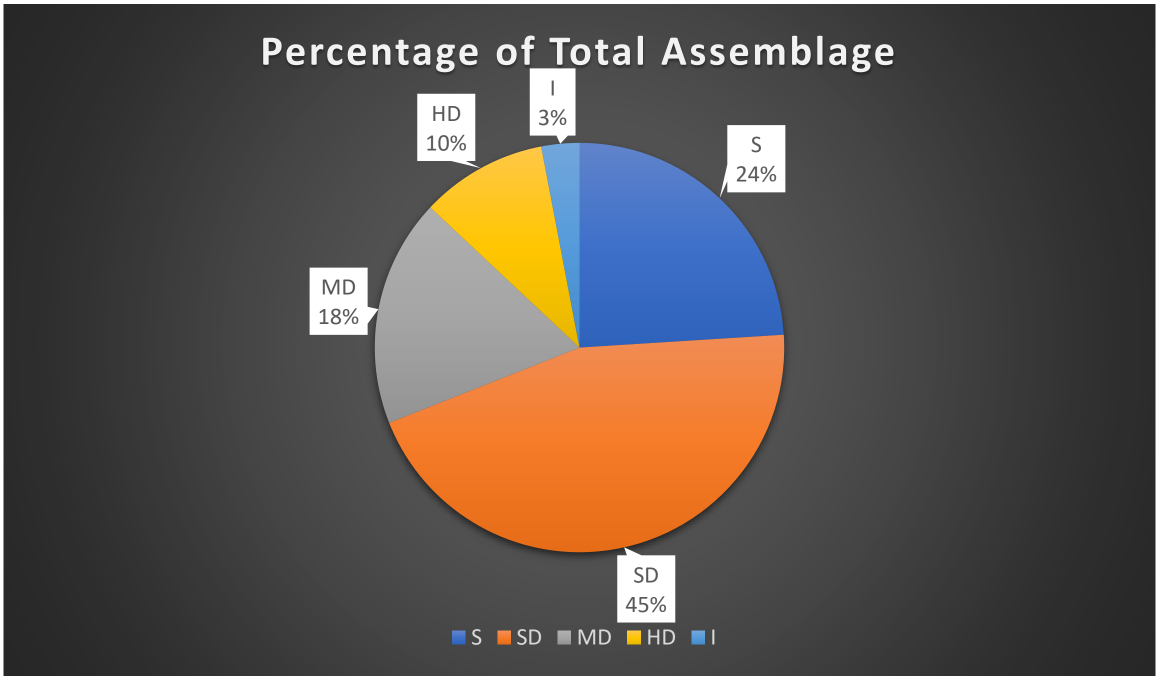

Figure 8.108: Distortion level per percentage of total assemblage.

85 bullets are recorded a spherical in shape and 158 bullets are categorised as slightly distorted, comprising 24% and 45% of the total assemblage respectively. The remaining 31% of the assemblage was allocated to the bullets from the distortion levels of moderate, heavy and irregular.

8.2.6.1 Overall Impact Evidence

79% of the total assemblage exhibits impact evidence. Out of the 351 total bullets that made up this assemblage, 277 show impact evidence. The experimental reference collection created in the experimental firing trials in Chapter Seven of this thesis was instrumental in creating an advanced understanding of the stone impact evidence seen in the Oudenaarde bullet assemblage; however, many forms of impact evidence remain unknown within this assemblage. The amount of corrosion on the Oudenaarde bullet assemblage made identifying diagnostic evidence difficult and, in some cases, impossible.

127 bullets exhibit fine tight linear striations, gouges and/or clefts that are consistent with stone impacts during the bounce and roll process after the bullet's trajectory decayed and the bullet impacted the ground. 49 of these bullets impacted a single stone during bounce and roll, while another 78 bullets contained multiple stone impact events. The battle of Oudenaarde was fought in between and through enclosures, with much of the open fields beyond or within the enclosures consisting of arable land, as previously discussed in Chapter Five (section 5.3). All bullets determined to have evidence consistent with single or multiple stone impacts can be seen in figure 8.109 below.

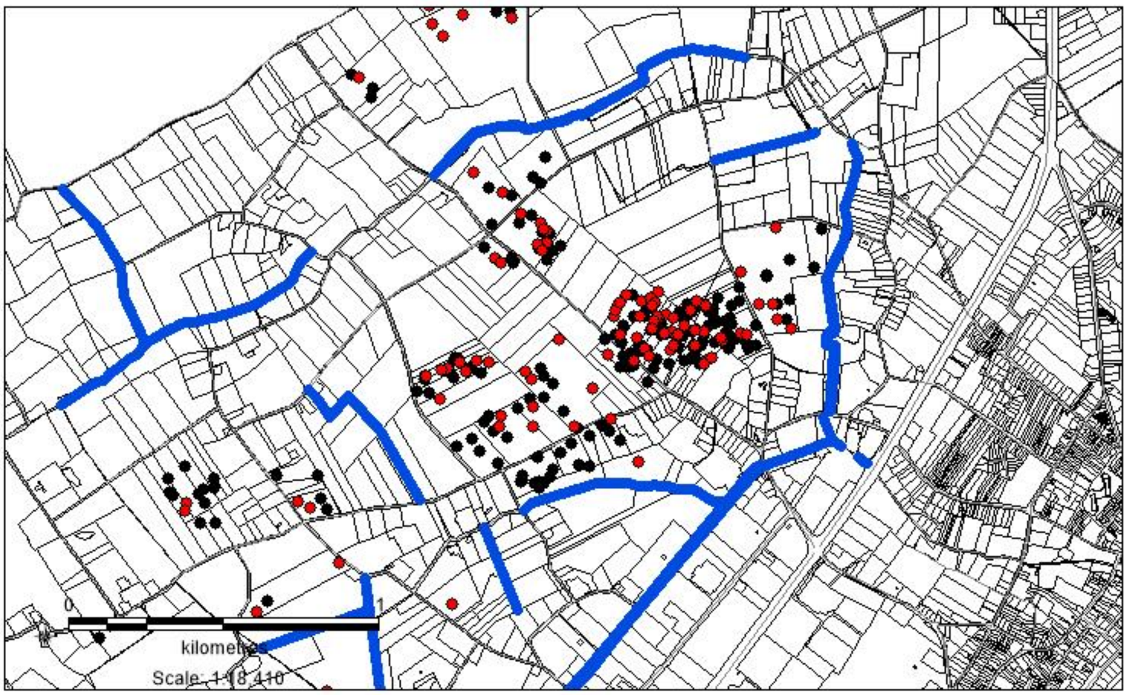

Figure 8.109: All stone impacts are seen in red, the remaining bullets in black. GIS data courtesy of Glenn Foard.

160 bullets contain the unknown linear rotational impact evidence in the form of superficial indentations, of various lengths that could be found across the surface of the bullet. No indentations reveal any striations for further identification and the side walls of the indentations are straight with little bending or folding of the lead. 6 of these bullets display a single rotational marker, while an additional 154 bullets exhibit multiple rotational markers. All bullets showing rotational impact evidence can be found in figure 8.110 below.

