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Indirect Fire:

A technical analysis of the employment, accuracy, and effects of indirect-fire artillery weapons

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January 2017



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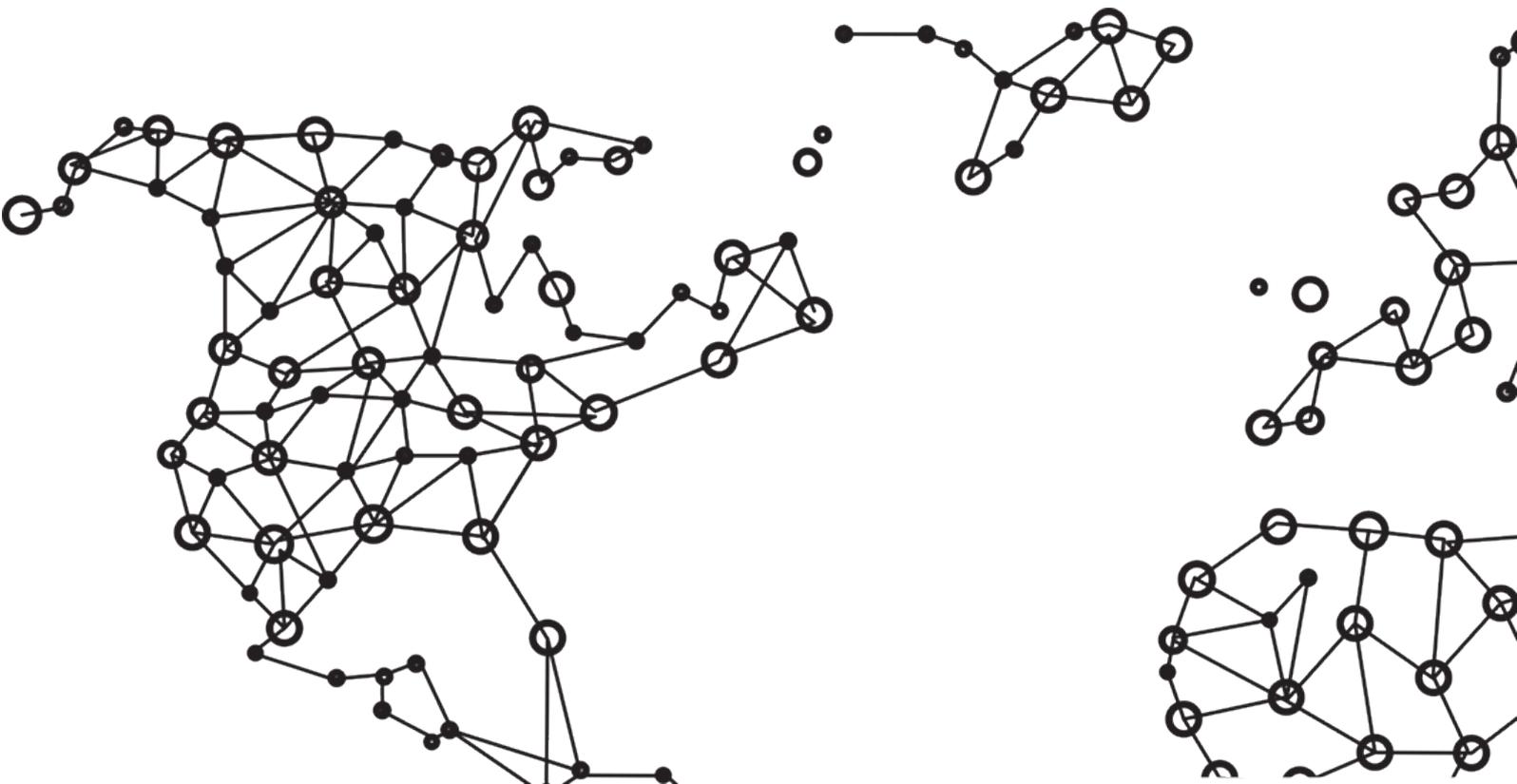
CREDITS

Prepared by Armament Research Services (ARES) for the
International Committee of the Red Cross (ICRC)

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BIBLIOGRAPHIC INFORMATION

Dullum, Ove S., Kenton Fulmer, N.R. Jenzen-Jones, Chris Lincoln-Jones & David G. Palacio. 2017.
*Indirect Fire: A technical analysis of the employment, accuracy, and effects of indirect-fire artillery
weapons* (N.R. Jenzen-Jones, ed.). Perth: Armament Research Services (ARES).



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ABOUT **THIS REPORT**

This report was commissioned by the International Committee of the Red Cross (ICRC), as part of its work to foster a better understanding of the effects of explosive weapons when used in populated areas. It is intended exclusively to provide background information on the technical characteristics of explosive weapons and other factors relevant to their effects. It is meant to be a general reference document. This report reflects the analysis and views of the authors and not necessarily those of the ICRC.

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The following authors have contributed to the report in their personal capacity. Their views do not necessarily reflect those of the Norwegian Defence Research Establishment, the British Army, or the United States Marine Corps.

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Mr. Jenzen-Jones served as both an author and editor for this report.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to those who assisted with the production of this background report. At the ICRC, we would like to extend our thanks to Kathleen Lawand and Thomas de Saint Maurice, both of whom have made possible the publication of this report. Thanks are also due to colleagues at Armament Research Services (ARES), especially Stefan Elliott, Kenton Fulmer, Yuri Lyamin, Graeme Rice, and Jean Yew, without whom this report would be both less accurate and less precise.

The authors are also thankful for the valuable input provided by a number of current and former senior artillery officers, whose names are withheld on grounds of confidentiality and security.

All errors remain those of the authors and editor.

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Remember, all arms and munitions are dangerous. Treat all firearms as if they are loaded, and all munitions as if they are live, until you have personally confirmed otherwise. If you do not have specialist knowledge, never assume that arms or munitions are safe to handle until they have been inspected by a subject matter specialist. You should not approach, handle, move, operate, or modify arms and munitions unless explicitly trained to do so. If you encounter any unexploded ordnance (UXO) or explosive remnants of war (ERW), always remember the 'ARMS' acronym:

AVOID the area

RECORD all relevant information

MARK the area from a distance to warn others

SEEK assistance from the relevant authorities

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In order to present a politically-neutral report, the technical characteristics and/or makes and models of certain arms and munitions have been described in a generic or generalised manner. As such, the figures may not represent specific weapon systems or ordnance which may be employed or encountered. For specific technical information, please contact ARES.

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Abbreviations & Acronyms

ATACMS	Army Tactical Missile System
BB	Base bleed
BDA	Battle damage assessment
BDAR	Battle damage assessment report
CDE	Collateral damage estimate
COC	Combat operations centre
COP	Combat outposts
DPICM	Dual purpose improved conventional munitions
ECR	Estimated casualty radius
FASCAM	Family of scatterable mines
FCS	Fire control system
FDC	Fire direction centre
FPF	Final protective fire
GMLRS	Guided Multiple Launch Rocket System
GPS	Global Positioning System
HIMARS	High Mobility Artillery Rocket System
JFO	Joint fires observer
JTAC	Joint terminal attack controller
LOAC	Laws of armed conflict
MBRL	Multiple-barrel rocket launcher
MET	Meteorological (data)
MRSI	Multiple rounds, simultaneous impact
NEW	Net explosive weight
PB	Patrol bases
PMCS	Preventative maintenance checks and services
RAP	Rocket assisted projectile
ROE	Rules of engagement
RPV	Remotely piloted vehicles

SOP	Standard operating procedure
SOSRA	Suppress, obscure, secure, reduce, and assault
T&R	Training and readiness
T/E	Table of equipment
T/O	Table of organisation
TOC	Tactical operations centre
TQC2	Trained, qualified, competent, and current
UAS	Unmanned aerial systems

Introduction

In current usage, artillery systems primarily exist to deliver ‘indirect fires’ onto targets. Direct fires are employed when the target is within line of sight, and the weapon can be aimed directly at the target. These are often employed by tanks, field guns, shoulder-fired infantry weapons, and many air-delivered munitions¹. In contrast, indirect fires are most commonly² employed when the target is not within line of sight. This is generally due to the target being obscured by geographic or structural features in defilade, or by the curvature of the earth over long distances³. Indirect fires may be commonly employed to fire into defilade, out of defilade, or over forces or structures other than the target, including friendly forces (See Fig. I). Weapons systems which typically employ this method of engagement include artillery guns/howitzers, mortars, rocket systems, and guided missiles (Cross et al., 2016).

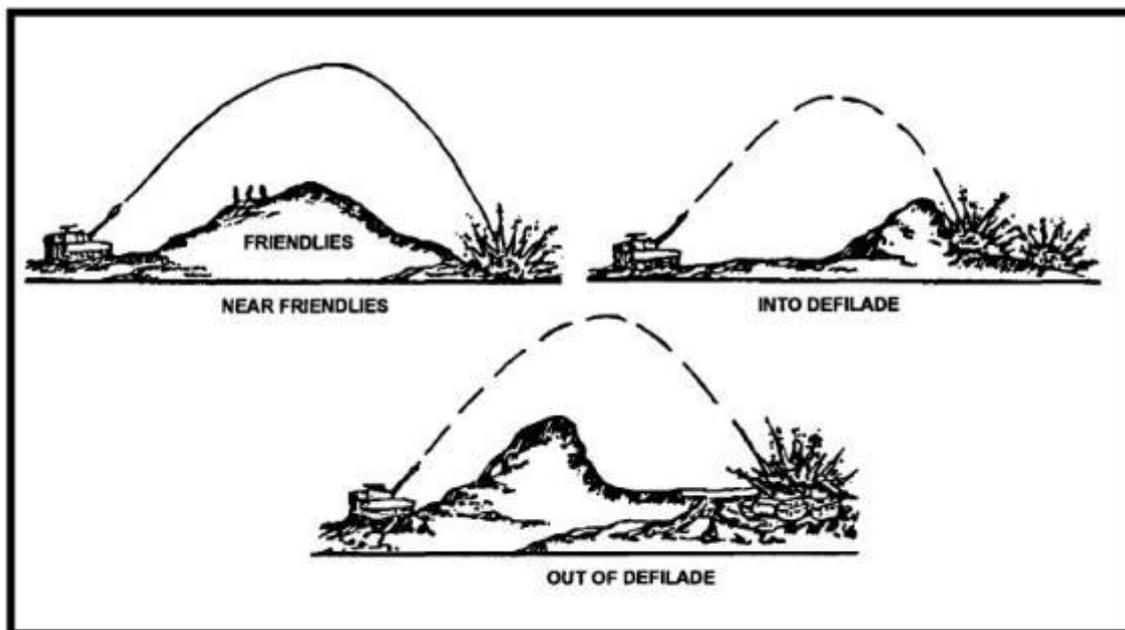


Fig. I Typical scenarios for the employment of indirect fires from artillery systems (source: USMC).

Artillery systems have played a critical role in modern warfare. Estimates place the total number of casualties inflicted by artillery during the conflicts of the 20th century at between 50 and 80 per cent (Bellamy & Zajtchuk, 1991). **Section 1** introduces the three broad types of indirect-fire artillery systems – guns, mortars, and rockets – and discusses some general characteristics of these and of artillery systems more broadly.

Usually the characteristics of indirect-fire systems are exploited to cause casualties in the first moments of an engagement, and thereafter to suppress and disorientate an adversary in order to

¹ NATO targeting policy, in particular, is very air-centric. See Cross et al., 2016 for further discussion of air-delivered munitions.

² In some cases, the term ‘indirect fire’ may be used to describe fires delivered when the target is visible from the weapon system, but where the direct ‘vision link’ between the operator and target is not used for aiming (Ryan, 1982).

³ Without accounting for atmospheric refraction, the formula used to calculate the apparent horizon is $d \approx 3.57 \sqrt{h}$; the distance from a point at an average observer’s eye-level (1.70 m) to the horizon is approximately 4.7 km (Young, 2012).

allow freedom of action for one's own forces. **Section 2** discusses the primary considerations affecting the employment of indirect-fire systems, including their role, operational considerations and doctrine, and some discussion of sustainability and survivability⁴. It devotes a substantial subsection to a discussion of the targeting process, examining how this affects the use of indirect-fire artillery systems, and covering some measures of effectiveness. Much of the policy and procedure for targeting has been skewed towards the application of direct fire.

To ensure relative accuracy of indirect-fire weapon systems, military forces need to ensure operators and commanders are conversant with the correct employment of indirect-fire weapon systems, including their limitations and specific characteristics when employed in populated areas; regularly determine the accuracy and precision that fire units and systems can deliver under combat conditions (see Section 3 for a further discussion of accuracy and precision); and conduct realistic, scenario-based training simulating the use of indirect-fire weapon systems in populated areas in order to better understand and anticipate their effects and the risks posed to the civilian population and civilian objects.

Most conventional artillery systems are designed to affect an area and the dispersion (or imprecision) within that area is exploited to produce the desired outcome (i.e. area effects)⁵. The artillery problem is as follows: in order to improve accuracy (with the aim to impact the desired area), conventional artillery systems require that the impact of rounds be observed and the fall of shot adjusted. Even though great effort is made to calculate the effect of environmental and ballistic variables, an unguided artillery projectile will not reliably strike the exact point at which it is aimed. Although artillerymen strive for first round accuracy, this will still be measured in tens of metres, and in deliberate targeting or combat engagements this introduces a degree of uncertainty when assessing the safety of friendly forces and non-combatants. Properly employed, artillery gun and mortar projectiles and rockets land in a predictable area (accuracy) in a non-predictable fashion (precision), and in common with small arms fire (especially machine guns), the employment of artillery systems yields a 'beaten zone' or field of fire into which rounds will fall. This zone is generally cigar-shaped with the long axis falling along the line from the gun to the target, as deviation tends to occur in range rather than azimuth. The length and breadth of the zone is range dependant, as with greater range, external factors have more time to exert influence on the projectile flight. **Section 3** discusses these factors in greater detail.

Different types of munitions can generally be employed by indirect-fire weapon systems. The type of effect delivered to the target will vary according to munition type, and will be directly affected by the selection of fuze and fuzing options. **Section 4** discusses the types and effects of explosive munitions and fuzes. Weapon effects are contextual and therefore are influenced by the target, timing, platform, weather, natural and man-made geography, vulnerability of the surrounding population, and other factors; a weapon can be employed in different ways with varying effects. It is

⁴ Much of Section 2 draws from US and UK sources, as well as NATO publications. Some considerations regarding the employment of indirect-fire weapon systems by less technologically advanced forces have been included throughout the text, sometimes in footnotes.

⁵ Precision guided munitions (including guided projectiles and guided rockets, often known as guided missiles or simply 'missiles') are capable of striking their target with much greater precision than their unguided counterparts, even when employed in indirect-fire roles. PGMs are briefly addressed on p.85 of this report.

therefore vital to understand how explosive weapons functions, why a particular weapon is selected to engage a specific target, how the environment in which it is used influences its impact, and how these factors contribute to collateral damage concerns (Cross et al., 2016).

Finally, it should be noted that this report is intended only as a basic guide to the key considerations surrounding the employment of indirect-fire artillery. The practices used for reference in this paper are based on what is available in unclassified documents and open source material (notably UK, US, and NATO doctrine). This report also draws on author interviews with current and former senior artillery officers, who offered insights into contemporary practice in current and recent conflicts.

Complementing this set of standards are the methods of operating indirect-fire artillery systems which consist of the organisation, deployment, and operating procedures. Training is the critical 'glue' that binds all this together. It is important to note that when employed in populated areas, indirect-fire systems may have indiscriminate effects due to their so-called 'wide area effects'.

The International Committee of the Red Cross (the ICRC) considers the following weapons as cause for concerns when used in populated areas because of their wide impact area (ICRC, 2015):

Weapons with a large destructive radius have a large blast, fragmentation range or effect, regardless of guidance. They include large bombs, large calibre mortars and rockets, large guided missiles, and heavy artillery projectiles.

Weapons that have an inaccurate delivery system are typically unguided or are indirect-fire weapons where the target is not observed by the platform firing the weapon. These encompass mortars, rockets and artillery.

Weapons systems designed to deliver multiple munitions over a wide area (fired en masse or in salvos). This includes multiple launch rocket systems.

This background report concerns itself primarily with land-based indirect-fire artillery systems, which constitute the vast majority in historical and present usage. Naval systems are also examined, however air-delivered weapons which are used to engage targets beyond visual range are outside the scope of this report.



SECTION 1

Indirect-fire Weapon Systems

Ove Dullum, N.R. Jenzen-Jones & David Palacio

Historical Background

The concept of employing standoff weapon systems to inflict maximum damage on enemy forces from afar is one that dates back to ancient times with weapons such as catapults and trebuchets featuring prominently throughout world history. Not only did standoff weapon systems increase the survivability of one's forces, they were oftentimes the deciding factor in successfully prosecuting siege warfare (US Army, 1984). By the time of Henry VIII, the term 'artillery' had come to encompass a broad range of weapon systems; a charter bestowed upon the Gylde of Saint George in 1537 instructed they become: "*the overseers of the science of artillery... to witt, long bowes, cross bowes and hand gonnies for the better encrease of the defence of our realme*" (Wilson, 1945). In modern usage, the term is generally applied to indirect-fire systems, especially guns, mortars, and rockets. It may also include some air-defence systems, however these are beyond the scope of this report.

Artillery was used to devastating effect following advances in gunpowder and cannon technology through the Middle Ages and into the Modern period. By the time of Gustavus Adolphus (1594-1632), artillery had begun to become mobile, with the use of light guns allowing for battlefield flexibility. Another critical step forward was embodied in the works of great thinkers like Niccolò Tartaglia (1499-1577), Galileo Galilei (1564-1642), and Benjamin Robins (1707-1751), each of whom contributed significantly to the understanding of ballistics – the science of the projectile (Ryan, 1982). The early Modern period up until the First World War saw the advent of a number of key improvements to gun, mortar, and rocket systems, which are covered under the respective subsections, below.

During World War I, full-scale trench warfare and the improvement and common use of early machine guns saw artillery once again take centre stage as one of the primary means to wage war and as a critical tool in attempting to break the enemy's will. Artillery guns and mortars dominated the First World War, and were responsible for some sixty to seventy per cent of casualties over the course of the conflict (Kramer, 2007; Manucy, 2011).

Whilst the employment of artillery systems has a long and storied history, these weapons are continuing to benefit significantly from recent advancements in technology. The new generation of artillery systems offer the ability to reach farther, faster, and with greater efficiency, accuracy, and precision relative to their predecessors. In most modern self-propelled howitzers, for example, cannoneers have been replaced by automatic loaders, in much the same way as similar advancements have benefitted main battle tanks. Hydraulic systems that assist in the loading process are increasingly installed in towed artillery systems. In new generation systems, the firing process has also been improved, and made more accurate and efficient through the increasing use of integrated fire control systems (FCS), incorporating ballistic computers, self-locating Global Positioning System (GPS)⁶ units mounted on weapon systems, supported by fully-digitised systems used to facilitate the conduct of fire missions from a separate fire direction centre (FDC) and allowing for the monitoring of artillery units through a broader battlefield management system (BMS). Although these technologically advanced systems are increasingly common on the battlefield, especially among western armed forces, not all are yet in widespread use by armed forces globally (Foss & O'Halloran, 2014).

Since the successful employment of artillery often depends directly on the ability to reach deep into contested or enemy-held territory, *rocket* artillery has taken on an increasing importance on the post-WWII battlefield. These systems may offer a more-than-double increase over the range of artillery gun systems (Ryan, 1982).

⁶ Or equivalents, such as GLONASS. Targeting is enabled by understanding the relative positions of the gun and the target, with such systems greatly aiding in determining the former.

Whilst precision guided munitions (PGMs) may offer significant new capabilities to artillery units, they also find themselves at odds with the basic tenet of artillery employment and unguided munitions therefore remain the norm in modern conflict⁷. Artillery fire is generally employed in order to achieve area effects and, to that end, is most effective when it is concentrated *en masse* and when munitions are launched in salvo.

The Purpose of Artillery

Artillery weapons are designed to provide fire support for armour and infantry by launching or firing munitions at greater distances than small arms. Artillery systems are most often employed in the indirect-fire role and predominantly make use of unguided munitions, although limited numbers of guided artillery munitions are in use. On occasion, some artillery systems (most commonly artillery guns) may be employed in a direct-fire role (Cross et al., 2016). Broadly speaking, artillery is an area effect weapon. It is not designed to destroy individual targets such a vehicle or a single combatant, but to inflict damage across a wider area, often several hectares in size. Similarly, artillery systems are generally not intended to be employed individually, but rather to operate as a unit or ‘battery’ and deliver salvo fire *en masse*⁸.

Artillery is intended to support manoeuvre forces such as infantry and armoured forces. It is commonly employed to create a barrage of covering fire ahead of an allied advance, in order to ‘soften’ the enemy forces and to restrict the freedom of enemy forces in employing their weapons against the advancing friendly units. Another important task of artillery is to destroy or suppress enemy artillery, referred to as counter-fire or counter-battery fire. Artillery is superior to infantry or armoured formations’ weapons in terms of range, and this range has steadily increased over time. At the beginning of the 20th century, the typical range of an artillery piece was a few kilometres, but the typical range of modern artillery can be 30 – 40 km, depending on system type. Moreover, many artillery weapon systems are considered ‘all weather’ capable, and offer greatly increased availability compared to other fire support options, such as close air support (CAS). Technological advances and changes in doctrine have significantly increased the responsiveness and flexibility of modern artillery units (see *Doctrine & Deployment*, Section 2 for further details).

⁷ Unless otherwise indicated, analysis of artillery systems in this report assumes the use of unguided munitions. For a brief discussion of PGMs, see p.85.

⁸ It should be noted, however, that there are a number of instances where both military and non-state actors have employed individual artillery pieces, particularly in the course of low-intensity conflicts.

Technical characteristics typical of artillery

High- and low-angle fire capability

An important characteristic of many artillery guns and some mortar systems is their ability to fire at both high and low angles. The difference between these modes of fire is illustrated in Figure 1.1.

When engaging a target at a known range from the firing element⁹, there are two methods by which these systems may strike the target; from a low-angle where the gun elevation angle is less than 45 degrees, or from a high angle with an elevation of 45 degrees or more. The low angle is preferable in many respects, as the flight time is shorter, and consequently accuracy is likely to be improved. High angle fire may be required in mountainous terrain, where the low angle trajectory may be blocked, necessitating indirect-fire techniques. Different types of artillery system will fire at differing angles when firing indirectly (see Fig 1.2). This report concerns itself with artillery pieces when employed in the indirect-fire mode.

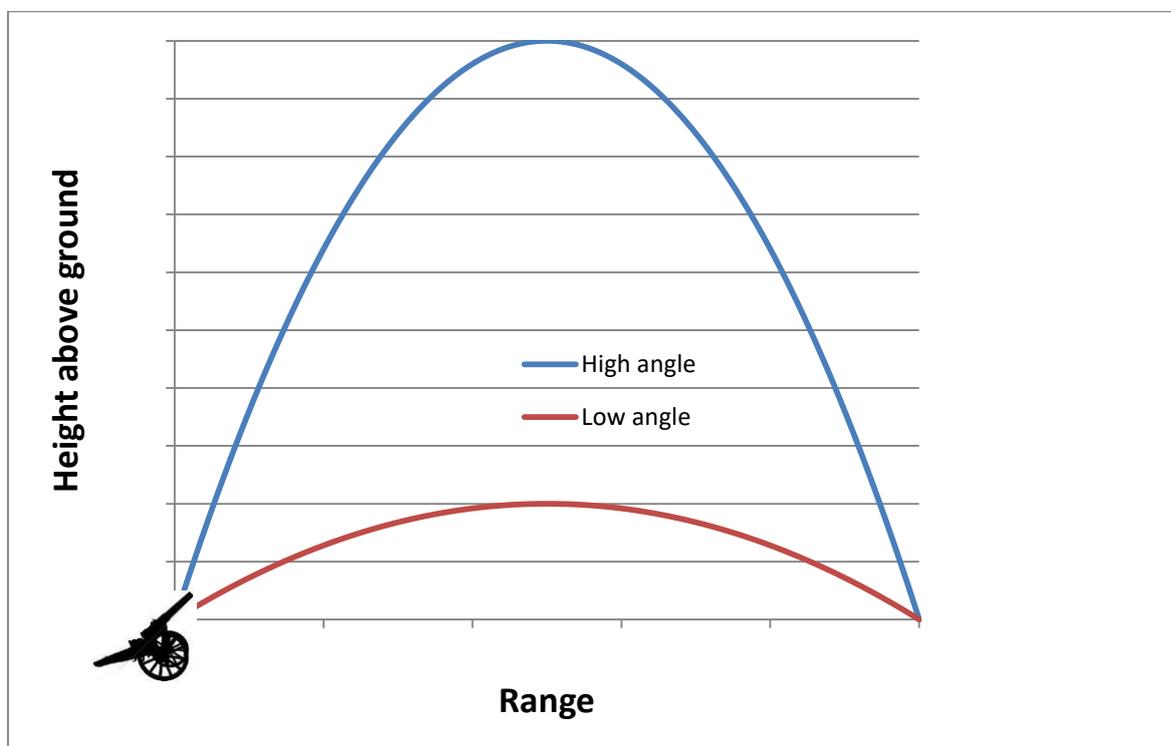


Figure 1.1 High- and low-angle fire capability (source: ARES).

⁹ The firing element is the part of an artillery unit which is equipped with the primary artillery weapon systems. Sometimes known as a 'firing agency'. Firing elements (firing platoon, firing battery, etc.) are often supported by other elements responsible for logistics, fire control, etc.

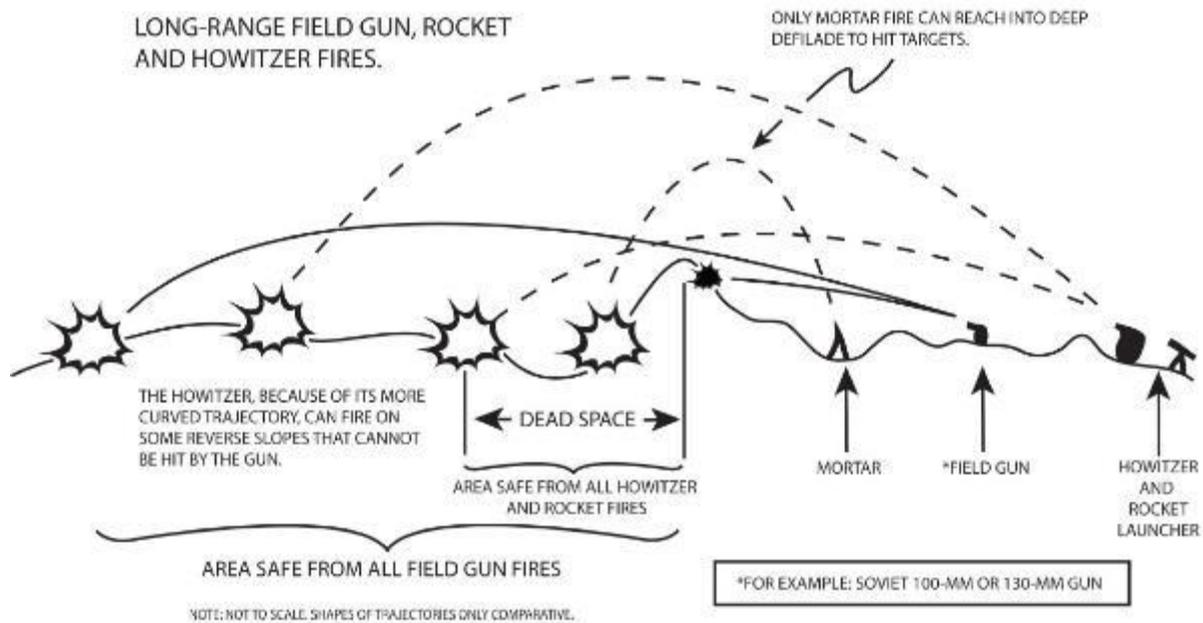


Figure 1.2 Comparative trajectories for indirect-fire artillery systems (Source: USAFAS, 2004).

Propellant charge selection

A unique property of many gun and mortar artillery systems is the option to vary the size of the propellant charge.

Most ammunition for artillery systems can be considered fixed, semi-fixed, or separate loading ammunition. Fixed ammunition design is commonly encountered in cartridges for small arms, heavy machine guns, and tank guns. In fixed ammunition, the propellant charge is entirely contained within the cartridge, with the cartridge case crimped around the projectile. This renders the propellant inaccessible to a combatant in the field. The muzzle velocity of the projectile is thus almost always beyond the control of the unit firing this ammunition.

The majority of ammunition fired by artillery systems is either semi-fixed or separate loading. Semi-fixed ammunition¹⁰ consists of two assemblies; the projectile assembly and the cartridge case assembly. The projectile assembly is comprised of the projectile and one or more fuzes, whilst the cartridge case assembly consists of the cartridge case, primer, and one or more propellant charges, as well as usually containing wadding, a distance piece, and a plug to close the open end of the case. Separate-loading ammunition consists of a projectile (fuzed or unfuzed), a primer, and one or more propellant charges. Thus, loading a round of separate-loading ammunition may require either three or four operations. Different projectiles used in a separate-loading format will often have differing minimum charge requirements. Failing to meet these requirements may result in projectiles which fail to clear the barrel of the weapon ('stickers') (US Army, 1994).