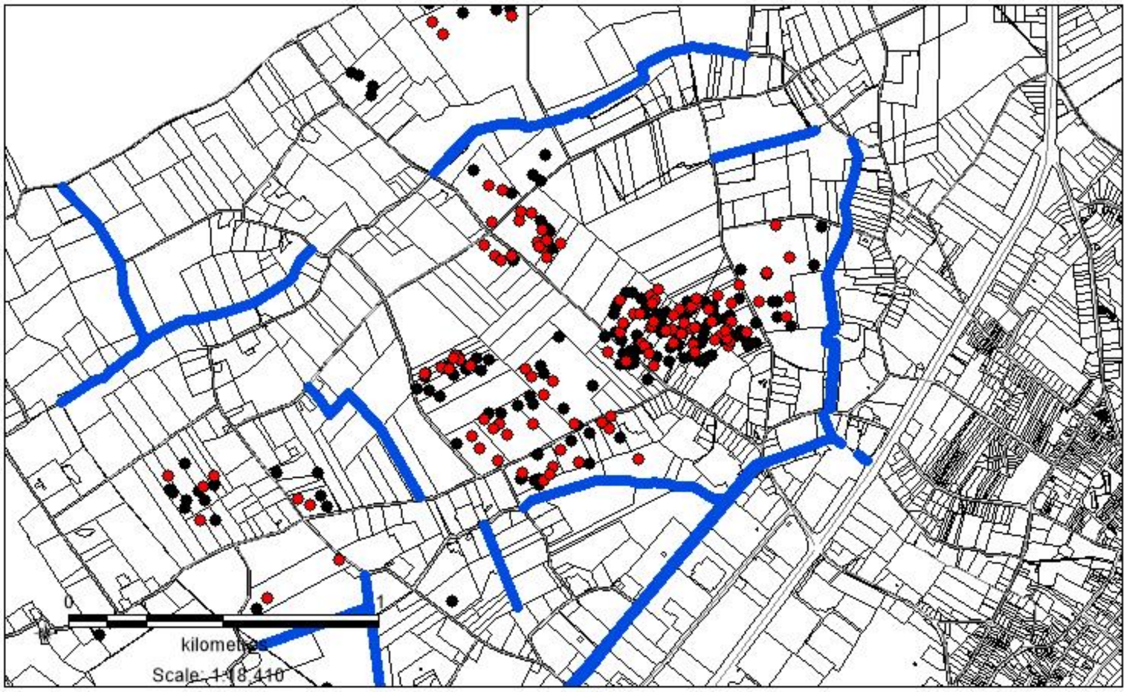

Figure 8.110: All bullets that show rotational impact evidence can be seen in red, the remaining bullets are in black.

A further 59 bullets show evidence from both stone impacts and from the unknown linear rotational markers across the surface of the bullet. As previously stated, this could be an implication that whatever is causing this linear rotational evidence is originating from the ground surface. Further experimental firing to expand the reference collection is necessary to understand this linear rotational evidence.

43 bullets are semi-hemispherical in shape and originally recorded as potential wood impacts. However, without linear striation or a central point of impact, it is possible that these bullets could also be categorised as stone impacts or as impact evidence from an unknown origin. The corrosion on the surface of the bullets makes it impossible to draw a definitive conclusion. The bullets that were originally listed as potential wood impacts can be seen in figure 8.111 below.

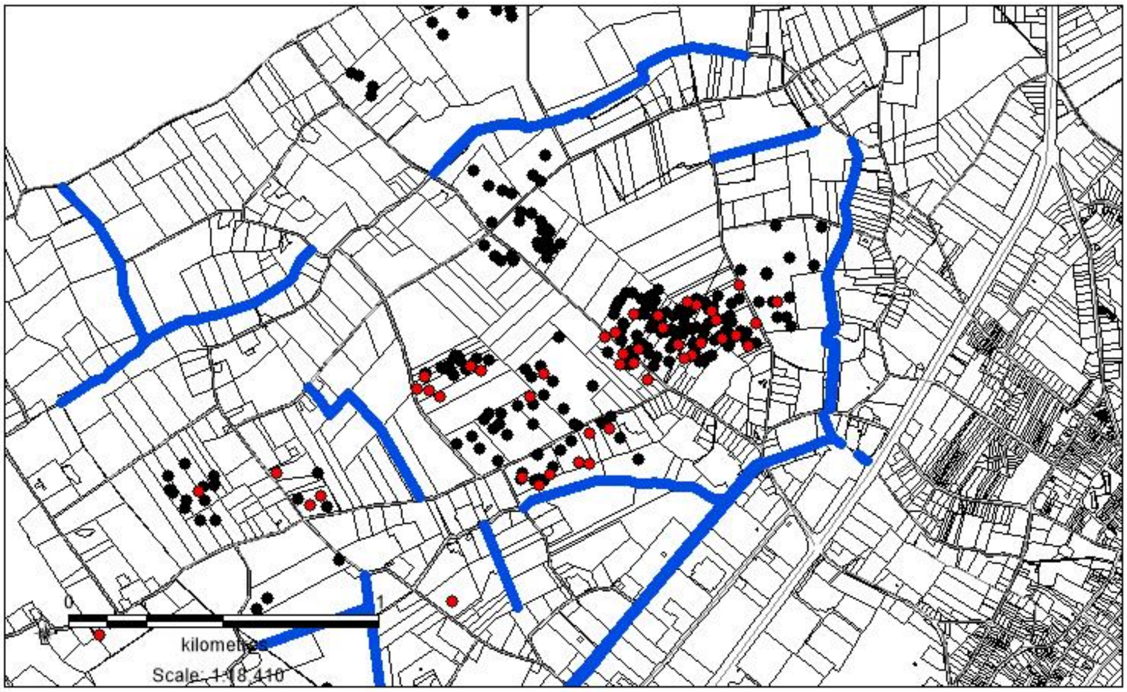

Figure 8.111: Bullets in red are the potential wood impact evidence, bullets in black are the remaining evidence.

Finally, 25 bullets remain as unknown impact damage. The forms of impact evidence on the surface of these bullets are varied and further experimental firing is needed in order to assist in revealing the cause of this unknown impact evidence.

8.3 Bullet Assemblage Comparison Conclusions

The bullet impact analysis methodology introduced in Chapter One, section 1.5, was applied to both the Edgehill and Oudenaarde bullet assemblages to investigate the evidence found on the bullets' surfaces and to isolate specific diagnostic traits and to rule them out as non-impact related evidence. With those specific diagnostic traits fully understood, the remaining evidence on the bullets' surfaces could be attributed to either impact evidence or evidence from an unknown origin. The next step was to use the experimentally fired bullets created in Chapter Seven known as the reference collection of known bullet impact evidence to act as a comparative tool for the archaeologically recovered bullets from both battlefields. The bullet impact analysis methodology was effective in determining specific diagnostic traits on the bullets' surfaces that allowed for a better understanding of the bullets on both an individual scale and as an assemblage. The methodology allowed these traits to be isolated and effectively removed from the analysis so that impact evidence from the archaeological assemblages could be focused on when compared to the reference collection. The experimental reference collection effectively identified 508 out of 822 forms of impact evidence from a total of 608 impacted bullets between the two assemblages. Due to no failure of the reference collection, the remaining 38% of the forms of impact evidence was unable to be identified due to either corrosion obfuscating the surface of the bullet or from unknown impact evidence which has no comparisons within the reference collection.

When comparing the two assemblages, Edgehill contained over twice the number of bullets than the Oudenaarde assemblage. The Edgehill assemblage consisted of 803 bullets, whereas the Oudenaarde assemblage consisted of 351 bullets. Oudenaarde's smaller sample size contributed to a limited number of impacted bullets that could be analysed, compounded by the fact that 96% of the bullets from the site were badly corroded. Despite these limitations with the Oudenaarde assemblage, 79% of the bullets were impacted, whereas, 41% of the Edgehill assemblage exhibited impact evidence.

There seems to be a trend between distortion levels and the types of impact evidence present on the bullets' surfaces and this trend remains true for both assemblages. Bullets showing spherical to slight distortion levels on both sites, not only represent the bulk of the assemblages but also exhibit the most identifiable impact evidence in the forms of stone impacts and the unknown linear rotational impact damage. With most of the impact evidence on these spherical and slight distortion levels being scientifically and experimentally identified as stone impacts, one can begin to theorise how this occurred. One possibility is that these bullets are a result of over shot or undershot of the enemy position, and without impacting anything other than stone and/or other possible ground obstructions, theoretically the bullet was able to complete its firing trajectory without hitting its intended target and the flight of the bullet naturally decayed until it came into contact with the ground at a reduced velocity. Once the bullet impacted the ground, it would continue to bounce and roll, until its remaining kinetic energy was spent.

Although wood impact evidence was explored experimentally and is included in the reference collection in Chapter Seven, an issue with identifying them within the archaeological assemblages became apparent. The experimental bullets contained a central point of impact, with adhering wood grain impressions, and thick linear striations on the perimeter of the bullet that radiated towards the backside of the bullet. When the experimental bullets grazed a wooden target, thick linear striations could be seen in the region of the bullet that had grazed the target. However, the potential wood impacts identified within the archaeological record from both sites do not exhibit the central point of impact and, no bullets show the adhering wood grain impressions. The thick linear striations have also become difficult to separate from the fine linear striations that are attributed to stone impacts due to corrosion.

The experimental bullet reference collection, alongside both the Oudenaarde and Edgehill bullet assemblages, reveal that there is no definitive correlation between firing evidence and impact evidence. The Oudenaarde bullet assemblage shows that 11% of the total assemblage contained firing evidence, while 79% of the total assemblage exhibited impact evidence. The Edgehill assemblage shows that 26% of the total bullets contained firing evidence, while 41% of the site exhibited impact evidence. During analysis with this study's methodology, both assemblages show that a bullet's surface can exhibit firing evidence while exhibiting no distinctive impact evidence and that bullets can display definitive impact evidence without having any previous firing features. As a result, it is entirely circumstantial as to what impressions and features appear on the bullet's surface during the firing and impact processes.

Both the Oudenaarde and Edgehill bullet assemblages acted as a proof of concept for both the impact analysis methodology at analysing the bullets for impact evidence and for the reference collection of known bullet impacts at reliably determining the type of impact evidence seen on a bullets' surfaces. The impact analysis methodology proved sufficient when categorising bullet assemblages in a way that reduced visual subjectivity and broad interpretations as well as provided a step-by-step identification and elimination process for all non-impact related evidence on a bullet’s surface. The reference collection provided a useful comparative tool to scientifically analyse and identify impacted bullets, and the proof of concept, that experimentally fired bullet can retain characteristic traits from the impact surface, which can be used as diagnostic traits to allow for classification to take place has been established throughout this chapter. These bullets have also established their reliability and importance to site data as seen above. Stone impact evidence can be found across the battlefield; however, the ability to relate wood impact evidence to site specific data is not feasible at this time.

With the combination of both the methodology and the reference collection, this thesis has created a viable, objective and practical way to analyse bullet impact evidence from the archaeological record, thereby advancing the interpretive abilities of not only bullet impact evidence, but for archaeological bullet assemblages. As the bullets can be of importance to specific site data, as future studies increase the reference collection of known bullets impacts, perhaps one day the bullet impact evidence can enable a greater understanding of the battlefield landscape.

Conclusions

The predominant archaeological find recovered from battlefield sites dating to the early modern period in Europe, North America and the United Kingdom, is the spherical lead bullet fired from small arms. Established analytical techniques have been developed to gather a wealth of information from these bullet finds on both an individual scale and as an assemblage. The size of the bullet is its primary diagnostic indicator. Knowledge of the size or calibre of the bullet can enable the identification of the firearm type that fired it as well as troop type that fired it. In some contexts, this can allow for an understanding of troop placements and movements across the battlefield. Distribution maps can also allow for a more advanced understanding of the events of the battle within the battlefield landscape as the scatters of bullets can allow for the identification of the location, intensity and the extent of the battle. The analysis of bullets on an individual scale can allow for a greater understanding of the life span of the bullet. Previous experimentation has demonstrated the transfer of various characteristic and diagnostic traits from the manufacture, transport, loading and firing processes of the bullet, as well as many other forms of evidence. However, bullet impact evidence remains largely unexplored and poorly understood. The objective of this thesis was to investigate impacted bullets by creating a reference collection of known bullet impacts through a series of proof of concept experimental firing trials. This reference collection was then used as a comparative tool against two case study battlefield bullet assemblages that were recovered archaeologically. The evidence collected in this thesis demonstrates that impacted bullets can retain diagnostic traits transferred from the impact surface to the surface of the bullet. These diagnostic traits permit classification and reveal an advanced understanding of the nature and character of the bullet impact surface within the archaeological record, although due to the size and scope of this study further experimentation is required to fully understand the impact surfaces seen on archaeologically recovered bullets as many forms of unknown impact evidence remain.

Before the proof of concept experimental firing trials were completed, a method was first created to investigate impacted bullets using a series of iterative steps using visual macro and microscopic techniques, in which the entirety of the bullet’s surface evidence could be accounted for. This method considers all of the previously identified forms of bullet evidence identified by experimentation by Dr Glenn Foard and Mr Dan Sivilich. With all known forms of evidence accounted for, the remaining evidence on the bullet's surface could be treated as either impact evidence or evidence of an unknown origin. Various objective and quantifiable methods were tested in the early stages of this thesis to create a method of analysing bullets and all were found to be subject to observer error, therefore the proposed subjective method in Chapter One (section 1.5) was implemented. While the bullet impact analysis methodology (Chapter One) created in this thesis was effectively used to examine the surface of the bullet for various forms of evidence and diagnostic traits, it fails to find a completely objective method to quantify the level of deformation on the bullet's surface. That aspect of the methodology lies in subjective observations which will likely vary from person to person. The *Lead Ball Deformation Index* created and detailed by Scott et al (2017) in Chapter One appears to be the first method created for analysing distorted bullets based on objective measurements; however, the Scott method was published after the data in this thesis was already collected and analysed, and therefore could not be implemented. Future experimental firing studies are advised to use the Scott method to verify if the trend between impact velocity and deformation are linked and if so, continue to build upon that data set, so that the deformation level of the bullet may be quantified. If the deformation level of an impacted bullet can be quantified in future studies, then it can be used in combination with the bullet impact analysis methodology created in this thesis as a foundation on which to continue research on impacted bullets and improve upon overall objectivity.

The creation of a reproducible experimental firing methodology that was used for the creation of the known bullet impact reference collection was the next step. Before the experimental firing methodology was created, specific variables and experimental parameters had to be identified and investigated. This was completed by using military manuals and scientific publications dating to the early modern period in conjunction with modern ballistics. The variables identified by modern ballistics affect the way in which the bullet arrives and impacts its target and cannot be overlooked. While ballistics identified general variables needed for consideration in the experimental firing trials such as the choice of gunpowder, the ratio of bullet weight to the gunpowder charge size, the composition of the bullet, muzzle velocity, the use of a wad, firearm barrel length, and windage as stated in Chapter Two, section 2.1; the use of military manuals and scientific publications, as stated in Chapter Four, provided the specifics for each variable to ensure overall parameters were applicable to the early modern period.

The choice of gunpowder used in the experimental studies is problematic. Chapter Four, section 4.1, details the amount of variation not only within gunpowder but even of the ingredients used to create it. Currently, no known examples of gunpowder from the early modern period have survived in which scientific experiments can be conducted to create a baseline for comparison. Therefore, it is simply not possible to recreate or reproduce an accurate gunpowder recipe from the period. The type of priming powder used is a subject of debate with modern historians which cannot be clarified in this thesis. Period sources rarely make any mention of priming powder until the late 18th century after gunpowder had undergone drastic changes and cartridges became standard. The ratio of bullet weight to gunpowder charge size is held constant from as early as 1632 until at least 1780; however, there is no way to guarantee that the practises outlined in the military manuals were followed by the soldiers in the field. The composition of the bullet is not outlined in early modern sources, but is becoming better understood due to modern scientific experimentations, such as XRF analysis. The ratio of bullets archaeologically recovered to bullets tested for composition is extremely high, and this is mainly due to the destructive nature of the testing required to understand the bullet's composition. Current results show that the composition of recovered bullets is around 99% to 90% pure lead, with other materials such as tin and pewter included. This is a subject that requires its own dedicated study as further expansion in sample sizes could reveal a greater understanding of this practise. Finally, the use of a wad, barrel length and windage are all variables that affect the impact of the bullet as well. However, these variables are very complex and deserve their own independent research to be clearly understood, for this thesis these variables were held constant to minimize their affects.