For semi-fixed and separate-loading ammunition, at least one propellant charge is essential, and this is most often supplemented by further propellant charge increments, typically contained within plastic or cloth cylinders, horseshoes, doughnuts, or other shapes. Some must be correctly oriented

¹⁰ Sometimes called 'separate ammunition'; the authors advise avoiding this term as it may be readily confused with 'separate-loading ammunition'.

before loading, whilst others may be multi-directional. Increments may be combined to achieve the desired muzzle velocity for a given gun tube elevation. This allows the artillery unit commander, in accordance with standard procedure, to vary the quantity of propellant used to fire some projectiles, and hence the range of the system (US Army, 1994; US Army, 1999).

This dramatically increases the flexibility of the artillery system, allowing targets to be engaged at ranges of, say, 3 to 30 kilometres (see Figure 1.3). By varying the propellant charge, an artillery commander can alter the range error of a projectile (see *Section 3: Accuracy & Precision*, below) and decrease the vertex height making it more difficult for hostile radar to detect battery locations and ensuring freedom of action to friendly air assets operating in the same battlespace.

With variable propellant charges, the muzzle velocity of a modern gun tube may vary between 250 and 900 m/s. In a well-trained artillery unit, the commander can typically select between four or five different total propellant charge sizes. However, some systems have enabled the commander to select from up to twelve different charges (Foss & O'Halloran, 2014). Some armed forces and, in particular, non-state armed groups may not take advantage of this capability.

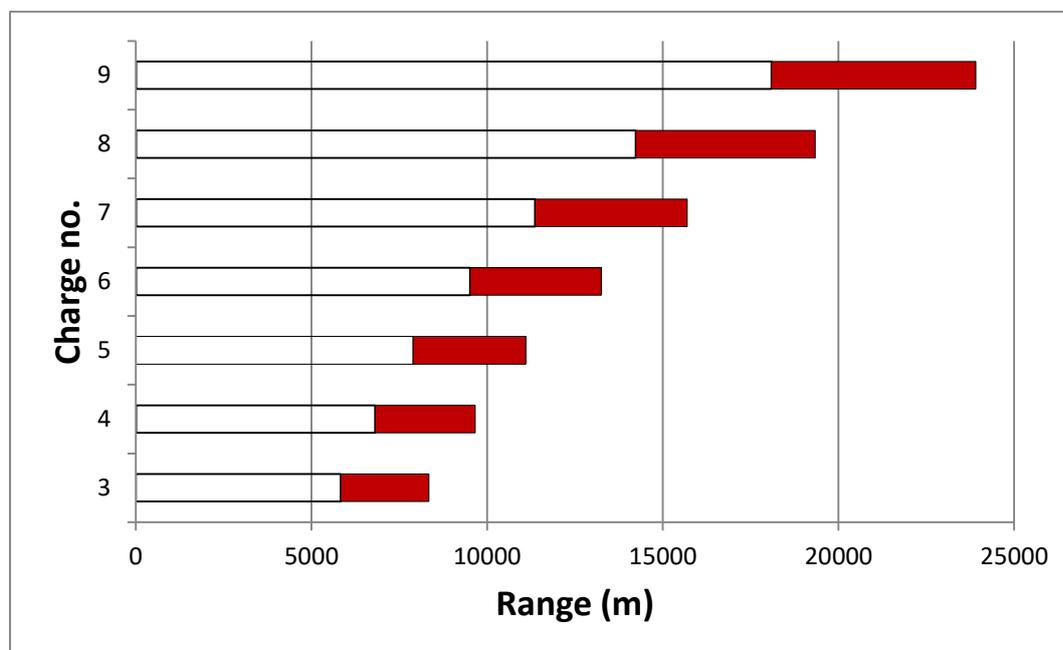


Figure 1.3 An example of the recommended range interval for each of a series of generic charges. Note that these overlap; when firing at 10 km, for instance, charge increments 5 and 6 are both possible options (source: ARES).

Auxiliary propulsion during flight

A novel technique employed by some artillery guns and mortars is the use of auxiliary propulsion methods¹¹. The first approach was the addition of auxiliary rocket propulsion, with such munitions often being described as rocket-assisted projectiles (RAP)¹². In these projectiles, a rocket motor is typically located towards the rear of the projectile and functions to give a short impulse boost early in the trajectory. This method can extend the range of such a projectile by a few kilometres, but as

¹¹ Whilst not commonplace, artillery projectiles using auxiliary propulsion methods are increasingly available to a range of military forces.

¹² 'RAP' is sometimes understood to stand for 'rocket assisted propulsion'.

range increases, accuracy and precision typically decrease. Additionally, unless the projectile is made larger overall, there is an approximate 20 per cent loss in volume with the inclusion of a RAP unit (Ryan, 1982).

Another method, first developed in the 1970s, relies on a slow-burning charge at the base of the projectile. This is known as the 'base bleed' (BB) or 'base burn' concept (see Figure 1.4). This unit does not directly increase the projectile's velocity, but the exhaust of subsonic hot gases released into the wake formed behind the projectile during flight reduces the suction force acting on the rear end of the projectile. The net drag force acting on the projectile is thereby decreased, and the projectile range is increased by some 20 to 30 per cent¹³. Payload loss for BB projectiles is less than for RAP, somewhere in the order of 10 per cent (Kubberud & Øye, 2011; Ryan, 1982).

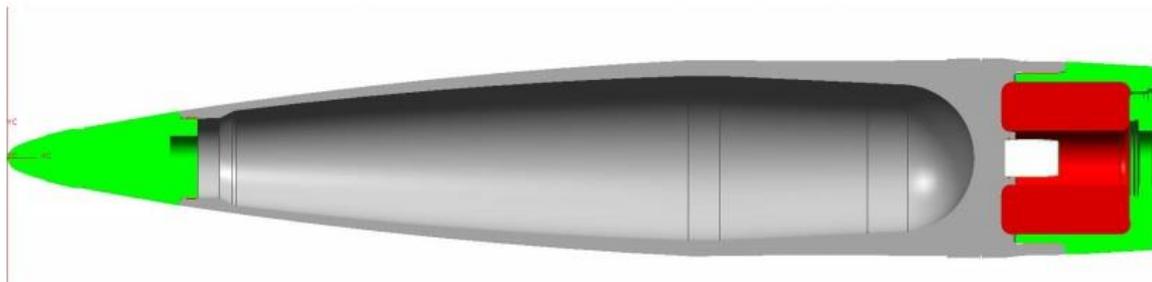


Figure 1.4 A cutaway diagram of a 155 mm artillery projectile showing the base bleed unit (source: Nammo).

The use of projectiles with auxiliary propulsion methods – particularly RAP – may necessitate additional collateral damage considerations. For example, ignition failure in the rocket motor of some projectiles could lead to their falling several kilometres short of the intended target (US Army, 1991b).

Wide selection of munitions & fuzes

Traditionally, artillery almost exclusively fired high explosive projectiles with point-detonating (impact) fuzes. Historically, the term 'shell' referred to artillery projectiles with an explosive or other filling inside a relatively thin metal projectile body. This was to differentiate these projectiles from solid 'shot' and other types. In modern usage, the term shell is often applied to any artillery projectile, however it may also be applied by some to small and medium calibre ammunition or to fired cartridge cases or other ordnance items. As such, the authors prefer the term 'projectile'.

Modern artillery gun systems can deliver a wide variety of projectiles including:

- High explosive (HE) or high explosive fragmentation (HE-FRAG)
- Incendiary¹⁴
- Obscuring smoke
- Illumination
- Landmines¹⁵ (anti-personnel and anti-vehicle)

¹³ Note that accuracy and precision general decrease with extended range as a result of greater magnitude in errors associated with aim point, flight time, and other factors. See Section 3 for further details.

¹⁴ See Protocol on Prohibitions or Restrictions on the Use of Incendiary Weapons, 10 October 1980, in force 2 December 1983, 1342 UNTS 171.

¹⁵ See Convention on the Prohibition of the Use, Stockpiling, Production and Transfer of Anti-Personnel Mines and on their Destruction, Oslo, 18 September 1997, in force 1 March 1999, 2056 UNTS 211; and Protocol on

- Cargo munitions (sometimes called cluster munitions)¹⁶
- Sensor-fuzed warheads (so-called ‘smart’ munitions)
- Information warfare payloads (primarily leaflets)
- Electronic warfare payloads (primarily radio jamming units)
- Precision guided munitions

This paper will focus on HE and HE-FRAG projectiles, which constitute the vast majority of lethal munitions employed.

See Section 4 for further details on the types of projectiles available and their effects¹⁷.

With the great majority of artillery projectiles and some rockets, a fuze is placed at the front end of the munition. The fuze is a sophisticated mechanical and/or electronic device. The role of the fuze is:

- To ensure that the crew can safely handle the munitions during the loading process;
- To arm the munition at a given time or position; and
- To function the munition at a given time or position.

A fuze may have several modes of operation, including:

- Detonation on impact, also called point initiation;
- Detonation at a certain time after firing, known as a time fuze; or
- Detonation by proximity relative to the target or other features.

With artillery guns and mortars in particular, munitions are often supplied unfuzed, or with a multifunction fuze, allowing the operator to select the appropriate function for a given target and mission. A modern fuze may have multiple options available for the operator to select, or which may be set by an automated loading system¹⁸.

A fuller discussion of fuze types and functions is included in Section 4.

Artillery guns

The earliest artillery guns – known simply as cannon – were likely constructed by arranging wrought iron staves around a white-hot metal core, over which wrought iron hoops were fitted. These latter compressed on cooling, and this ‘coopering’ gave rise to the use of the term ‘barrel’ in relation to guns. During the 15th century, cannon with trunnion began to appear. These features of the weapon are essentially stubby axles, fitted to the barrel’s point of balance, and allowing the elevation and depression of the weapon.

Building on the great works of early ballisticians, the mid-19th century saw the advent of rifled artillery pieces, allowing for significant increases in both range and accuracy. This development precipitated the reintroduction of breech-loading weapons, allowing for faster rates of fire and safer

Prohibitions or Restrictions on the Use of Mines, Booby-Traps and Other Devices as amended on 3 May 1996, Geneva, in force 3 December 1998, 2048 UNTS 93.

¹⁶ See Convention on Cluster Munitions, Dublin, 30 May 2008, in force 1 August 2010, 2688 UNTS 39.

¹⁷ Further details on the effects related to the use of explosive weapons in populated areas can be found in Cross et al., 2016.

¹⁸ Multifunction fuzes are increasingly common on the battlefield, especially amongst western armed forces, however they still account for only a small portion of fuzes used in conflict globally.

operation. By the late 19th century, an effective recoil mechanism had been introduced, which both absorbed the recoil on firing, and returned the barrel to a ready position (Ryan, 1982).

In modern usage, the term ‘cannon’ is generally used to mean an automatic gun chambered for high-velocity ammunition of at least 20 mm and no more than 57 mm in calibre¹⁹. The term ‘gun’ is broadly taken to mean a weapon which typically uses the combustion of a propellant to generate high-pressure gas in a sealed chamber in order to accelerate a projectile in a controlled manner²⁰ (Ferguson et al., 2015). Hence, all mortars are a subset of guns, but not all guns are mortars (see *Mortars*, below).

In this report, the term ‘artillery gun’ is used to refer specifically to self-propelled, towed, and emplaced guns (i.e. not man-portable²¹) of a calibre greater than 57 mm which are designed for indirect-fire and capable of hitting targets at a considerable range. Artillery guns are characterised by a heavy barrel, generally several meters long and most commonly fitted to a self-propelled vehicle or a towed buggy. In contrast to mortars, all modern artillery guns feature recoil mechanisms, and many are capable of being used in the direct-fire role if necessary (Margiotta, 1997; Ryan, 1982). Artillery guns are also taken to include those weapons termed ‘howitzers’, which are generally understood to be comparatively short range artillery guns firing a relatively heavy projectile at a relatively low muzzle velocity (Ryan, 1982).

Artillery guns are generally arranged at the medium to high organisational levels of a military force, often in battalions consisting of three or four batteries with six to eight guns each. Such a battalion would ordinarily be assigned to support a specific regiment or brigade. At higher levels, artillery guns, often together with heavy mortars and rocket artillery, are organised in artillery brigades or divisions.

Current artillery systems are most commonly chambered for calibres from 105 mm to 208 mm, but calibres beyond 155 mm are rarely employed in modern conflicts. Today, almost all guns are manufactured in one of the following four calibres:

- 105 mm – mainly used by light units. These guns are usually towed, but may also be transported by helicopter;
- 122 mm – mainly used by former Warsaw Pact nations and organised at medium level. These systems are commonly seen in both towed and self-propelled formats;
- 152 mm – mainly used by former Warsaw Pact nations and organised at high level. These systems are usually self-propelled, but may also be towed; and
- 155 mm – mainly produced and used by NATO countries and organised at medium or high level. These systems are often towed or self-propelled.

¹⁹ The US Army's definition of cannon is the barrel and breech of any large-calibre weapon, including mortars. Broadly speaking, Europe regards ‘cannon’ as implying ‘automatic cannon’. A common definition for the US usage is: “a complete assembly which consists of a tube and a breech mechanism with a firing mechanism or base cap and which is a component of a gun, howitzer, or mortar; may include muzzle appendages; the term is generally limited to calibers greater than 1 inch” (McGraw-Hill, 2003).

²⁰ Experimentally, these may rely on electromagnetic force instead of chemical combustion (railgun, coilgun, etc.).

²¹ The term ‘man-portable’ is taken to mean a weapon which can be transported (disassembled as required) with its requisite mounting hardware and ammunition by no more than 3 individuals (Ferguson et al., 2015).

Table 1.1 gives some generic technical specifications for field artillery projectiles in the four common calibres, whilst Figures 1.5 to 1.8 show examples of both towed and self-propelled artillery guns in these calibres.

Table 1.1 – Generic Technical Specifications for Field Artillery Projectiles

	105 mm	122 mm	152 mm	155 mm
Weight	18 kg	27 kg	40 kg	40 kg
Explosive weight	2 kg	3.6 kg	6.25 kg	11 kg
Maximum range	12 km	12 km	17 km	23 km
Accuracy (see Section 3)	Range dependent	Range dependent	Range dependent	Range dependent
Fragmentation	495 m ²	550 m ²	605 m ²	665 m ²
Fragments	<1,000	1,000	3,000	>2,000

Source: Cross et al., 2016; Ness & Williams, 2011

Artillery guns chambered for other calibres remain in limited use. These include 76 mm, 85 mm, 100 mm, 130 mm, 180 mm, 203 mm and 208 mm systems; most of these calibres would be considered obsolete in military usage. Those guns with calibres greater than 200 mm were typically designed for firing nuclear projectiles at very long range, a role which has now been fulfilled by other weapon systems. Nonetheless recent conflicts have seen the use of limited numbers of high calibre artillery systems, including 203 mm self-propelled guns in Ukraine in 2014 and Second World War-era howitzers in Syria in 2015 (Loveluck, 2015; Smallwood, 2014).

Self-propelled systems generally offer increased mobility and crew protection, and may also offer an increase in the achievable rate of fire. Self-propelled guns are most commonly integrated into tracked armoured fighting vehicles, but may also be mounted on other types of vehicles, including armoured, partially-armoured, or unarmoured wheeled chassis.

Artillery guns generate significant recoil on firing, and modern guns are typically fitted with advanced recoil systems to mitigate this. Additionally, artillery guns require high structural strength in both gun and platform or vehicle, and often rely on enhanced contact with the earth via spades or other devices.



Figure 1.5 A 105 mm towed artillery gun (photo credit: US Army).



Figure 1.6 A 122 mm self-propelled artillery gun (photo credit: Norinco).



Figure 1.7 A 152 mm towed artillery gun (photo credit: Russian Ground Forces).



Figure 1.8 A 155 mm self-propelled artillery gun (photo credit: Wikimedia Commons).

Artillery guns are, broadly speaking, the most accurate of the three main types of indirect-fire weapons covered in this report. See Section 3 for a fuller discussion of the accuracy of indirect-fire weapon systems.

Mortar systems

Mortars are generally smooth-bore, muzzle-loading, indirect-fire guns. Conventional mortars do not have recoil mechanisms, with the main recoil force being transmitted directly to the ground via the baseplate. Additionally, most mortars are restricted in elevation, and are only capable of firing at high-angle trajectories (above 45°), meaning that they cannot be used in the direct-fire support role²² (Jenzen-Jones, 2015; Ryan, 1982).

The US army describes the primary role of mortar units as *“to provide a commander with immediately available, responsive, and both lethal and nonlethal indirect fires in support of company/troop and battalion/squadron maneuver”* (US Army, 2011).

Mortars are sometimes referred to as ‘the poor man’s artillery’. They are generally simple, rugged, light, and inexpensive, and are generally considered to provide the most responsive indirect fire support for many armed forces (US Army, 1992). They are also versatile and can deliver significant lethal effects relative to their size and weight, two key reasons for their widespread use by almost all military forces and many non-state armed groups. Mortars may be seen as a supplementary weapon to artillery guns. While artillery guns tend to require some distance from the target and adequate time for planning to be employed effectively, mortars are generally suitable for engaging targets relatively quickly and at shorter distances. Consequently, many mortar systems operate close to, or as a part of, the manoeuvring forces. They are commonly organised at a lower level than other artillery systems (Margiotta, 1997). Normally, mortar units are part of an infantry battalion as a mortar company, or may comprise one or two platoons in the battalion’s support company.



Figure 1.9 An 82 mm mortar (photo credit: Romanian Land Forces).

²² Note that there are limited numbers of mortar systems which have features uncommon to other mortars, including rifled barrels, recoil mechanisms, low-angle firing capability, and breech-loading mechanisms.



Figure 1.10 A 120 mm mortar (photo credit: US Army).

A mortar is a very simple device that consists of three essential components: (see Figures 1.9 & 1.10)

- A barrel ('mortar tube') generally made of steel or titanium²³. Normally this is a smoothbore tube, but rifled tubes are in service;
- A base plate, to which the rear end of the tube is attached, which transmits recoil forces to the ground; and
- An adjustable bipod that allows adjustment of elevation and azimuth angle before and during firing.

Almost all mortar systems are muzzle-loaded. The operator lifts a round to the muzzle and drops it down the tube. A firing pin at the bottom of the tube strikes the primer at the rear end of the round, causing the primer to ignite, in turn igniting the base propellant charge and any incremental charges and propelling the projectile out of the barrel.

In order to easily slide down to the bottom of the tube, the projectile must have a somewhat smaller diameter than the inside of the tube. A flexible obturator band will, when the propellant gases are formed, ensure a tight sealing between the tube wall and the projectile (see Figure 1.11).

Just like artillery guns, most mortar systems fire ammunition with incremental propellant charges. The typical mortar projectile has a base charge, located inside the tail of the round, which can propel the projectile at a low velocity. For engaging targets at very close ranges, this charge is adequate. For longer-range targets, a higher muzzle velocity is required, and the operator will place a number of additional charges (increments) on the round (see Figure 1.11). Incremental charges are commonly attached to tail of the projectile in modern rounds; however, older projectiles will have these attached to the fins.

²³ Some lightweight systems make use of composite materials in their construction.

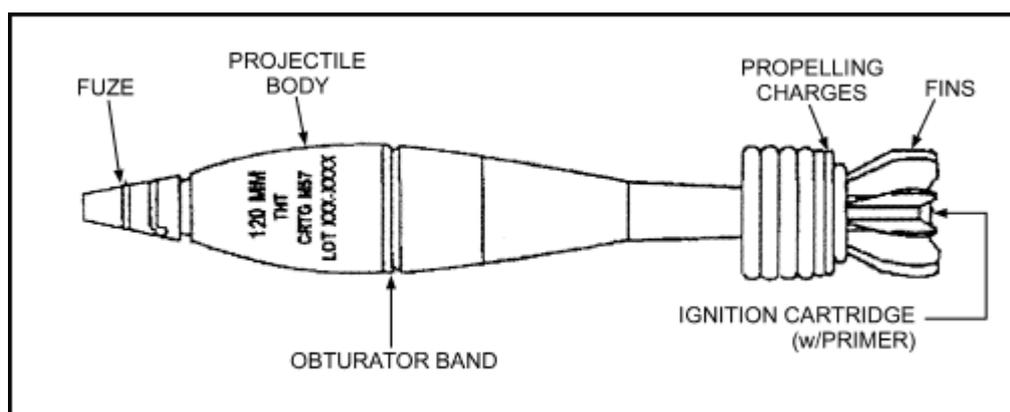


Figure 1.11 Arrangement of a typical mortar projectile (source: US Army).

Mortars can be classified in three broad groups or classes according to calibre (Margiotta, 1997):

- Light mortars – 60 mm calibre or less. In many armed forces these systems are obsolescent;
- Medium mortars – between 61 mm and 100 mm in calibre. 81 mm or 82 mm systems are in service with most armed forces and many non-state armed groups; and
- Heavy mortars²⁴ – greater than 100 mm calibre. 120 mm is the dominant system in this class, and is used by all major armies.

Other calibres still in limited service include 51 mm, 107 mm (4.2 inch), 160 mm and 240 mm. 51 mm is now largely obsolete, but was often called ‘pocket artillery’ as the whole system, including ammunition, could be carried by a single person. Smaller mortar systems have been phased out as 30 mm and 40 mm spin-stabilised grenades offer increasingly similar capability and higher flexibility. Generic technical specifications for mortars are given in Table 1.2, whilst typical values for the range of different mortars systems by calibre are given in Table 1.3.

Table 1.2 – Generic Technical Specifications for Mortars

	60 mm	81/82 mm	120 mm	240 mm
Warhead weight	2 kg	4 kg	10 - 15 kg	130 kg
Warhead Explosive	200 – 400 g HE	750 – 900 g HE	2.5 kg HE	32 kg HE
Range	3,500 m	5,500m	To 7,500m	9,500 m
Fragmentation	150 m ²	250 m ²	650 m ²	1800 m ²
Fragments	~350 .5g and ~100 2-10 g	~1,400	~4,250	Not available

Notes: All values are genericised estimates. **Source:** Cross et al., 2016; Jones & Ness, 2013; Ness & Williams, 2011

Some mortar systems, particularly those of 160 mm calibre or greater, and some automatic and vehicle-borne systems, are breech-loaded. Breech-loaded mortars are generally also able to fire in a low-angle mode.

²⁴ Mortars of 160 mm calibre and greater are sometimes considered ‘super-heavy’ mortars.

Table 1.3 – Typical Range Intervals for Mortar Systems by Calibre

Calibre	Minimum range (m)	Maximum range (m)
51 mm	50	800
60 mm	70	3500
81/82 mm	100	5500
107 mm	840	5700
120 mm	500	7000
160 mm	750	8000
240 mm	800	9000

Sources: Gander & Hogg, 1993; Isby, 1998

As the firing process depends on gravity for the firing pin to strike and initiate the primer, conventional mortar systems cannot typically be fired from an elevation angle of less than 45°. This means that targets are always engaged in a high angle mode. To engage targets at short distances, the weapon is fired at a high angle of elevation. Mortar fire is subject to the same kinds of error as artillery guns. However, as mortar bombs are fired in a high angle mode, the flight time is long, and most error components will then have time to develop. Due to the high-angle firing mode a mortar may have better precision at long ranges than short ranges because, to a point, the flight time decreases with range. The fact that mortars are fired at low velocity makes the influence of wind less pronounced when compared to artillery guns. However, compared to artillery guns, the mortar is generally a substantially less accurate design. See Section 3 for a fuller discussion of artillery accuracy. Whilst, in theory, it would be possible to adjust for accuracy in mortar systems in much the same way as artillery guns, this is often not done in order to preserve some of the essential characteristics of the system: simplicity and speed.

Mortar systems generally exhibit relatively low muzzle velocity. As the system does not typically have any recoil system other than the baseplate to distribute recoil to the ground, the muzzle impulse must be limited. The velocity of mortar projectiles is therefore almost always in the subsonic or transonic regime, i.e. less than 340 m/s.

Mortar systems are generally capable of a higher rate of fire than artillery guns. The maximum rate for a medium mortar is some 30 rounds per minute; 15 rounds per minute for sustained fire. For heavy mortars, such as those in 120 mm, the maximum rate is approximately 16 rounds per minute, and just 4 rounds for sustained fire (US Army, 2007). Mortars typically require a crew of three to six combatants to operate, depending on calibre and configuration.

Guided mortar systems have been developed to provide increased accuracy and reduced ammunition consumption over conventional mortars. Guided mortar systems allow for precision targeting and increased first-round hit probability, and may greatly reduce civilian harm. Nonetheless, precision guided mortar munitions have not seen widespread use in current and recent armed conflicts. For a fuller discussion of guided mortar systems, see Jenzen-Jones, 2015.

Rocket artillery

Rockets were first used as meaningful artillery weapons by the British Royal Navy in the early 19th century, most famously during Admiral Nelson's siege and bombardment of Copenhagen in 1807, where thousands of rockets had a devastating effect on the city. Following this period, artillery rockets largely fell out of favour until the Second World War, during which both Russian and German forces, in particular, made use of significant numbers of rockets, primarily on the Eastern Front (Dullum, 1993; 2009).

In its simplest form, a rocket motor consists of a tube in which fuel is burned, with an opening at one end. The escaping gases cause an equal and opposite reaction on the closed end of the tube, propelling the rocket forwards (Ryan, 1982). Artillery rockets are primarily unguided, and these munitions are often referred to as free-flight rockets (FFR).

Spin-stabilised rockets generally have a relatively short overall length. Spin is achieved through a series of obliquely-mounted nozzles placed off-centre at the rear end of the rocket. Spin is imparted to the rockets partially on launch and partially during the first stages of flight as the hot gases propel the rocket forward whilst simultaneously causing the munition to rotate around a central axis. This method of stabilization cannot be used on long rocket bodies. Spin-stabilised rockets will have a short motor and, consequently, a comparatively short range.

Fin-stabilised rockets will also spin, however this is typically just a few revolutions per second. Stabilisation is almost entirely dependent on the fins. In most systems, these are wrap-around fins that are deployed a few meters after launch. The spin is ordinarily induced by helical rails on the inside of the launch tube. As the spin is rather slow, fin-stabilised rockets have a significant overall length; typically, the length of a fin-stabilised rocket is 20 to 30 times its diameter. Thus, both the motor and the payload section can be longer, resulting in the ability to deliver large payloads to more distant targets (Dullum, 1993).

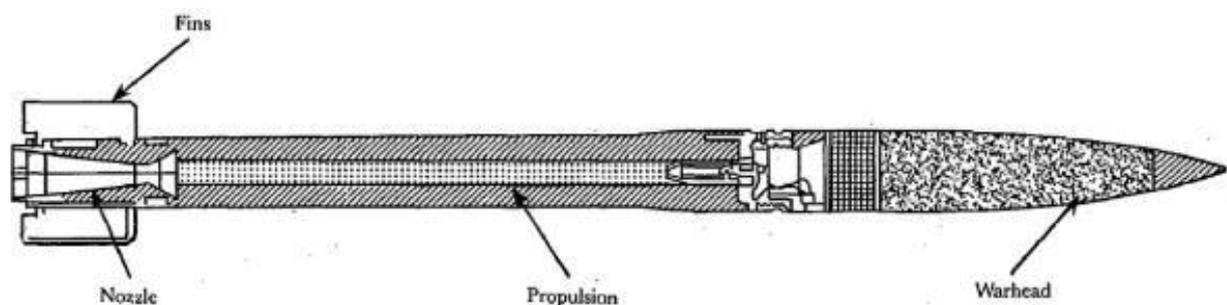


Figure 1.13 Arrangement of a typical artillery rocket (source: Dullum, 2009).

Compared to artillery guns and mortars, rockets have some distinct advantages:

- The weapon system can be placed on a relatively light vehicle, as the recoil from the launch of rockets is typically much lower than that of an artillery gun or mortar; and
- Due to the relatively low acceleration of a rocket compared to projectiles, the munition and its payload can be made less ruggedized, with thinner walls and higher explosive content.

Artillery rockets vary significantly in size, range, technological sophistication, and role. In military usage, rocket artillery is a high-level weapon that is usually organised one level higher than artillery guns. Medium systems may belong to a brigade. Heavy systems are generally found at the division or corps level. There are a wide variety of calibres and sizes of rocket artillery systems in common service around the world. These are primarily single-barrelled and multi-barrelled, although there are other types in service, including rail-launched models. Figures 1.16 and 1.17 show two examples of larger systems, with calibres exceeding 200 mm. There are two calibres that dominate the rocket artillery inventory:

- 107 mm systems with short barrels, firing spin-stabilised rockets; and
- 122 mm systems with long barrels, firing fin-stabilised rockets.

These two types are both multi-barrelled systems, often referred to as multiple-barrel rocket launchers (MBRL) or multiple-launch rocket systems (MLRS), and are depicted in Figures 1.14 and 1.15. MBRL are often less accurate and less precise than other artillery weapons, and in some modern militaries are increasingly being adapted to fire guided munitions, either in place of or in addition to unguided rockets. Due to the inaccuracy and imprecision inherent to most of these systems, many military commanders consider firing unguided munitions from MBRL into populated areas to be unacceptable under normal warfighting circumstances²⁵.

Table 1.4 – Accuracy of Common Artillery Rockets

Rocket Calibre	Max. range (km)	Total 'across x along' error single fire (m)
107 mm	8	80 x 130
122 mm	20	160 x 300
227 mm	32	200 x 430
240 mm	11	210 x 460
300 mm (guided)	70	150 x 150

Notes: All values are genericised estimates. **Source:** Cross et al., 2016; Dullum, 2010

Table 1.5 – Estimated Lethality of Common Artillery Rockets

Rocket Size	Explosive Mass (kg)	Lethal Area (m ²) - PD	Lethal Area (m ²) - Airburst
107 mm	1.3	450	550
122 mm	6.4	700	850
160 mm	9	1050	1200
220 mm	52	1700	1950
240 mm	42	1500	1700
300 mm	75	2400	2600
333 mm	60	2400	2700
610 mm	200	5300	5600

Notes: All values are genericised estimates. **Source:** Cross et al., 2016; Dullum, 2010

²⁵ Interviews with current and former senior artillery officers from different countries.