Of all the variables researched, muzzle velocity supplied the direct link into early modern firing practices by providing a scientific baseline in which results with modern methods could be compared. The experiments conducted by Benjamin Robins in 1742 and his recording of muzzle velocity provided a foundation for modern experimental firing to build from.

Due to a moratorium on the usage and handling of black powder, this thesis created another completely new experimental firing methodology using modern nitro gunpowder, which fired the bullet from a shotgun cartridge. This method was proven viable during the ground firing experiments conducted in Chapter Seven, although higher velocities still need to be discovered to further round out the firing data.

The reconstructed historic landscape from the battlefields of Edgehill and Oudenaarde were examined to create the experimental firing designs and parameters used in this thesis. Mentions of the features in the terrain are hints at what a bullet may have impacted during the battle. As mentioned in Chapter Five, section 5.6, certain avenues for experimentation were not plausible due to legal reasons or accessibility in the United Kingdom, such as firing into human proxies and outdoor firing. This created a limited approach where firing inside became mandatory. As a result, it was decided to begin experimental firing by examining both case study battlefields reconstructed historic landscape for common features that could be recreated indoors. Common features on both battlefields included the open terrain, consisting of arable and pasture fields and hedged enclosures. Due to the complexity of the ground surface within open fields and hedge enclosures, as outlined in Chapter Five, it was decided to begin experimental firing by creating a baseline for future comparison by examining bullet impact evidence against the ground surface and a variety of wooden targets. Ground surface firing consisted of the bounce, roll and ricochet of bullets into both sterile and stony ground condition within a simulated ploughed field. Wood test firing was completed by examining bullet impact evidence against differing species of wood, dead wood against living wood, along with a variety of simulated hedges of varying thickness.

Research into musket range and accuracy was completed in Chapter Six to create a regimented experimental firing design. At the outset of the experimental firing trials, the idea was to fire at every target at 25m intervals along the maximum range of the musket to investigate how bullets impacted at varying distances and to determine if distance could be implied by impact damage and bullet distortion level. However, the legendary inaccuracy of the musket at medium to long ranges was a growing concern. The proof of concept established by Graham Green (2010) that the manipulation of the charge size imparted onto the musket could simulate distance, along with modern ballistic trajectory modelling fostered the idea that through experimentation one could model the external ballistic trajectory of a ‘musket ball’, and that through this route one could understand the bullet’s distance and velocity at predetermined points along its flight path. This led to the creation of the 19-bore external ballistic trajectory modelling program created in this thesis, as well as the first ever modelling program created specifically for ‘musket balls.’ The modelling program created in this thesis was designed to create a regimented firing methodology, by having an advanced knowledge of the bullet’s velocity at predetermined distances along the maximum range of the musket. The knowledge of the bullet’s velocity at predetermined distances enables the manipulation of the gunpowder charge size to a specific quantity so that the desired velocity is produced during experimentation. However, the inconsistent burn rate and firing of black powder does not allow for one to be that precise. As noted in Chapter Six, the velocity of a bullet fired with the same charge size using black powder can vary enough to vary the distance the bullet travels, so the idea of firing at 25m intervals became impractical. The experimental firing trials were then redesigned to vary the charge sizes between experiments to investigate the effects of bullet impact evidence with changes in velocity, and the recorded velocity data was then input into the modelling program to understand the extent of the simulated distance travelled by the bullet in each experiment.

With the creation of the experimental firing methodology in Chapters Two-Four, and the creation of the experimental designs in Chapters Five and Six, the proof of concept experimental firing trials to create a known bullet impact reference collection began in Chapter Seven. Experimental firing into sterile and stony soil ground conditions to simulate a ploughed field was conducted to examine bullet impact evidence against the ground surface. The bullets were subject to the effects of bounce, roll and ricochet after the bullet impacted the ground. The results from the experiments clearly show that bullets that impacted the soil would either exhibit impact evidence in the form of pitting from direct soil impact, or the bullet would exhibit fine tight linear striations, including a variety of forms of clefts and gouges from impacting stones within the soil. This evidence could be found on any portion of the bullet, depending on where and how the bullet impacted the stone within the soil matrix. Further elaboration and inferences regarding the size of the stone impacted could not be completed due to the force in which the bullet impacted the soil. Since this experimental firing trial was a proof of concept, the sample sizes were too low to establish meaningful statistical data; however, the proof of concept was established in Chapter

Eight when the reference collection bullets were compared to bullets from the archaeological assemblages. However, it is advised with any future ground firing experiments to increase the sample size to at least 3-5 bullets per variable to create a more meaningful statistical data set. A further increase in ground surfaces also needs to be examined, such as the firing into pasture fields and fields with vegetation of various levels of growth. This was originally a subject of this thesis, but due to limitations outside of the control of this thesis those experiments were cancelled, and no such conclusions could be drawn between bullet impact evidence and different ground conditions.

Experimental firing into wooden targets was also undertaken to investigate the impact impressions from different species of wood, as well as the impact impressions from dead wood and living wood. The results clearly show that wood grain impressions from any wooden target are identical, mainly in the form of a central point of impact with adhering wood grain impressions, along with thick linear striations located on other regions of the bullet from where the bullet impacted, perforated or grazed the wooden target. The wood grain impression was much more pronounced on living wood than from dead wood, and much more pronounced on wood with an exposed, coarse surface texture than to wood covered in bark. However, a troubling issue became apparent during the wood impact firing trials, that the bullet only retained the wood impact impression 70% of the time. As the sample size was low during each firing experiment, a further increase in sample size could see this problem increase or decrease, although this thesis cannot comment further on that possibility. Another issue that arose was that the wood grain impressions on several bullets were faint, and only visible under 10X magnification. Between these two issues, concern began to grow regarding the ability to identify wood impact evidence on bullets from the archaeological record. As certain bullets may have impacted a wooden target, but the transfer of characteristic traits did not take place. In that event, it would not be possible to definitively determine what the bullet impacted. This could also cause a non-definitive determination with bullets from the archaeological record as the bullet's impact surface could be covered in corrosion, thus the bullet evidence would be relegated to unknown impact evidence. Again, the sample sizes were too low to establish any meaningful statistical data in the wood firing experiments, but the further expansion of this series of experiments could provide useful data.

The experimental firing trials also demonstrated that there is a correlation between bullet distortion upon impact and the terminal velocity of the bullet, although this correlation could not be quantified due to too low of a sample size. However, it was also noted that this correlation was superseded by the characteristics of the target being impacted. The thickness of the target could create a higher distortion level on the surface of the bullet when impacting a target at a low velocity. The experimental firing trials also demonstrate that the number of targets being impacted influence the distortion level of the bullet. Bullets that contained multiple impact events were much more deformed than bullets that contained evidence of single impact events. Both target thickness and the number of targets being impacted need further investigation in future experimental firing studies to fully understand this process.

The bullet impact analysis methodology was then used in conjunction with the proof of concept reference collection of know bullets impact evidence in Chapter Eight. The reference collection of know bullets impact evidence was used to compare impact evidence with the bullets from the two-case study battlefield bullet assemblages. The subjective bullet analysis methodology was effective in allowing for the characteristic traits throughout the bullets’ lifespan to be identified and isolated on the bullets’ surfaces, allowing for a clear investigation of the impact evidence.

The proof of concept was established when the reference collection was able to identify stone impact evidence on bullets from within the archaeological record, as stone impact evidence was present in large numbers from both case study battlefields. Bullets exhibiting stone impact evidence were plotted on distribution maps for both case study battlefields, and the results demonstrate that bullets containing stone impact evidence are found across the entire battlefield landscape. Further experimental firing with other ground surfaces, such as grass and pasture fields may enable a greater understanding of the battlefield terrain when compared to stone impact evidence, as stone impact evidence may indicate the presence of arable land as opposed to pasture fields. However, no wood grain impressions could be located on any bullets from either case studies bullet assemblage. Whether this was due to the faint details of the thick linear striations being removed or obfuscated by corrosion is difficult to determine but seems probable. Further experimentation with wooden targets is warranted to tease out a more defined answer.

Furthermore, the thick linear striations from impacting or grazing the wooden surfaces were easily confused with the fine tight linear striations from the stone impact evidence once corrosion had obfuscated the impact surface resulting in the inability to properly identify the impact evidence. Bullets that were originally listed as potential wood impact evidence were plotted on distribution maps from both case study battlefields. Almost none of these bullets were found in the locations of the hedged enclosures. This could imply that there were other objects on the battlefield made of wood during the battles that were not mentioned within the primary accounts; however, it is just as likely that these bullets represent impact evidence with an unknown surface.

This thesis has demonstrated that bullet impact evidence can be better understood with the appropriate scientific experimentation and objective analysis. However, further experimentation needs to take place to expand the reference collection of known bullet impacts. This study recommends further experimental firing trials into different ground conditions with varying levels of ground hardness to study the effects of bounce and roll and the associated bullet impact evidence with pasture fields, and fields containing different crop types and crop stubble, as this may create a greater understanding of not only the bullet impact evidence, but possibly allow one to infer unstated landscape features from within the primary accounts and documentary evidence. Experimental firing into human and animal proxies are needed as well, as humans and sometimes horses were the main targets on the battlefield. The need for the overall expansion of the reference collection in general to include varying types of targets would be beneficial to create a more rounded and all-encompassing reference collection of known bullet impacts.

This thesis provides new insights into the poorly understood issue of impacted bullets in battlefield archaeology. Knowledge of what the bullet impacted could enable a greater understanding of the events and terrain of the battle thereby advancing our knowledgebase within battlefield archaeology. Ultimately this thesis proves that by using military sources from the early modern period, one can reconstruct the firing methods for experimental purposes. Then one can use experimental firing to collect impact evidence which can assist in a greater understanding of bullets from the archaeological record. However, this thesis is a proof of concept and further experimentation is needed, not only creating a greater sample size as this may either overturn the results found in this study or further bolster them, but other impact surfaces need to be investigated to continue the expansion of the reference collection of known bullet impacts as this may enable a further understanding of bullet impact evidence.

Battlefield archaeology is a relatively new discipline within the international archaeology community that has gained traction within the past few decades. Battlefield archaeology uses interdisciplinary techniques and interpretations to better understand past battles and fields of conflict throughout the world. The use of scientific techniques and objective methodologies as demonstrated throughout this thesis can help advance battlefield interpretation of not only the battle action itself but also of the human material record of our past.

Appendices

Appendix 1: Ballistics Equations for External Ballistic Trajectory Modelling

A. Units of Measurements: S.I. units

Experiments require numerical measurements and the numbers used to describe theses physical measurement are called physical quantities (Grant & Phillips 2001: 5; Breithaupt 2010: 3; Young et al. 2012: 4). This quantitative information is represented by a standard symbol and these standard symbols are used in equations to show a relationship between physical quantities (Young *et al.* 2012: 6). While measurements are typically taken using the metric system; for example bullet weight (mass) is taken in grams; it must be converted into kilograms for the usage in equations in accordance with the SI units of measurements. This conversion creates dimensionally consistency. This will be explained in greater detail below.

The metric system is a system of units for measurements that are accurate, reliable and most importantly reproducible by other scientists; this ability to duplicate measurements is paramount in scientific research. Since 1960, the metric system has been more commonly known as the International System or SI; this is termed from its French name ‘Système International’ (Serway et al. 2000: 4; Young et al. 2012: 4).

Listed in table 1A below are the SI units used in this study; a few such as electric current and frequency were left out but can be found in the referenced texts. This table was created as an amalgamation of the following texts for ease of reference (Serway et al. 2000: 2-12; Breithaupt 2010: 1; Young et al. 2012: A-1).

Quantity	Name of Unit SI base Unit	Symbol	Equivalent Unit
Length	Meter	M	
Mass	Kilogram	Kg	
Time	Second	S	
Thermodynamic temperature	Kelvin	K	
Quantity	Name of Unit SI derived Unit	Symbol	Equivalent Unit
Area	Square meter	m^2	
Volume	Cubic meter	m^3	
Mass density	Kilogram per cubic meter	Kg/m^3	
Speed/ velocity	Meters per second	m/s	
Acceleration	Meters per second squared	m/s^2	
Force	Newton	N	$Kg*m/s^2$
Work, energy, quantity of heat	Joule	J	N*m

Table 1A: SI units

B. Explanation of the Calculations

Before delving into the equations, a brief explanation of unit measurements conversions is in order. Bullet weight is typically measured in grams (g) in the typical battlefield report; however, the S.I system for mass units is in kilograms (kg), hence conversions were made in the data to avoid miscalculations. The converted units can be seen in the raw bulk data see in Appendix 2. Table 1B below are the S.I. system units

Physical Quantity	Unit
Mass	Kilogram (kg)
Length	Metre (m)
Time	Second (s)

C. Acceleration

The first step was to calculate the bullet's acceleration. Newton's first law states that acceleration is the rate of change in velocity of an object with time (Breithaupt 2010: 133; Kisak 2014: 95). This was done by subtracting the initial velocity (u) from the final velocity (v) and dividing by the time step (t) in seconds between the two velocities. Acceleration is therefore measured in metres per second squared (m/s^2).

$$\frac{dv - du}{dt} = a$$

Meaning:

d= a derivative, or the rate of change. It has no mathematical quantity, but is written to signify a rate of change. So dv is the rate of change in the final velocity, du is also the rate of change in initial velocity and dt is the rate of change in time or the time step.

v= the final velocity 426m/s

u= the initial velocity 456m/s

t= time 30ms- converted to SI units (seconds) is 0.03s

a= acceleration

Example: 456-426/ 0.03= -1000m/s^2

D. Drag Force

The second step was to calculate the force of drag on the bullet. Newton's second law states that the net force on an object is equal to the rate of change of the linear momentum of the object with time (Breithaupt 2010: 144-145; Kisak 2014: 20.97). Drag force is expressed as force (f) equals mass (m) multiplied by acceleration (a). Force is expressed as either kg·m/s² or Newton (N).

$$f = ma$$

Meaning:

F= force

m= mass of the bullet 24.18g- converted to SI units (kg) is 0.02418kg

a= acceleration of the bullet taken from previous equation, -1000m/s²

Example: 0.02418*-1000= -24.18N

E. Coefficient of Drag

The third step was to calculate the coefficient of drag for the bullet. The forces acting on the bullet while in flight depend on the density of the air or fluid in which the bullet is traveling (Moss *et al.* 1995: 79). In a total vacuum, gravity is the only force acting on a bullet in flight. However, in air the force retarding the momentum of the bullet is created by air resistance, this is called drag (Moss *et al.* 1995: 71). There are several types of drag acting on a bullet while in flight and can be quickly summarized as Skin friction and pressure drag (Moss *et al.* 1995: 72). This calculation is completed by taking two multiplied by the force of drag (FD) which is divided by Rho (P) multiplied by velocity squared (V^2) multiplied by the area of reference (A) of the bullet. As with all coefficients, the drag coefficient does not have a unit of measurement as it does not affect the measurements. All units of measurement cancel each other out.

$$\mathrm{CD} = \frac{2\mathrm{FD}}{\rho * \mathrm{V}^2 * \mathrm{A}}$$

Meaning:

CD= Coefficient of drag

FD= Force of Drag

ρ= Rho

V= Velocity

A= Area of reference

To calculate the coefficient of drag, both Rho (ρ) and the Area (A) of reference equations need to be calculated.

Rho is calculated by using an air density calculator or a look up table. Rho is difficult to calculate without using a look up table since air pressure, density, temperature and viscosity all vary with altitude. The changes in the atmosphere affect the air resistance of the bullet (Moss *et al.* 1995: 67). In this instance, an air density calculator was used. To calculate Rho the ambient air temperature (°C), dew point (°C) and barometric pressure (hPa) must be recorded on the day of the firing trial.