Figure 1.14 A multi-barrelled 107 mm towed spin-stabilised rocket artillery system (photo credit: Al Jazeera).



Figure 1.15 A multi-barrelled 122 mm fin-stabilised self-propelled rocket artillery system (photo credit: Worldwide-Defence).



Figure 1.16 A twin-barrelled 333 mm self-propelled spin-stabilised rocket artillery system (photo credit: Hossein Fatemi/FARS News Agency).



Figure 1.17 A multi-barrelled 333 mm self-propelled fin-stabilised rocket artillery system (photo credit: Military Today).

Rocket artillery is very popular among non-state armed groups, as many systems are relatively straightforward and comparatively safe to operate. Significant quantities of artillery rockets have formed part of the inventories of some non-state actors for decades (Schroeder, 2014). Rockets are frequently repurposed for use in improvised weapons system, or improvised entirely from propellant and explosives taken from other ordnance, or manufactured in basic workshops. Conventional artillery rockets may also form the basis for so-called improvised rocket-assisted

munitions (IRAMs), in which an over-calibre warhead²⁶ is fitted, drastically reducing range and accuracy but delivering a significant explosive payload (Jenzen-Jones & Wright, 2016). Such systems have become increasingly commonplace in recent conflicts (Jenzen-Jones, Lyamin & Wright, 2014; Smallwood, 2014). Rocket bodies, fins and fuzes can also be manufactured with fairly primitive tools. Air-to-surface rockets are frequently repurposed as surface-to-surface rockets, both by non-state actors and by state militaries (Lyamin & Jenzen-Jones, 2014). Generally, the use of low-quality materials and crude manufacturing processes means that the accuracy of improvised rocket artillery is inferior and their range and direction of fire can be quite random (see, for example, Jenzen-Jones & Lyamin, 2014).

Improperly balanced rocket designs often result in the munition stalling or tumbling in flight. Poor manufacturing tolerances and a lack of consistency between designs commonly results in aerodynamic issues, causing munitions to spiral away from their original firing trajectories. Generally, the accuracy of many improvised rocket artillery munitions can be said to be comparable – or worse than – some pre-WW1 military designs.

While artillery guns and mortars can be fired with different arrangements of incremental charges, a rocket has a fixed propulsive force. This severely restricts the use of such rockets at short ranges. As an example, a system capable of engaging targets at ranges up to 30 km, may not be able to fire at a target 6 – 7 km away, as vegetation, low hills, and high-rise structures could obstruct the relatively flat projectile trajectory. In some cases, a device may be added to increase aerodynamic drag (most often a brake ring or flaps, sometimes called a ‘spoiler’), typically reducing both the maximum and minimum range of the system.

Rocket artillery can achieve a rate of fire higher than that of other artillery types. A single weapon system loaded with 40 122 mm calibre rockets can launch all rounds within 20 seconds. Heavier systems may require up to five seconds per round. Reloading the unit is generally a time-consuming process, however, often requiring some 15 – 30 minutes.

Naval Artillery

Whilst the focus of this report is on ground-based indirect-fire systems, many of the same concepts apply to naval systems. Naval artillery has, over the course of history, included gun, mortar, and rocket systems. In contemporary usage, the term ‘naval artillery’ is generally understood to refer to artillery guns mounted on warships. Depending on the specific weapon system and platform in question, naval guns may be capable of both direct and indirect fire, and employed to engage other surface vessels, land-based targets, and missiles and aircraft.

Most of the projectiles fired by these artillery systems are unguided, although there are some guided munitions with extended ranges available. Although the majority of projectiles lack terminal guidance, some systems use a complex fire-control system to provide fires accurate enough to destroy high-velocity anti-ship missiles. Ammunition is selected based on target from an internal carriage holding numerous types of projectiles with various warhead options (US Army, 1989).

²⁶ An over-calibre warhead is one which exceeds the calibre of the munition body. A well-known example is the PG-7V projectile fired from the RPG-7 shoulder-fired recoilless gun.

Within a given range of sea states, naval gunfire can be considered to be as accurate as land-based artillery despite the seeming disadvantages of a moving platform. Predicted fire and observed fire is brought to bear on the target in the same way for both environments, making use of observers, fire control, and other common elements. Common calibres for naval artillery are in the region of 4.5inch (76 mm) to 155 mm, though some navies retain and use very heavy guns with calibres greater than 12in (300 mm). Table 1.6 gives some sample specifications for naval artillery. The high muzzle velocity and relatively flat trajectory of naval gun artillery makes them suitable for employment in the direct fires role, however this also results in a roughly elliptical dispersion pattern, with the long axis in the direction of fire (US Army, 1989).

Table 1.6 – Generic Technical Specifications for Naval Artillery

	76 mm	127 mm
Warhead weight	12.4 kg	30 kg
Warhead Explosive content	1.5 – 2 kg	4 – 5 kg
Range	16 km standard round 40 km GPS guided	24 km 100 km with extended range projectiles
Accuracy²⁷	Range dependent	Range dependent
Fragmentation	300 m ²	650 m ²
Fragments	Not available	Not available

Source: Cross et al., 2016; King, 2011

²⁷ Can vary significantly with range, system, and platform.



SECTION 2

Employment

Chris Lincoln-Jones & David Palacio

Mission and role

At the most basic level, the core mission of artillery is to destroy, neutralise, or suppress enemy land warfare activity (US Army, 1988). Artillery remains a core military capability and has exercised a decisive influence on many battlefields. Historically, artillery has been the most lethal system employed in conflict (US Army, 1984). Although conducting artillery operations requires a certain level of training and technical understanding, hundreds of groups of armed actors across the world retain artillery capabilities. These range from highly advanced, well-established military forces to non-state armed groups.

The United States Marine Corps outlines the mission of artillery as follows:

“The mission of artillery is to furnish close and continuous fire support by neutralizing, destroying, or suppressing targets that threaten the success of the supported unit. To accomplish its mission, artillery has the following responsibilities:

-Provide timely, close, accurate, and continuous fire support.

-Provide depth to combat by attacking hostile reserves, restricting movement, providing long range support for reconnaissance forces, and disrupting threat command and control (C2) systems and logistics installations; i.e., shaping the battlespace.

-Deliver counterfire within the range of the weapon systems to ensure freedom of action of the ground forces.”

(USMC, 2002)

The successful employment of artillery will limit an opponent’s ability to mass forces in a given area, for fear of artillery fire devastating their ranks. Similarly, it can mean that a smaller force can project power beyond what might be indicated by the total number of troops present. Well-directed artillery fire is a force multiplier to both attacking and defending forces.

In the offensive role, artillery can be used to the attacker’s advantage. In the case of a well-entrenched enemy force, the attacking force can seek to first eliminate the defensive forces’ observation posts with their own artillery to significantly degrade the defence’s indirect-fire capability. Many breaching standard operating procedures (SOPs) call for suppression, obscuration, securing, reduction, and then assault (SOSRA) of enemy positions (US Army, 2002a). In this case, two or more different projectiles may be employed to further the attacking forces’ advance: smoke or white phosphorus, for example, may be employed to obscure the enemy’s ability to observe friendly forces, followed by high explosive projectiles intended to destroy entrenched enemy positions such as observation posts or machine gun bunkers.

Artillery can also be employed in the defensive role. The ability to employ artillery during defensive operations can compensate for a lack of manpower and resources. Defending forces often try to fortify their position in the face of an impending attack, which often includes the use of obstacles (US Army, 2002a). Ranging artillery systems and identifying pre-designating target zones (a process sometimes known as ‘registration’) dramatically increases the likelihood of inflicting massive casualties on an enemy force attempting to breach. Artillery systems can also be used to reinforce weaknesses in the defensive lines or provide final protective fires (FPF) (see below).

However artillery also plays a critical role in supporting other combat elements. It is a basic tenet of combat that “fire supports manoeuvre”, allowing infantry and armoured formations the freedom of movement to achieve their objectives. Since infantry and artillery work intimately together to accomplish these objectives, some armed forces strive to maintain a close relationship between

artillery units and the manoeuvre unit they support. Deployment and training schedules may not always align perfectly, but specific battalions and their subordinate batteries are often assigned to support specific infantry regiments and their subordinate battalions (USMC, 2002).

With respect to ground forces, artillery is usually surpassed in overall number of units and manpower only by the infantry, which functions as the basic element for ground combat. In many armed forces, artillery formations are divided into roughly equivalent sized forces to infantry formations; typically, an artillery battery is equivalent to an infantry company, and both have battalions, regiments, and in some cases, division-level staff and units. The basic fighting element of artillery is the battery. Typically, this will consist of six to eight artillery systems, a fire direction centre, supporting elements of communications and transportation (if the artillery pieces are not self-propelled), and associated observers and liaison officers. Conventionally, a unit of artillery will typically support an infantry unit one organisational level higher. An artillery battery will support an infantry battalion; an artillery battalion will support an infantry regiment; and an artillery regiment will support an infantry division.

The table of equipment which is assigned to an artillery element is far beyond what most manoeuvre units are assigned, due to the requirements of employing and maintaining artillery. Each artillery gun requires a vehicle to serve as a prime mover (if it is not self-propelled), a dedicated ammunition resupply vehicle, and multiple trailers; the unit further requires a fire direction centre (FDC) and other equipment such as generators and maintenance equipment, as well as other light tactical vehicles for key personnel within the unit (commanding officer, executive officer, multiple observer teams, etc.)

The experience of recent low-intensity conflicts has resulted in some modification to the doctrine of using a battery as the minimum element of employment. In many armed forces, this now allows for small firing units, consisting of one platoon of two or three artillery pieces. This subdivision of firing elements became necessary due to the dispersed nature of the enemy. Artillery deployments during recent conflicts also saw artillery units being assigned a wide range of provisional missions²⁸.

Doctrine and Deployment

In many armed forces, artillery units have well-established doctrine that permeates all aspects of firing operations. This includes, for some modern armed forces, targeting doctrine and operational considerations specific to the use of indirect-fire weapons in populated or urban areas. However appropriate doctrine and SOPs are not standardised between armed forces, and may be absent or rudimentary for some armed forces. These procedures guide the deployment and use of indirect-fire systems.

An artillery unit will require three components to deliver accurate fires: the firing element itself (towed or self-propelled systems), an FDC, and observers. Each component has doctrine guiding their employment, and as a whole, there are doctrinal directives that guide what is required of artillery as a supporting arms formation. One of the most critical is for the artillery unit commander to be intimately familiar with the operation the unit has been assigned, and particularly how it will impact the manoeuvre unit it is supporting. The four types of support missions that can be assigned

²⁸ In the authors' experience, owning a robust equipment set and having significant manpower often made artillery units suitable alternatives to infantry forces in conducting a range of missions such as convoy security and even provisional infantry roles. In some cases artillery batteries were employed to accomplish infantry missions, and also required to maintain several artillery pieces at their patrol bases, to furnish fire support to their own patrolling units.

to artillery are direct support, general support, general support-reinforcing, and reinforcing (US Army, 2014a)²⁹.

Direct support is used when a formal relationship has been established with a manoeuvre unit. In this case, the artillery unit is required to provide observers and liaison officers to the assigned manoeuvre unit. Planning between the two agencies is frequent and detailed. When the manoeuvre unit requires fire support, the assigned artillery unit is responsible for answering directly and primarily to all requests. That being said, this role does not necessarily preclude the supporting firing element from providing fires to other manoeuvre units or other elements that require them.

General support missions can be assigned either to units that do not already have a habitual relationship with a manoeuvre unit, or to weapon systems deemed to be a higher echelon asset, such as various rocket artillery systems (particularly those capable of firing precision guided munitions within some armed forces)³⁰. A unit assigned to general support is not required to provide observers or liaison officers to specific units, but will often have representatives in the higher command's operation centre. In a general support role, the firing element can answer calls for fire from any element that requests them. Typically, approval for fires from higher-level assets resides with regiment or division-level commands or higher, depending on the rules of engagement (ROE) that forces are required to operate under.

Units tasked with a **general support-reinforcing** role are not required to provide observers to specific units, and still operate under similar conditions as general support units. They can receive calls for fire from any element, but will always have a primary responsibility to support the unit they are assigned to reinforce.

Similarly, a unit assigned as a **reinforcing** element will be responsible to another firing element of similar or greater size. The reinforcing firing element does not have to be co-located with the unit it is reinforcing, but their fire needs to be able to reach targets that the primary firing element will be engaging.

The successful employment of a firing element, at all levels, is achieved through the harmonious interaction between the three core components of an artillery unit: the 'brawn', or weapon systems; the 'eyes', or observers; and the 'brain', or fire direction centre. This is most readily explained at the battery level.

Weapon systems in the battery execute the commands to deliver fires on target. For unguided munitions, the process of striking a target area is typically conducted using a process of adjusting fire. Adjusting fire is conducted off a single artillery piece, unless the observer chooses to employ more than one. Modern guns are increasingly fitted with advanced fire control systems (FCS) which allow for the rapid input and computation of data from a range of sources. Once accurate firing data has been collated and computed, correct data is applied to all systems so that the battery can mass fire, in accordance with the nature of the target they are engaging. As an alternative to adjusting fire, the battery may receive commands to "fire for effect" as an initial volley, which is generally a matter of confidence in the target location and the skill of the observer or observers calling for fire

²⁹ Whilst these terms are common to the US military and some other western armed forces, the broad-strokes approaches of specific support missions apply to artillery units generally.

³⁰ The process of target identification and selection in this type of role is typically conducted by the lower echelon unit or unit in direct contact requesting indirect fires; however, approval is conducted at a higher echelon (organisational level). Generally speaking, larger calibre and longer-range systems may be subject to this system of control due to their significant tactical or operational value and/or due to the greater risks of misemployment in proximity to the battle area.

(see *Fire for Effect*, below). Precision guided munitions add another capability to artillery units, enabling firing elements to enter the final phases of target engagement without requiring an adjusting fire.

Forward **observers** are integrated into almost all artillery units in modern militaries. These observers are most often situated many kilometres ahead of their own forces. Their task is to find and locate valuable targets for their units. Target size, level of protection, coordinates, and recommended type and amount of fire, are transmitted to the fire direction centre or firing element. Equally important is the ability of the forward observers to observe the impact point and the effect of the fire, and report back with recommendations to adjust the aim point, and to evaluate the damage inflicted on the target (see *Measure of Effectiveness*, below).