Air Temp = 23°C

Dew Point= 8°C

Barometric pressure= 1024.05hPa

Rho (ρ) = 1.1998kg/m^3

Area of reference is the area of the projectile. As the bullets are spheres, the area of reference is PI multiplied by the radius of the sphere squared. To calculate area, measurement of the diameter of the bullet is required because the radius is half of the diameter. Measurement of the diameter of the bullet is taken with a calliper at a 90° angle to the mould seam from one end of the bullet to another end encompassing 180°. The mould seam of the bullet is a casting mark created on the entire outside circumference of the bullet during the casting process when the two halves of the mould are together to form the spherical bullet. The area of reference is calculated as the area of a sphere which is PI multiplied by the radius squared of that bullet.

$$A = \pi r^2$$

Meaning:

A= Area of reference

π= PI or 3.14159265359 (and so on)

r^2= radius of the bullet squared 8.13mm- converted to SI units (m) is 0.00813

A= (PI*0.00813^2)

With all variables known, the drag coefficient can now be calculated.

$$CD = \frac{2FD}{P * V^2 * A}$$

Meaning:

CD= Coefficient of drag

FD= Force of Drag Given from previous equation= -24.18N

P= Rho 1.1998kg/m^3

V= Velocity mean velocity of the firing for this bullet = 440.33m/s

A= Area of reference PI *0.00813^2

Example:

CD= 2(-24.18) ÷ (1.1998) * (440.33^2) * ($\pi 0.00813^2$)

CD= -48.36 ÷ 48.3056

CD= -1.00

F. Mach Number

The final equation for understanding the ballistics of the firing trials is the Mach Number. For each firing trial, the mean velocity was calculated (add up all velocities and dived by the number of velocities; an average). This number was then divided by the ambient speed of sound at one kilometre above sea level (340 m/s) to calculate the Mach number (M).

Mach Number (M) = $\frac{\text{Mean Velocity}}{\text{Local Area Speed of Sound}}$

Example:

M= 440.33/ 340

M= 1.3

Appendix 2: Raw Maths Data

A. Raw Maths Data from all 21 bullets fired on 25-26-May- 2015

NO.3 Range: The Enfield Small Arms Experimental Range

41 inch barrel   TS2 powder container code 0027UN

Weather:

RAF Fairford: Barometric pressure: 1024.05 hPa   Air Temp: 23°C   Dew Point   8°C

ρ (rho) = 1.1998 (kg/m³)

Bullet 1 Bullet weight: 24.18g Bullet weight (kg): 0.02418kg Mean Velocity: 440.33m/s Mach Number: 1.295	Charge weight: 12g Bullet Diameter 90°: 16.26mm Bullet Radius: 8.13mm Bullet Radius (m): 0.00813m CD:
Time Step (ms)	Velocity m/s
5ms	457m/s
10ms	456m/s
20ms	447m/s
30ms	434m/s
40ms	426m/s
48ms	422m/s

Bullet 2 Bullet weight: 24.13g Bullet weight (kg): 0.02413kg Mean Velocity: 425.83m/s Mach Number: 1.25	Charge weight: 12g Bullet Diameter 90°: 16.20mm Bullet Radius: 8.1mm Bullet Radius (m): 0.0081m CD:
Time Step (ms)	Velocity m/s
4ms	446m/s
10ms	442m/s
20ms	431m/s

30ms	421m/s
40ms	412m/s
48ms	403m/s

Bullet 3 Bullet weight: 24.10 Bullet weight (kg): 0.0241kg Mean Velocity: 452.50m/s Mach Number: 1.33	Charge weight: 12g Bullet Diameter 90°: 16.20mm Bullet Radius: 8.1mm Bullet Radius (m): 0.0081 CD:
Time Step (ms)	Velocity m/s
5ms	472m/s
10ms	468m/s
20ms	457m/s
30ms	448m/s
40ms	438m/s
45ms	432m/s

Bullet 4 Bullet weight: 24.03g Bullet weight (kg): 0.02403kg Mean Velocity: 446.17m/s Mach Number: 1.31	Charge weight: 12g Bullet Diameter 90°: 16.25mm Bullet Radius: 8.125mm Bullet Radius (m): 0.008125m CD:
Time Step (ms)	Velocity m/s
5.5ms	463m/s
10ms	461m/s
20ms	452m/s
30ms	442m/s
40ms	432m/s
46ms	427m/s

Bullet 5 Bullet weight: 24.14g Bullet weight (kg): 0.02414kg Mean Velocity: 446.5m/s Mach Number: 1.31	Charge weight: 12g Bullet Diameter 90°: 16.24mm Bullet Radius: 8.12mm Bullet Radius (m): 0.00812m CD:
Time Step (ms)	Velocity m/s
6ms	464m/s
10ms	462m/s
20ms	451m/s
30ms	443m/s
40ms	432m/s
46ms	427m/s

Bullet 6 Bullet weight: 24.30g Bullet weight (kg): 0.0243kg Mean Velocity: 320.25m/s Mach Number: 0.94	Charge weight: 8g Bullet Diameter 90°: 16.26mm Bullet Radius: 8.13mm Bullet Radius (m): 0.00813m CD:
Time Step (ms)	Velocity m/s
6ms	346m/s
10ms	346m/s
20ms	343m/s
30ms	337m/s
40ms	319m/s
50ms	301m/s
60ms	288m/s
65ms	282m/s

Bullet 7 Bullet weight: 24.65g	Charge weight: 8.5g Bullet Diameter 90°: 16.29mm

Bullet weight (kg): 0.02465kg Mean Velocity: 350.43m/s Mach Number: 1.03	Bullet Radius: 8.145mm Bullet Radius (m): 0.008145m CD:
Time Step (ms)	Velocity m/s
5ms	363m/s
10ms	362m/s
20ms	358m/s
30ms	353m/s
40ms	344m/s
50ms	339m/s
60ms	334m/s

Bullet 8 Bullet weight: 24.24g Bullet weight (kg): 0.02424kg Mean Velocity: 335.36m/s Mach Number: 0.99	Charge weight: 8.5g Bullet Diameter 90°: 16.32mm Bullet Radius: 8.16mm Bullet Radius (m): 0.00816m CD:
Time Step (ms)	Velocity m/s
8ms	348m/s
10ms	347m/s
20ms	343m/s
30ms	338m/s
40ms	332m/s
50ms	329m/s
60ms	325m/s
62ms	323m/s

Bullet 9 Bullet weight: 24.23g Bullet weight (kg): 0.02423kg	Charge weight: 9g Bullet Diameter 90°: 16.25mm Bullet Radius: 8.125mm

Mean Velocity: 378.29m/s Mach Number: 1.11	Bullet Radius (m): 0.008125m CD:
Time Step (ms)	Velocity m/s
6.5ms	392m/s
10ms	392m/s
20ms	386m/s
30ms	378m/s
40ms	372m/s
50ms	366m/s
55ms	362m/s

Bullet 10 Bullet weight: 24.28g Bullet weight (kg): 0.02428kg Mean Velocity: 383.5m/s Mach Number: 1.13	Charge weight: 9g Bullet Diameter 90°: 16.26mm Bullet Radius: 8.13mm Bullet Radius (m): 0.00813m CD:
Time Step (ms)	Velocity m/s
7ms	395m/s
10ms	394m/s
20ms	388m/s
30ms	383m/s
40ms	373m/s
50ms	368m/s

Bullet 11 Bullet weight: 24.12g Bullet weight (kg): 0.02412kg Mean Velocity: 356.29m/s Mach Number: 1.05	Charge weight: 9g Bullet Diameter 90°: 16.27mm Bullet Radius: 8.135mm Bullet Radius (m): 0.008135m CD:
Time Step (ms)	Velocity m/s

7ms	367m/s
10ms	367m/s
20ms	363m/s
30ms	357m/s
40ms	353m/s
50ms	345m/s
58ms	342m/s

Bullet 12 Bullet weight: 24.09g Bullet weight (kg): 0.02409kg Mean Velocity: 376.57m/s Mach Number: 1.11	Charge weight: 9.5g Bullet Diameter 90°: 16.26mm Bullet Radius: 8.13mm Bullet Radius (m): 0.00813m CD:
Time Step (ms)	Velocity m/s
8ms	393m/s
10ms	391m/s
20ms	383m/s
30ms	376m/s
40ms	371m/s
50ms	363m/s
56ms	359m/s