Such teams typically have a number of aids to observation and target location as well as radios for communication with the command and control nodes of the indirect-fire assets. These aids may include thermal imaging and laser rangefinders as well as laptop-based software that provides very accurate geolocation and other relevant data. Geolocation accuracy is essential for increasing the accuracy of target engagement with both unguided and precision guided munitions. Some munitions available to the artillery controller can be terminally controlled, usually by laser guidance, and the laser equipment in an observer party can also mark a target for a terminally-controlled PGM.

In addition to ground-based observers, aerial observers have been employed since air power came into maturity and was first integrated with ground manoeuvre (Unikoski, 2009). Pilots and other aerial observers can provide visual acquisition of a target, which may have an impact on grid fidelity, or use available sensors to provide target identification and location with accuracy. The proliferation of unmanned aerial vehicles (UAVs) is also providing alternative options for aerial observer capability. With the range of artillery such that it can now outpace the position of an observer or their communications capability, UAVs can offer an alternative means of target acquisition, and may offer the ability to communicate over long distances via their organic communication systems. Non-state armed groups have increasingly made use of small commercial-off-the-shelf UAVs in a target acquisition and surveillance role (for a fuller discussion of this phenomenon, see Friese, Jenzen-Jones & Smallwood, 2016).

The roles of observers are discussed in further detail under *Target Identification & Development*, below.

The **fire direction centre** (FDC) is the nerve centre of an artillery unit. An FDC may employ either manual gunnery techniques³¹ or automated systems to compute the data necessary to accurately engage a target. For more advanced military forces, manual gunnery is usually only performed in emergency situations, if the more accurate and expedient automated systems cannot be used³². Nonetheless, manual gunnery remains a foundation of training for all forces. The FDC translates target information into a deflection or azimuth³³ (lateral movement left and right) and quadrant (vertical movement up and down) that are communicated to the weapon systems (USMC, 2009).

A senior operations chief and the fire direction officer, as well as several junior members, run FDCs. The FDCs will be located in close proximity to the artillery pieces, but are not necessarily required to be adjacent to them. Once emplaced, the fire direction officer assumes the role of position

³¹ Using appropriate firing tables, atmospheric data, location data, and appropriate calculations; this is sometimes known as manual production of data (MPOD). Reversionary firing techniques may also be employed (see below), as opposed to automatic input and calculations.

³² Automated systems may not be available to some less-advanced armed forces.

³³ For a fuller discussion of the azimuth and deflection methods, see McDonald, 1992.

commander and controls operations. In the case that a battery needs to displace from their current position, the battery commander and selected personnel form an 'advance party' and reconnoitre and select the subsequent position.

Technological advances and modernisation of employment doctrine have substantially increased the responsiveness and flexibility of modern artillery units. Where forward observers, advanced FCS, and dedicated FDCs are not available – as is the case for many militaries or non-state armed groups – there is a significant reduction in the situational awareness, responsiveness, and likely accuracy and precision of indirect fire weapon systems.

Employment of Artillery

Artillery can be employed in several different ways in order to achieve the desired effect on target.

A request for supporting fire – known as a 'call for fire' – follows an established format (a standardised set of transmissions) in most modern militaries. A call for fire is a request for fire containing data necessary for obtaining the required fire on a target (US Army, 2014a). A standard call for fire format may include the following three transmissions:

1. Observer identification and warning order³⁴;
2. Target location; and
3. Description of target, method of engagement, and method of fire and control (US Army, 1991a).

Precision calculation of firing data takes multiple details into consideration, including the temperature of the propellant, the temperature of the atmosphere, wind conditions, elevation changes between firing element and target. The more accurate the data, the more likely that the firing element will be able to deliver accurate, effective fire on target. Artillery units understand this critical requirement; a common saying in gunnery is "garbage in, garbage out".

Due to these requirements, trained observers must spend hours training to ensure they can provide accurate target data, mitigating error as best as possible. However, since artillery is a supporting arms specialty, it seeks to provide its 'customer' with support fires regardless of the training level of the requesting individual. As such, calls for fire are sometimes made by untrained observers. FDCs frequently practice handling requests from untrained observers. Training is usually conducted in a controlled environment with highly trained observers providing oversight. A lack of familiarity with calling for fires on the observer's behalf can largely be mitigated if the standard call for fire format is followed.

In the case of a wholly untrained observer who is not familiar with the call for fire, it is possible that they can still receive support, as long as they have a general knowledge of their location and the location of the target. In the case of a fire mission assigned in such a manner, the command element will have to take extra care in identifying where all friendly and civilian elements are to ensure the fire mission does not result in fratricide or civilian harm.

The untrained observer may provide adjustments in cardinal directions, if they are unfamiliar with the proper format for providing corrections during adjusting fire. If the intended target is 'danger close' (relatively close to the observer, supported unit, civilians, or protected objects), the firing element will typically provide 'creeping fire', slowly bringing the rounds closer to the observer in 100

³⁴ A warning order (WARNORD) is a preliminary notice of an order or action which is to follow used by the US and other armed forces (DOD, 2013). In the case of a call for fire, it consists of the type of mission, the size of the element to fire for effect, and the method of target location. It is a request for fire unless prior authority has been given to order fire.

m increments rather than the typical manner of ‘bracketing’, which requires one round to fall long of the target and one round short before conducting the final ‘fire for effect’ stage (US Army, 1991a). Whilst these measures were primarily developed with force protection in mind, similar approaches have been taken by commanders seeking to limit damage to civilians and civilian objects.³⁵

The nature of the target, as well as concern for collateral damage, and the availability of different platforms, systems, and munitions will largely determine the way in which it is engaged. For example, in an environment with heavy vegetation, single, double, or triple canopy can hinder the effectiveness of a round if not accounted for. However, if understood, this potential weakness can be turned into a strength. A traditional indirect-fire shot could be slowed by vegetation, falling short of the intended target. To mitigate this, the FDC could choose to employ a high-angle shot with a delayed fuze setting. Manipulating the shot in this way allows the round to penetrate the overhead vegetation in a more direct manner, and making the projectile less likely to deviate from the target area. Detonation at the correct height may also produce additional secondary fragmentation that results from the surrounding vegetation (see Section 4 for further details on secondary fragmentation).

In a similar vein, the urban employment of indirect-fire systems poses challenges due to so-called ‘urban canyons’ and intervening crests between the firing element and the target. High angle fire may assist in such an environment in minimising civilian harm in much the same way that it would help to avoid a trajectory through vegetation in a tropical or wooded environment. However, high-angle fires often lead to reduced accuracy and precision, primarily due to increased flight time (see Section 3). Fuzing is particularly important in urban environments. A delay fuze can allow a projectile to punch through walls or ceilings in order to localise the blast and fragmentation effects within the targeted structure, maximising casualties within, but limiting collateral damage nearby. On the other hand, using a proximity fuze or time fuze to function the projectile above the target, may allow the artillery unit to direct explosive effects against the outside of a structure without collapsing it. These effects, desirable under certain circumstances, must be weighed against the limitations such functions may impose – such as, for example, the potential for wider area effects if proximity fuzes are employed.

Application of Fire

When an observer makes a call for fire, the third transmission in the process largely consists of providing a target description. In addition, the observer may request a particular munition/fuze combination. The target description should include the size and nature of the target (e.g. single individual, company of infantry, platoon of lightly armoured vehicles, command and control structure, etc.), as well as the degree of protection the target has (infantry dug in with overhead cover, armoured vehicles, mortar team in the open, etc.). In many armed forces, an observer will also include information relating to the presence of protected persons or objects, and an assessment of potential collateral damage.

Observers providing target location can either use an estimated grid from the map, estimated direction and distance from binoculars and compass, the direction and distance provided from more advanced optics, or use both a map and information derived from optics to serve as a form of verification. From the deduced target location, the observer provides the information for an initial adjusting round to the FDC (USMC, 1998).

³⁵ Author interviews with current and former senior artillery officers.

The firing element will deliver adjusting fire (generally one round) to the desired initial grid. Due to any number of factors (such as bad location data, a cold firing tube, ambient factors impacting the round's flight, etc.) the round may not hit exactly where it is intended to. The observer then attempts to determine if the round landed short or long, or left or right, of the intended target, and by how much (see *Adjusting Fire*, below).

When a battery or a unit consisting of more than one gun fires simultaneously into the same area, the amount of ammunition fired may be measured in layers; one layer indicating one round from each gun. A typical salvo³⁶ may consist of three to six layers. For a battery of eight guns (typical batteries being of 6 to 8 guns), that will mean 24 to 48 shells fired on the target. Weight of fire may also be described in terms of the 'number of rounds at fire for effect' (see *Fire for Effect*, below). The observer can further specify how he or she suggests the target is engaged by specifying the type of 'sheaf' – the pattern of munition impacts in the target area – to employ against the target. The sheaf may differ according to the weapon, munition, and target type and by the doctrine of a given military. Artillery guns most commonly employ a circular sheaf, with individual aim points differing for each gun in the battery. Mortars are more likely to use a linear or open sheaf, in which the points of impact of individual projectiles are separated by one to one and a half times the maximum effective blast of the type of munition fired. Another common sheaf is the parallel sheaf, in which the lines of fire are parallel, with the pattern of impact roughly approximating the pattern of deployment. Also available are converged (sometimes called 'closed') and irregular sheaves (whatever shape the observer determines) (see Figure 2.1). The use of the term 'sheaf' applies to all artillery systems – towed or self-propelled guns, mortars, and rockets (USMC, 1998).

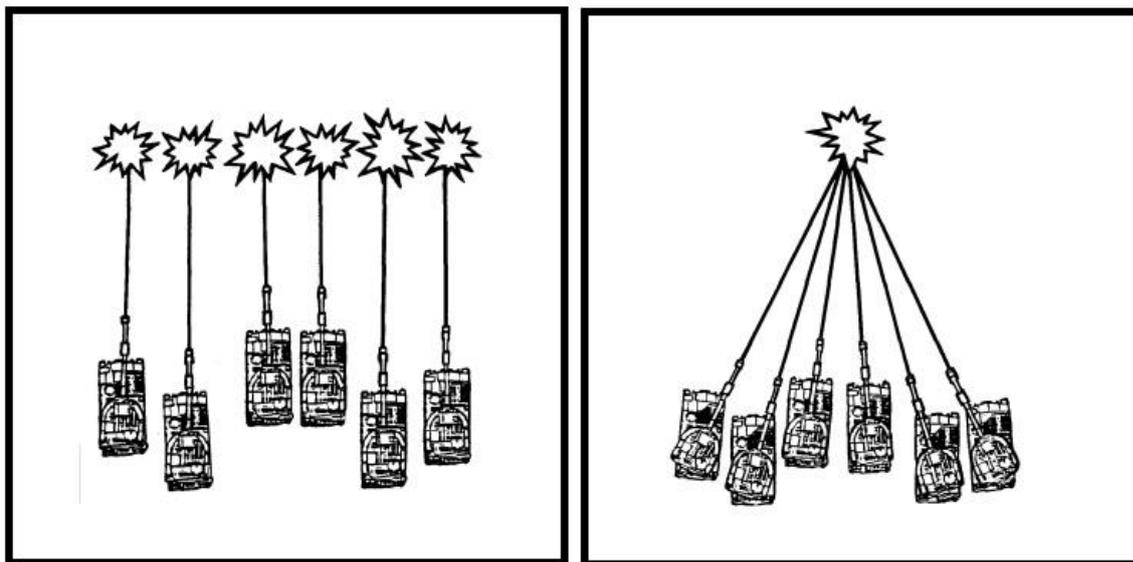


Figure 2.1 Open (left) and converged (right) sheafs (source: USMC).

Final control over how a target is engaged may rest with different components, depending on the structure and doctrine of the military force. In some armed forces, the observer does not have final control over how a target is engaged, but is often able to offer a recommendation to the FDC. There are various reasons an FDC may choose to change the final projectile/fuze combination. These include the varying levels of training for different observers; limitations in the availability of certain munitions or fuze types; and second- and third-order effects that the observer is not as capable of considering (some of these are discussed under *Weapon-Target Matching*, below).

³⁶ In some militaries, the term 'salvo' is reserved for naval gunfire.

In other armed forces, however, fires are ordered rather than requested, and the observer remains responsible for determining how a target is engaged. Some forces maintain that the FDC should have access to better information regarding adjacent unit locations, situational awareness about the developments of a battle or engagement, and the current quantity of munitions available to the firing element. In relation to the prevention of civilian harm, there are pros and cons from both approaches; it is essential in either case that the observer and FDC are able to communicate effectively and efficiently.

Although observers may initiate a request for artillery support, fire authorisation is not guaranteed. All fires require some form of approval. This approval is often conducted on an active, case-by-case basis; a designated individual will advise via a predetermined communications channel that the requested fire is 'approved'. Other commands that may be issued are 'denied', or 'modified', with any modifications announced. A unit may enact a passive approval SOP, under which a fire is approved unless explicitly denied. Due to the high level of risk associated with this practice, it remains uncommon amongst some military forces, and is generally discouraged, in particular where civilian harm is expected.

Since artillery fires are generally within areas typically deemed to be a manoeuvre unit's battlespace, the approving agents will typically reside in the manoeuvre units' combat operations centre (COC) or tactical operations centre (TOC). Within these COCs/TOCs, the overall area of operations commander and his battle staff will conduct command and control of forces, to include the tracking of friendly positions. These commanders will be advised by a fire direction officer or similar, taking input from the various FDCs of firing elements. The positive control of friendly units and known positions of friendly elements is essential in fires approval, since this will often be one of the most significant factors in determining whether a request for fire can be authorised (US Army, 2014b). If there is a particularly high risk of collateral damage to civilians or civilian objects, the authorisation may be assessed by the battlespace commander, or routed to the appropriate higher echelon command (see *Targeting Considerations*, below, for a fuller discussion of the fires approval process).

Adjust Fire

To overcome the limitations of first-round accuracy, adjusting fire may be employed. Typically, this is one round fired based on an observer's initial estimate of target location, however if a weapon has been 'registered', this point may be used to effect more accurate adjustments. Based upon the impact of the first round, the observer will offer a correction to the FDC. Generally, adjusting fire will not be conducted within a populated area, but may be conducted in a designated area which is, ideally, free from friendly forces and civilians and civilian objects³⁷.

For many militaries, a 'good' initial impact may be considered to be one that lands within 400 meters of the target. Ideally, adjusting rounds should be brought in line with the target as quickly as possible to better determine if impacts are short or long, however both deviation and range corrections are sent simultaneously. Corrections are offered in range increments relevant to the weapon system in question. For many systems, these will be increments of 800, 400, 200, 100, and 50 metres. Once the final correction has been made, the fire for effect request will be given. This process is referred to as 'successive bracketing' and ensures that rounds will land within an area such that the target is covered by the effective lethal radius of the munition (USMC, 1998).

³⁷ In many militaries, adjusting fire is subject to a CDE just like any other employment of a weapon system.

A highly professional force confident of its ability will often forego the adjust fire procedure, and take the chance of some minor inaccuracy to achieve surprise, and therefore maximise effects on the enemy in the early stages of an engagement. In many militaries, this would not be undertaken if harm to civilians or the proximity of friendly forces were factors³⁸.

When civilian harm is of particular concern, an offset is applied to the first round to guarantee that it will land a safe distance from the object or area of concern³⁹. From this initial impact, the observer will adjust the fall of subsequent impacts before calling for fire for effect. After a battle damage assessment (BDA) is conducted, the target may be re-engaged if necessary.

Fire for Effect

Fire for effect distinguishes between adjusting or spotting rounds and the command to deliver the full weight of fire from a number of weapon systems. Under typical conditions, once a target has been identified and the adjusting fire procedure has been conducted, fire for effect will be requested.

Suppressive Fire

Suppression is generally understood to be the degradation of an opposing unit below the level needed to fulfil its mission objectives (DoD, 2010a). Suppressive fire is employed, not primarily for inflicting damage, but to sustain a continuous fire of low to moderate intensity in order to prevent an enemy from using their weapons, or to hinder them in taking other tactical actions. In effect, suppressive fire may act as a form of area denial. The target for this effect may be an area or a specific unit or units, and the number and types of munitions used may vary. The effect of this kind of fire is difficult to predict, as it depends primarily on parameters of the enemy force which are difficult to quantify, such as motivation, tactical state and training standard. Consequently, it is difficult to select the correct intensity of suppressive fire. However, it is generally accepted that the degree of suppression is related to the frequency of impacts and explosive quantity of the munitions used (US Army, 1980). Generally, in current practice, if suppressive fire is employed in populated areas, it is typically subject to a similarly robust collateral damage estimation process as fires for effect⁴⁰. Generally, when fires are more restricted, less suppressive fire can be used (US Army, 2002b).

Surprise/Coordination Effect (Time on Target)

Guns, mortars and rockets will have optimal effect on the target when the fire comes without warning and with high intensity. As soon as the target takes cover in ditches or foxholes, or behind natural obstacles, the effectiveness of the fire may be significantly reduced. The surprise effect is sometimes expressed as time on target (TOT), which is defined as “the actual time at which munitions impact the target” (DOD, 2014). Artillery units will strive for simultaneous impact, with a difference in TOT for multiple projectiles or rockets of a few seconds, in most instances.

³⁸ Author interviews with current and former senior artillery officers.

³⁹ Author interviews with current and former senior artillery officers.

⁴⁰ Author interviews with current and former senior artillery officers.

Multiple Rounds, Simultaneous Impact

Multiple rounds, simultaneous impact is a relatively new firing concept designed to enhance the surprise effect, and is generally understood to refer to the capability to deliver multiple rounds from one weapon system⁴¹. It is made possible by modern, highly-automated systems with long range and relatively high accuracy. As the flight time may be more than 60 seconds when firing at a high angle, it is possible to achieve simultaneous impact with several rounds around the desired mean point of impact. The technique requires that the first shot is fired at a high angle and with a high charge, the next with a lower angle and lower charge, and so on, until the last shot is fired with low elevation and high charge. This requires a reloading time of less than five seconds, which can be achieved by using a predetermined firing schedule and a fully-automated system for loading both projectiles and propellant charges. Some producers and programme managers have claimed that a simultaneous impact of up to eight projectiles is possible (GAO, 1997).

Direct Fire

Some artillery systems, particularly artillery guns, can operate in the direct-fire role by aiming directly at the target. For most systems in modern usage, this mode is intended to be used as a last resort in the case of perimeter penetration or ambushes by enemy forces. In these cases, an emergency firing procedure is conducted using specialised projectiles and a high charge. For some systems, special shaped-charge anti-tank projectiles and anti-personnel projectiles have been designed for this purpose (see Section 4 for further information on these types of projectiles).

Emergency Fire Missions

The term 'emergency fire mission' may be used to cover a number of scenarios where indirect-fire systems are deployed in haste or used in a reversionary mode (see below). Given the time-sensitive nature of emergency fire missions, they are most often subject to a more abbreviated assessment of CDE, known as a field CDE (see *Collateral Damage Estimation*, below).

Hasty Deployment

A hasty deployment is one in which an observer needs immediate fire support and there are no assets within range which have been surveyed in and set up, but a battery that may be re-deploying or moving for another reason is within range. Under these circumstances, the systems will deploy from the line-of-march, usually in a straight line. Most modern artillery guns can self-survey using GPS or inertial navigation devices, and thus may quickly locate and orient themselves to produce accurate firing solutions; older systems will use a reversionary mode to point the guns when they do not have the time to geolocate and orient the barrels.

Reversionary Firing

Guns firing in reversionary mode are brought in to action using manual gunnery techniques which rely on the simplest of survey techniques and generally do not use IT systems for ballistics calculations. These methods, used only in emergencies by relatively sophisticated forces, may be the only method available for obsolete weapon systems in service with less-advanced military forces or non-state armed groups. Indirect-fire systems can be crudely aimed using a compass held by a soldier standing behind the barrel or tube of the weapon, and with an elevation taken from firing tables, or by trial and error. The resulting fall of shot may be inaccurate, but can be corrected by an experienced observer. A well-trained force relying on a prismatic compass may typically expect a 20

⁴¹ Early examinations of this concept were described as "single gun, multiple round time-on-target capability" (see, for example Kogler, 1995).

mil error which, at 10 km, would result in an azimuth inaccuracy of 200 m; this is generally considered within tolerances for some militaries but would likely only be considered acceptable from a modern military viewpoint under self-defence fire conditions, due to the increased potential for causing harm to friendly forces or civilians and civilian objects⁴². The same calculations can be achieved using a smart phone or tablet if the barrel does not have a sight fitted, which is increasingly common when irregular forces obtain indirect-fire weapons and do not have correct sights available. There are mobile apps available that give accurate bearings, and can be used as a clinometer⁴³ to apply an elevation to the tube or barrel. If a sight breaks, older guns usually have a gunner's quadrant in the toolbox, which is an accurate clinometer that is held against a special surface on the breech block to apply elevations; a compass is used in this case as well. These methods are all gunnery techniques that pre-date computers and are, in many cases, relatively fast and accurate. If complex computerised systems are not used, artillery pieces are aligned using trigonometrical calculations from theodolite data. Although slow, this type of survey ensures that multiple weapons within a battery are aligned parallel to one another, so that one bearing can be applied to every weapon. The weapons would be arranged and employed to deliver fire in an open sheaf pattern. Mortars, because of their shorter range, are usually aligned by compass. Such manual gunnery techniques remain commonly employed by less-advanced armed forces and non-state armed groups.

Final Protective Fire

Another form of emergency fire mission is the final protective fire. In the case that friendly forces face overwhelming enemy forces, FPF may be called. FPF designates a priority target and takes the highest precedence over any other mission when requested (USMC, 1998). In some military forces, otherwise out-of-action guns are laid on this target so that it can be engaged immediately if called. The FPF will typically use a linear or open sheaf; the lethal radius of one projectile will determine the spacing of the rounds. All weapons that are used will fire in such a way that their effects are touching or overlapping. The intent is to create a 'wall of steel' (USMC, 1998).

Military forces differ in how FPF is delivered. In some cases, there is no set number of rounds assigned to this mission. Since FPF is only employed when there is a threat that a unit may be overrun, once called the mission will be fired until the requesting unit declares "end of mission," "cease loading," or the supporting unit runs out of rounds. To this end, in some military forces, if a unit runs out of high explosive projectiles, the standard projectile for engaging enemy forces, they will load in white phosphorus rounds, illumination rounds, or any other round available to them in order to provide support. A CDE conducted in conjunction with FPF will typically be abbreviated⁴⁴.

⁴² Author interviews with current and former senior artillery officers.

⁴³ A clinometer, also known as a gunner's quadrant, is a tool that is used to measure the angle of elevation in a right-angled triangle. It is used to adjust a weapon's barrel to the desired angle of elevation.

⁴⁴ Author interviews with current and former senior artillery officers.

Targeting considerations

In modern militaries, targeting policy is set at the highest level by policymakers, supported by their military staff; it consists of targets that may legitimately be struck in pursuit of a nation's politico-military objectives, and the rules of engagement that must be followed to ensure legality. Rules of engagement are a key method by which political control is exercised over the use of force (MOD, 2014).

The range of artillery, its destructive ability, all-weather capability, and – increasingly – the precision that can now be achieved with PGMs makes artillery an efficient weapon system for striking targets of high importance on the battlefield. With the question “may I strike this target?” which requires that the law of armed conflict be respected in the selection and attack of targets, employing forces must ask the question “should I strike this target?” Most military forces have mechanisms in place to answer that question. In large part, this is provided by a nation's rules of engagement (ROE).

ROE will frame the approval process to employ lethal force. ROE can vary across different geographic areas, over time within a conflict, according to the lethal system or munition used, and between different national forces, even when all other conditions are equal. The levels of command and control which are exercised may vary by system, formation, and even munition type. High-value munitions – either in total cost or strategic/operational value – or those deemed politically sensitive or posing potential IHL implications – may require approval from a higher level in the chain of command, in much the same way as certain target types.

Typically, manoeuvre units are assigned a given battle space and assume responsibility for controlling their battle space and the use of lethal force within it. Manoeuvre commanders are generally granted approval authority in accordance with broad guidelines which have been established by higher echelon command. Manoeuvre commanders may, in some cases be allowed to adjust ROE and other authorities to be more restrictive than what the higher command has dictated, but cannot approve a less restrictive process. Under this system, artillery fire is usually approved at the battalion level. Rocket artillery approval may reside with the higher-level command since these systems are usually coordinated by higher-level commands. One of the most important considerations in targeting an enemy force with artillery is achieving an appropriate weapon-to-target match. There is a certain degree of flexibility in employing artillery systems due to the range of munitions available. These concepts are discussed in further detail, below.

Types of Targeting

Targeting is either deliberate or takes place in contact. The use of indirect-fire systems most commonly takes place in contact. The critical difference is that deliberate targeting is planned, and requires formal clearance and a collateral damage estimate (CDE) – even if the target is emerging or fleeing. In contrast, as troops in contact usually have little or no time for a formal plan, the system operator or observer does not require clearance and can conduct a more abbreviated assessment of CDE, known as a field CDE (see *Collateral Damage Estimation*, below). Deliberate attack doctrine in NATO usage is appropriate for all platforms, but is skewed in favour of direct-fire from air platform, and generally assumes a precision weapon will be used by a weapon operator who can see the target. This is not the case for indirect-fire artillery systems, where an observer must calculate a target location and there will be some error in first round accuracy unless a guided projectile or rocket is used.

Deliberate Targeting is a formal and complex process, usually associated with the preparatory phases of a military campaign or targets beyond the contact zone. Strategic targets are always

deliberate, whereas tactical targets are only sometimes deliberate. Targets are invariably on a target list⁴⁵, even if this list only refers to a general type of asset that can be struck, rather than a detailed description and location. Recent smaller-scale air campaigns conducted by NATO nations offer good examples of the use of deliberate targeting, where target lists were cleared well before the attacks took place. These were adjusted and updated according to fresh reconnaissance and the results of the battle damage assessment (BDA) process (see *Measures of Effectiveness*, below). Each of the targets was analysed and presented to a targeting committee, who weighed the value of the target against the collateral risk represented in the collateral damage estimate. Where the risk of collateral damage was high, the decision on whether to engage the target was referred up the chain of command. Dynamic and emerging targets were similarly accounted for, and weapon operators could rapidly engage a high value fleeting target when it emerged. For example, long-range missile systems might be considered valid targets whose accurate location was not known; when such a system was spotted the firer could quickly assess the risk of collateral damage and engage the target⁴⁶.

Combat engagement relies on the active ROE to provide guidance and direction on the use of force. ROE will specify which adversary actions permit the use of force, and may place limitations on the type of attack or munition that can be employed. Very often, a commander with delegated authority may need to give permission for an attack. Reference to ROE will often save time in a dynamic environment, or when faced with a threat that does not allow for engagement in self-defence. ROE exercise political control over the use of force and translates in simple terms what is permitted or not permitted, so that in a stressful environment combatants can more easily discriminate between the potential for lawful and unlawful actions. An example of a combat engagement governed by ROE might be the engagement of a group of combatants emplacing a mine or improvised explosive device along a roadside. This engagement could be authorised as a response to a hostile act or to defend a community under protection.

Some military doctrines consider that there is an absolute right of **self-defence** in the face of a direct attack or immediate threat of attack. Under international humanitarian law, the prohibition of indiscriminate attacks and the rule of proportionality in attack must be respected at all times, even when self-defence and other time-sensitive situations may affect the feasibility of collateral damage estimation, munition selection, and other precautions. If the attack originated from a protected site such as a place of worship or a medical facility, for example, it might be permitted to return fire under certain circumstances; however, the use of particularly destructive munitions may not be considered appropriate for use in conformity with the law. For this reason, indirect-fire systems are generally subject to special guidance and this places extra responsibility on those using artillery in a self-defence engagement. Many military forces consider there to be a responsibility to identify the point at which an engagement should end, and a responsibility to ensure a qualified observer carries out the attack wherever practicable⁴⁷. If no qualified commander is available to authorise the use of an indirect-fire system in a self-defence engagement, the responsibility falls to the most senior

⁴⁵ Sample lists may include a master target list, joint target list, no-strike list, restricted target list, etc. (MOD, n.d)

⁴⁶ Authors' operational experience.

⁴⁷ Author interviews with current and former senior artillery officers.

person present who must, together with a qualified controller, make sure the use of indirect-fire is justifiable, necessary, and respects the law of armed conflict including the prohibition of indiscriminate attacks and the requirements of proportionality and precautions in attack.

Targeting Criteria

There are some general criteria for deliberate targeting and for combat engagements⁴⁸. These provide a list of considerations that, if followed, should ensure that an engagement is justifiable. Qualified controllers will need to satisfy themselves that they have fulfilled these criteria before initiating fires. Self-defence scenarios may use an abbreviated set of targeting criteria, varying by state.

- a. The target must be positively identified (PID) to ensure that there is a reasonable certainty that it is valid. If the attack is pre-planned, this will have been done as part of the targeting process, but in a combat engagement this responsibility may lie with the observer.
- b. Rules of engagement must be satisfied, and the specific rule must be identified.
- c. There must be an assessment of the incidental effects of the engagement; both lethal and non-lethal attacks must take account of collateral damage. The CDE can be a formal process, or can be a field collateral damage estimate carried out by the observer.
- d. To aid the collateral damage assessment, a pattern of life should be known; this may require prolonged observation reported by intelligence or by direct observation over time. Tactical engagements often have an advantage in this respect, as the troops concerned may have spent a long time in the vicinity of the target and are sometimes familiar with the local pattern of life. Pattern of life is specifically concerned with reducing the likelihood of incidental civilian death.
- e. Before any engagement that does not constitute self-defence takes place, the attacker will need clearance from the command authority that holds the delegated responsibility for the use of force. Levels of clearance vary from the weapon operator or authorised observer, right up to the highest political level for some high-risk pre-planned targets.