Bullet 13 Bullet weight: 24.08g Bullet weight (kg): 0.02408kg Mean Velocity: 418.66m/s Mach Number: 1.23	Charge weight: 10g Bullet Diameter 90°: 16.24mm Bullet Radius: 8.12mm Bullet Radius (m): 0.00812m CD:
Time Step (ms)	Velocity m/s
5ms	443m/s
10ms	432m/s

20ms	422m/s
30ms	414m/s
40ms	404m/s
50ms	397m/s

Bullet 14 Bullet weight: 24.21g Bullet weight (kg): 0.02421kg Mean Velocity: 323.13m/s Mach Number: 0.95	Charge weight: 7.5g Bullet Diameter 90°: 16.28mm Bullet Radius: 8.14mm Bullet Radius (m): 0.00814m CD:
Time Step (ms)	Velocity m/s
6ms	333m/s
10ms	333m/s
20ms	330m/s
30ms	325m/s
40ms	321m/s
50ms	318m/s
60ms	314m/s
63ms	311m/s

Bullet 15 Bullet weight: 24.29g Bullet weight (kg): 0.02429kg Mean Velocity: 440.43m/s Mach Number: 1.3	Charge weight: 12g Bullet Diameter 90°: 16.23mm Bullet Radius: 8.115mm Bullet Radius (m): 0.008115m CD: Shot at block of wood 20m down range
Time Step (ms)	Velocity m/s
6ms	485m/s
10ms	482m/s
20ms	468m/s (hit target---> perforated--->)

21ms	425m/s (first reading after perforation)
30ms	415m/s
40ms	408m/s
48ms	400m/s

Bullet 16 Bullet weight: 24.15g Bullet weight (kg): 0.02415kg	Charge weight: 6g Bullet Diameter 90°: 16.23mm Bullet Radius: 8.115mm Bullet Radius (m): 0.008115m
Time Step (ms)	Velocity m/s
5ms	233
15ms	231
25ms	231
30ms	231
40ms	231
50ms	230

Bullet 17 Bullet weight: 24.26g Bullet weight (kg): 0.02426 kg	Charge weight: 5g Bullet Diameter 90°: 16.26mm Bullet Radius: 8.13mm Bullet Radius (m): 0.00813m
Time Step (ms)	Velocity m/s
10ms	278
20ms	276
30ms	273
40ms	271
50ms	269
60ms	267
70ms	266
80ms	264

Bullet 18 Bullet weight: 24.16g Bullet weight (kg): 0.02416kg	Charge weight: 4g Bullet Diameter 90°: 16.22mm Bullet Radius: 8.11mm Bullet Radius (m): 0.00811m
Time Step (ms)	Velocity m/s
10ms	235
20ms	235
30ms	233
40ms	233
50ms	231
60ms	230
70ms	229
80ms	227
90ms	225

Bullet 19 Bullet weight: 24.36g Bullet weight (kg): 0.02436kg	Charge weight: 6g Bullet Diameter 90°: 16.22mm Bullet Radius: 8.11mm Bullet Radius (m): 0.00811m
Time Step (ms)	Velocity m/s
10ms	300
20ms	297
30ms	295
40ms	292
50ms	289
60ms	287
70ms	284

Bullet 20 Bullet weight: 23.97g	Charge weight: 3g Bullet Diameter 90°: 16.19mm

Bullet weight (kg): 0.02397kg	Bullet Radius: 8.095mm Bullet Radius (m): 0.008095m
Time Step (ms)	Velocity m/s
10ms	200
20ms	200
30ms	200
40ms	199
50ms	197
60ms	197
70ms	197
80ms	196
90ms	195
100ms	194
110ms	193

Bullet 21 Bullet weight: 24.29g Bullet weight (kg): 0.2429kg	Charge weight: 1.5g Bullet Diameter 90°: 16.22mm Bullet Radius: 8.11mm Bullet Radius (m): 0.00811m
Time Step (ms)	Velocity m/s
15ms	116
20ms	116
30ms	116
40ms	115
50ms	114
60ms	114
70ms	113
80ms	113
90ms	113
100ms	113

110ms	112
120ms	112
130ms	112

B. Maths Data Final Revision all 21 Bullets Fired

Bullet 1

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
457	456	0.01	100	2.418	0.09294244	1.342972171
456	447	0.01	900	21.762	0.840154765	1.340033501
447	434	0.01	1300	31.434	1.262916905	1.313585471
434	426	0.01	800	19.344	0.824436097	1.275382762
426	422	0.008	500	12.09	0.534807239	1.251873402

Bullet 2

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
446	442	0.01	400	9.652	0.392417913	1.310646801
442	431	0.01	1100	26.543	1.098769754	1.298892121
431	421	0.01	1000	24.13	1.050519236	1.266566752
421	412	0.01	900	21.717	0.99091606	1.237180052

412	403	0.008	1125	27.14625	1.293351705	1.210732023

Bullet 3

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
472	468	0.01	400	9.64	0.349940545	1.38705222
468	457	0.01	1100	26.51	0.978856996	1.37529754
457	448	0.01	900	21.69	0.839901544	1.342972171
448	438	0.01	1000	24.1	0.971096172	1.316524141
438	432	0.005	1200	28.92	1.219133584	1.287137442

Bullet 4

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
463	461	0.01	200	4.806	0.180196483	1.360604191
461	452	0.01	900	21.627	0.817935307	1.354726851
452	442	0.01	1000	24.03	0.945369153	1.328278821
442	432	0.01	1000	24.03	0.988629939	1.298892121
432	427	0.006	833.33333	20.02499992	0.86244132	1.269505422

Bullet 5

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
464	462	0.01	200	4.828	0.18046397	1.363542861
462	451	0.01	1100	26.554	1.001163958	1.357665521
451	443	0.01	800	19.312	0.764070401	1.325340151
443	432	0.01	1100	26.554	1.088884223	1.301830791
432	427	0.006	833.33333	20.11666659	0.867456551	1.269505422

Bullet 6

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
346	346	0.01	0	0	0	1.016779805
346	343	0.01	300	7.29	0.488838615	1.016779805
343	337	0.01	600	14.58	0.994854247	1.007963796
337	319	0.01	1800	43.74	3.091784041	0.990331776
319	301	0.01	1800	43.74	3.450544135	0.937435717

301	288	0.01	1300	31.59	2.799025203	0.884539657
288	282	0.005	1200	29.16	2.822232042	0.846336948

Bullet 7

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
363	362	0.01	100	2.465	0.149621072	1.066737195
362	358	0.01	400	9.86	0.601795397	1.063798525
358	353	0.01	500	12.325	0.769148084	1.052043845
353	344	0.01	900	22.185	1.42396433	1.037350495
344	339	0.01	500	12.325	0.833027102	1.010902466
339	334	0.01	500	12.325	0.85778139	0.996209116

Bullet 8

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
348	347	0.01	100	2.424	0.159501612	1.022657145
347	343	0.01	400	9.696	0.641689016	1.019718475
343	338	0.01	500	12.12	0.820928489	1.007963796

338	332	0.01	600	14.544	1.01447515	0.993270446
332	329	0.01	300	7.272	0.525737131	0.975638426
329	325	0.01	400	9.696	0.713825008	0.966822416
325	323	0.002	1000	24.24	1.828760537	0.955067736

Bullet 9

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
392	392	0.01	0	0	0	1.151958624
392	386	0.01	600	14.538	0.760426173	1.151958624
386	378	0.01	800	19.384	1.045666796	1.134326604
378	372	0.01	600	14.538	0.817797147	1.110817244
372	366	0.01	600	14.538	0.844390446	1.093185224
366	362	0.005	800	19.384	1.163069739	1.075553205

Bullet 10

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
395	394	0.01	100	2.428	0.12492365	1.160774633

394	388	0.01	600	14.568	0.75335151	1.157835963
388	383	0.01	500	12.14	0.647359327	1.140203944
383	373	0.01	1000	24.28	1.328743976	1.125510594
373	368	0.01	500	12.14	0.700472673	1.096123894

Bullet 11

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
367	367	0.01	0	0	0	1.078491875
367	363	0.01	400	9.648	0.574329755	1.078491875
363	357	0.01	600	14.472	0.880585347	1.066737195
357	353	0.01	400	9.648	0.606955727	1.049105175
353	345	0.01	800	19.296	1.241578063	1.037350495
345	342	0.008	375	9.045	0.609293482	1.013841136

Bullet 12

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
393	391	0.01	200	4.818	0.250421648	1.154897293

391	383	0.01	800	19.272	1.011960233	1.149019954
383	376	0.01	700	16.863	0.922842243	1.125510594
376	371	0.01	500	12.045	0.683945173	1.104939904
371	363	0.01	800	19.272	1.124007326	1.090246554
363	359	0.006	666.66667	16.06000008	0.978413569	1.066737195

Bullet 13

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
443	432	0.01	1100	26.488	1.0861778	1.301830791
432	422	0.01	1000	24.08	1.038360588	1.269505422
422	414	0.01	800	19.264	0.870524051	1.240118722
414	404	0.01	1000	24.08	1.130615688	1.216609363
404	397	0.01	700	16.856	0.831095631	1.187222663

Bullet 14

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
333	333	0.01	0	0	0	0.978577096

333	330	0.01	300	7.263	0.524505483	0.978577096
330	325	0.01	500	12.105	0.890142157	0.969761086
325	321	0.01	400	9.684	0.734193465	0.955067736
321	318	0.01	300	7.263	0.564453844	0.943313057
318	314	0.01	400	9.684	0.766872204	0.934497047
314	311	0.003	1000	24.21	1.966336989	0.922742367

Bullet 15

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
485	482	0.01	300	7.287	0.24960858	1.42525493
482	468	0.01	1400	34.006	1.179385248	1.41643892
468	425	0.001	43000	1044.47	38.42363793	1.37529754
425	415	0.01	1000	24.29	1.083537314	1.248934732
415	408	0.01	700	17.003	0.795469584	1.219548033
408	400	0.008	1000	24.29	1.175713231	1.198977343

Bullet 16

467

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
233	231	0.01	200	4.83	0.716852007	0.6847101
231	231	0.01	0	0	0	0.67883276
231	231	0.005	0	0	0	0.67883276
231	231	0.01	0	0	0	0.67883276
231	230	0.01	100	2.415	0.364659383	0.67883276

Bullet 17

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
278	276	0.01	200	4.852	0.503989368	0.816950248
276	273	0.01	300	7.278	0.766980039	0.811072908
273	271	0.01	200	4.852	0.522619575	0.802256899
271	269	0.01	200	4.852	0.530361982	0.796379559
269	267	0.01	200	4.852	0.538277723	0.790502219
267	266	0.01	100	2.426	0.273186006	0.784624879
266	264	0.01	200	4.852	0.550487793	0.781686209

Bullet 18

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
235	235	0.01	0	0	0	0.69058744
235	233	0.01	200	4.832	0.705863553	0.69058744
233	233	0.01	0	0	0	0.6847101
233	231	0.01	200	4.832	0.71803339	0.6847101
231	230	0.01	100	2.416	0.365260347	0.67883276
230	229	0.01	100	2.416	0.368443428	0.67589409
229	227	0.01	200	4.832	0.743336602	0.67295542
227	225	0.01	200	4.832	0.756492746	0.66707808

Bullet 19

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
300	297	0.01	300	7.308	0.655066796	0.881600987
297	295	0.01	200	4.872	0.445578203	0.872784978
295	292	0.01	300	7.308	0.677460633	0.866907638
292	289	0.01	300	7.308	0.691452566	0.858091628
289	287	0.01	200	4.872	0.470588328	0.849275618
287	284	0.01	300	7.308	0.715754854	0.843398278

Bullet 20

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
200	200	0.01	0	0	0	0.587733992
200	200	0.01	0	0	0	0.587733992
200	199	0.01	-100	2.397	0.485227719	0.587733992
199	197	0.01	-200	4.794	0.980233264	0.584795322
197	197	0.01	0	0	0	0.578917982

197	197	0.01	0	0	0	0.578917982
197	196	0.01	-100	2.397	0.500118754	0.578917982
196	195	0.01	-100	2.397	0.505235026	0.575979312
195	194	0.01	-100	2.397	0.51043021	0.573040642
194	193	0.01	-100	2.397	0.51570594	0.570101972

Bullet 21

Initial Velocity	Final Velocity	Time Step	Acceleration	Drag Force	CD	Mach NO
116	116	0.01	0	0	0	0.340885715
116	116	0.01	0	0	0	0.340885715
116	115	0.01	-100	2.429	1.456267285	0.340885715
115	114	0.01	-100	2.429	1.481703788	0.337947045
114	114	0.01	0	0	0	0.335008375
114	113	0.01	-100	2.429	1.507812603	0.335008375
113	113	0.01	0	0	0	0.332069705
113	113	0.01	0	0	0	0.332069705
113	113	0.01	0	0	0	0.332069705
113	112	0.01	-100	2.429	1.534617636	0.332069705
112	112	0.01	0	0	0	0.329131035
112	112	0.01	0	0	0	0.329131035

C. Averages of all 12g (charge) Bullets Modelled with Predicated Range

*****Using the 19 bore bullet Mach data*****

Bullet Number-Weight (g)/ Diameter	Charge Size	0m (muzzle velocity)	25m	50m	75m	100m	125m	150m	175m	Ground Impact distance and velocity

(mm)										
Bullet 1- 24.18g/ 16.26mm	12g	457m/s	407m/s	371 m/s	335 m/s	285 m/s	266 m/s	252 m/s	239 m/s	189m @233m/s
Bullet 2- 24.13g/ 16.20mm	12g	446m/s	400 m/s	364 m/s	323 m/s	280 m/s	263 m/s	249 m/s	237 m/s	186m@ 232m/s
Bullet 3- 24.10g/ 16.20mm	12g	472m/s	423 m/s	385 m/s	350 m/s	299 m/s	272 m/s	257 m/s	244 m/s	193m@ 235m/s
Bullet 4- 24.03g/ 16.25mm	12g	463m/s	412 m/s	375 m/s	340 m/s	288 m/s	267 m/s	253 m/s	240 m/s	190m@ 233m/s
Bullet 5- 24.14g/ 16.24mm	12g	464m/s	413 m/s	377 m/s	342 m/s	290 m/s	268 m/s	254 m/s	241 m/s	190m@ 234m/s
Bullet 6- 24.27g/ 16.23mm	12g	492m/s	462 m/s	412 m/s	376 m/s	341 m/s	290 m/s	268 m/s	254 m/s	203m@ 240 m/s
Bullet 7- 24.09g/ 16.23mm	12g	494m/s	467 m/s	416 m/s	380 m/s	345 m/s	293 m/s	269 m/s	255 m/s	204m@ 240 m/s
Bullet 8- 24.27g/ 16.25mm	12g	476m/s	430 m/s	390 m/s	354 m/s	304 m/s	274 m/s	258 m/s	245 m/s	195m@ 236 m/s
Bullet 9- 24.41/ 16.28mm	12g	420m/s	383 m/s	348 m/s	296 m/s	271 m/s	256 m/s	243 m/s	232 m/s	181m@ 229 m/s
Bullet 10-	12g	487m/s	450 m/s	402 m/s	366 m/s	327 m/s	281 m/s	263 m/s	249 m/s	199m@ 238 m/s

24.13g/ 16.28mm										
[redacted]										
Model of Averaged Bullet- 24.18g/ 16.24mm	12g	467m/s	416 m/s	380 m/s	345 m/s	293 m/s	269 m/s	255 m/s	242 m/s	191m@ 234 m/s

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