Target Identification & Development

In prosecuting a target, arguably the most important factor contributing to a successful attack is the ability to accurately locate and identify a target. This requirement is satisfied by a range of observers. Firing elements generally have observers organic to their unit. However, in most armed forces, any individual can make a request or 'call for fire', regardless of who they are and to which unit they are assigned. A competent authority within the artillery chain of command must then determine if the call for fire is approved (see *Application of Fire*, above).

For personnel assigned as observers (sometimes called 'spotters'), many militaries have made an attempt to professionalise the skill set beyond what scout observers/fire support personnel receive during initial military training (USMC, 1998). The push for professionalization is evidenced by the

⁴⁸ Adapted from US, NATO, and UK publications and input from interviews with current and former senior artillery officers.

creation of new, specialised qualifications in a number of NATO forces, many of which require that observers attend technical schools. Attendance on these types of courses is not always restricted to personnel from artillery units; they are often open to radio operators, infantry, and other combatants that may require training in the coordination of supporting fires (DoD, 2010b). Such personnel, known in some forces as joint fires observers (JFOs) are trained to be well-versed in basic and advanced calls for fire, and to provide target location and information for close air support when approved by a certified and qualified joint terminal attack controller (JTAC).

Observers are typically equipped with a map of the area in which they intend to locate targets, which will provide a grid location of an intended target asset. Additionally, observers are always outfitted with an optic of some variety; at the most basic level, these could be regular binoculars with a reticle pattern marked on one of the lenses to allow for deviation estimation. More complicated optical systems have integral laser rangefinders that determine range and direction with high precision (USMC, 1998).

The medium used to identify a target and the fidelity of the target data provided is also critical. This target data can determine the required volume of fire to be delivered, and the type of munition employed. When firing conventional unguided projectiles, artillery is typically massed during the final stage of fire. As a result, high precision is not ordinarily the intended result and artillery is considered an 'area effect' weapon system (USMC, 2002). Observers always strive for utmost accuracy, understanding that there are likely to be unknown errors in range and location estimation. In the case of precision guided rocket artillery munitions, for example, a target fidelity⁴⁹ of 10 m may be required in order to deliver the desired effects on target. Whilst the estimated casualty radius of many guided rocket artillery munitions is higher than 10 m (see above), they are generally considered a high-value asset and are not typically employed *en masse* like unguided projectiles or rockets, but rather at a specific target in order to capitalise on their precision guidance (USMC, 2001).

Organic to some higher-level commands, counter-battery and surveillance radars are also employed to identify and develop targets. These systems can range in size from vehicle-borne systems to more manageable man-portable devices. Ground surveillance radars are an observation aid to detect personnel and vehicles, including aerial systems. The detection range varies according to the system and target profile but many modern man-portable systems can deliver a geolocation accuracy of 10 metres under all weather conditions, day or night, out to 30 km, with several-vehicle borne systems operating at 60 km or further. The range of detection is principally affected by interference from environmental factors such as rain and the radar return which is governed by size and shape of the target, as well as its speed and angle of approach. Doppler radars only track moving targets effectively and are often referred to as ground moving target indicators (GMTI). Conversely, synthetic aperture radar (SAR) will detect stationary targets even through conventional concealment techniques such as camouflage nets, and are very good at detecting metallic objects with corners, making armoured vehicles particularly vulnerable. SAR is mounted in conjunction with GMTI on a number of fixed wing platforms (both manned and unmanned) designed for intelligence, surveillance, and target acquisition (ISTAR) purposes.

Counter-battery radar scans the ground horizon in an arc of azimuth that varies with the type of system, typically 45 degrees. A representative system can detect guns and rockets at ranges out to 25 km and 120 mm mortars out to 40km. The reliability of the radar is affected by the projectile size, its angle of flight through the radar beam in elevation and azimuth, and environmental interference such as rainfall. The flat trajectory of rockets can prove particularly challenging for these systems whereas the high angle of mortar fire renders mortar projectiles especially vulnerable to radar detection. The radar spots a munition when it breaks the horizon and measures its range and

⁴⁹ How accurately the position of the target can be described.

bearing at intervals as it rises. The system will then calculate the origin of the projectile and deliver a location with an accuracy based on range, typically between 2 and 3 per cent of the range (200-300 metres at a range of 10 km, for example). In military terms, this location is generally considered accurate enough for counter-battery fire, although a collateral damage estimate must be conducted⁵⁰. In densely populated areas, different thresholds may apply.

Radar can only detect and classify targets, it cannot identify them and in a restrictive ROE environment is usually unable to give rise to an authorised engagement without PID from another source.

Weapon-Target Matching

At a fundamental level, munitions are selected based upon the effects which military planners wish to impose on a given target (Cross et al., 2016). There are many ways to prosecute a target beyond the standard unguided high explosive projectile and point detonating fuze. The process of selecting the right weapon-to-target match is sometimes known as ‘weaponeering’, weapon-target matching, or weapon-target assignment. For artillery systems, this should begin with selecting the correct projectile/fuze combination in accordance with the selected target. Artillery and mortars have a significant destructive effect and offer a high lethality against unprotected targets, but they are primarily a suppressive weapon designed to prevent an enemy from using their weapons effectively or manoeuvring⁵¹. The use of artillery often has second and third order consequences that may be undesirable or illegal, particularly when used in complex terrain such as a built up area (British Army, 2015; US Army, 1992; DoD, 2010b).

Weapon-target matching seeks to make sure that the appropriate weapon is used to achieve the desired military aim in conformity with IHL. It is target effect that is paramount, and so artillery systems employing unguided munitions are generally inappropriate for striking a point target in a populated area or a small moving target. Indeed, attempts to successfully engage such a target using such means are likely to result in effects that are not limited to the target, occurring over a wide area around the target. In this case, a precision guided artillery projectile may be employed, or a direct-fire guided or unguided munition may be employed by another platform, provided the weapons’ foreseeable effects are not such as to cause disproportionate civilian loss, failing which a different tactic or method of warfare must be used. Weapon-target matching is directly informed by the collateral damage estimation process.

When making a call for fire, an observer may conduct some basic weaponeering by asking for a specific projectile/fuze combination to engage the target during the fire for effect phase. However, this recommendation may be rejected or modified by the fire direction centre (FDC), depending on the broader implications at hand. For example, a trained observer (of a State not party to the Convention on Cluster Munitions) will likely understand that armour is best engaged with dual purpose improved conventional munitions (DPICM), a projectile that air-bursts and dispenses small HEAT/FRAG sub-munitions. However, these munitions typically have a high failure rate, leaving unexploded ordnance on the battlefield. Because of this, such a munition will not be authorised for use if a friendly manoeuvre unit or civilians is likely to be passing through the target area at any point in the future. The same holds true for other munition types, such as artillery delivered anti-armour.

⁵⁰ Author interviews with current and former senior artillery officers.

⁵¹ Historically, several major militaries have employed artillery primarily for its destructive effects. “Massive and indiscriminate” use of artillery has played a part in several conflicts of recent decades (Baev, 2000).

Not all projectile/fuze combinations are available across the spectrum of artillery systems. HE or HE-FRAG munitions are available for all systems, from small 60 mm mortars up to the largest calibre rocket artillery. In most common artillery gun calibres, there is an almost-complete overlap of availability. Some rounds, however may be available for one class of weapons in a military's inventory, and not another.

Collateral Damage Estimation

Collateral damage analysis is conducted to estimate unintended or incidental damage to persons and/or objects which are not the intended target, and which are not otherwise lawful targets (DOD, 2013). A CDE is a formalised process which determines the projected effects of a range of weapon/munition/fuze combinations under various circumstances. Depending on the speed with which a target is engaged (deliberate versus dynamic targeting), the CDE process may be conducted by different individuals under differing circumstances. A rapid collateral damage estimate (CDE) process may be conducted in the field as necessary in time-sensitive situations, such as when troops are in contact, or when a target of opportunity is identified. Such estimates are almost always conducted at a lower command echelon than those forming part of a deliberate targeting process. In deliberate targeting, the CDE process may be complex, and will take into account a number of factors including the nature of the target, population density in the surrounding area, target composition, topography, soil type and density, weather, angle of attack, delivery platform, munition type, warhead type, and fuze type and setting. It will feed directly into the discussion of weapon-target matching. For a fuller discussion of the factors affecting CDE and weapon-target matching, see Cross et al., 2016.

Artillery, as a relatively blunt instrument of battle, can be most freely employed in open, undeveloped environments. Operating in urban environments or more developed areas can be one way for a force to mitigate an opponent's heavy armour or indirect-fire capability (USMC, 2016). Some military forces go to great lengths to conduct a thorough CDE prior to employing indirect-fire artillery systems.

According to the assigned ROE governing a particular conflict, certain levels of anticipated collateral damage may require commanders at different levels of authority to approve a particular strike or system usage. A lower-level commander will be able to approve a CDE with less collateral damage, and as the level of likely collateral damage increases, parties higher in the chain of command will be required to approve an engagement (CJCS, 2009; DoD, 2003).

Measures of Effectiveness

As in most military activities, prosecuting a target requires both immediate feedback and an assessment of the broader context. At the lowest level, the observer engaging a target will typically provide information after fire is provided. This information is collected and disseminated in the form of a report generally referred to as a battle damage assessment (BDA) or battle damage assessment report (BDAR). BDA reports include an estimate of the effect on the target in terms of destruction, neutralisation, or suppression. More detail is provided where available, such as total estimated casualties inflicted. Often the level of damage incurred is difficult to ascertain and must be estimated based upon observed munition effects on the environment and knowledge of troop densities, vehicle and equipment vulnerabilities, and degrees of protection (Cross et al., 2016).

One of the duties of an artillery observer is to assess the effects of a fire mission and report these to the chain of command in an end of mission report. This assessment, often known as an 'informal BDA', may result in the re-engagement of a target until the desired target effect is achieved. Depending on the nature and importance of the target, observed effects including collateral damage, and whether target engagement has met certain destruction criteria, an engaging force may choose to re-engage the target, either with the same system or a different system based on

input from previous engagements. Deliberate targets are part of the targeting cycle and are selected for engagement by a targeting board. Deliberate targeting will always incorporate a formal BDA as part of the targeting process, whilst a combat engagement will usually include formal BDA, although informal reporting may be sufficient in some cases (DOD, 2013).

Sometimes, a BDA will determine the desired effect was not achieved. Based on the intent of the fire mission (target destruction, neutralisation, or suppression) and whether or not the fire mission was successful, an observer may choose to 'repeat' the mission, which indicates to the firing element they should replicate the fire for effect (see *Fire for Effect*, above).

The use of imagery from aircraft or remotely piloted vehicles (RPV) is now typical in a formal BDA process for many armed forces, and qualified photographic interpreters will generally produce a report illustrating the target effect and comparing the damage against the desired effect. It is quite common for a BDA of indirect artillery fire effects to be initially conducted by a forward observer, and followed up by tactical or larger RPVs in order to provide better analysis and a more detailed record of effects. Non-state actors have also begun to incorporate small UAVs in a limited BDA process (Friese, Jenzen-Jones & Smallwood, 2016).

Operational considerations

Artillery systems can be complex pieces of equipment, particularly those which have been updated to include digital capabilities. This equipment withstands a tremendous amount of stress, during firing, and during transport and emplacement in austere environments. Additionally, artillery is designed as an all-weather fire support system, and must be capable of operating in any environmental condition.

Despite making systems as rugged as possible whilst ensuring they remain light enough to meet mobility requirements, many artillery weapons are maintenance-intensive platforms and require constant attention to ensure that all systems are properly operational, no parts are broken, and all sub-components that require calibration are reading accurately. Mortars are comparatively simple in terms of both number and complexity of components, and in their sighting systems and ammunition. Maintenance and operation of mortars is much simpler than for artillery guns, adding to their popularity amongst non-state armed groups and less sophisticated forces. Even though a firing battery may typically consist of six or eight weapon systems, it is not uncommon for an artillery unit to have one or two weapons out of action due to the intensive maintenance schedule. To mitigate this, many units take an aggressive approach to preventative maintenance checks and services (PMCS), and will take one (or more) artillery mechanics with them on firing operations or deployments. Having access to an artillery mechanic while firing provides units with the capability to perform a basic level of maintenance, which may be all that is required to render a system operational under battlefield conditions.

Since the purpose of artillery is to support manoeuvre units, all artillery pieces have mobile capability. These take the form of either self-propelled artillery system, most commonly tracked or wheeled, which can provide similar mobility to other tracked or wheeled units that it may support, such as mechanised infantry units. Towed systems will be pulled by a prime mover according to the weapon system's size and can generally travel via roads, unimproved surfaces, and are often capable of some limited cross-country movement⁵². In protracted operations (and occasionally during short-term deployments), a firing element may choose to employ itself from a firing base. A firing base is a position that has an element of deliberate protection developed so as to provide a suitable position

⁵² In service with non-state armed groups, artillery pieces are often moved by a variety of vehicle types, based on availability and suitability. In some cases, artillery may be rendered immobile for extended periods of time due to a lack of dedicated logistical support.

for providing prolonged fire support. This is most commonly seen when infantry units are assigned to an area of operation, and begin to place patrol bases and combat outposts⁵³.

There are other operational considerations for artillery that are not tied to personnel. Many of these are rooted in doctrine. For example, some armed forces subscribe to the idea that the optimal placement for an artillery firing element is with two thirds of its firing capability located beyond the unit it is supporting, which is known as the 'one-thirds, two-thirds rule'. In other cases, artillery may be pushed forward – sometimes known as an 'artillery raid' – in order to strike targets⁵⁴ which would ordinarily fall outside of the systems' maximum range (Burgess, 2011). Other considerations may include battery emplacement techniques that maximise defence and dispersion for survivability.

Other considerations concern the munitions being employed. All fuzes, projectiles, rockets, and propellants have an associated lot number marked on them. This may be used to identify batches or lots. In some cases, a deficiency may be identified in a certain batch and items from this batch may have to be discarded, or require special considerations to be applied when calculating firing solutions⁵⁵. Many GPS-guided artillery projectiles, for example, require the selection and setting of a special fuze to enable them to function as a PGM. However, some of these fuzes have a limited life span once they are set. If the round is not fired within the set time, the fuze battery will run down and the fuze cannot be used as intended. To avoid such a situation, many artillery batteries apply certain standard operating procedures (SOPs), such as not fuzing a round until the fire mission has been approved. A battery can, and often does, generate multiple SOPs applicable to a given operation or conflict to expedite successful engagements. These SOPs govern every aspect of battery life, such as how many rounds remain fuzed while emplaced, what data is considered standard in response to certain mission (immediate suppression, for example), or how a battery will divide operational tasks if it needs to be broken down to smaller elements in order to conduct split-battery operations.

Survivability is a significant consideration in the selection and occupation of firing positions. For every moment an artillery unit is unable to fire, they are not providing support to their assigned manoeuvre unit. Artillery systems on the battlefield are vulnerable both to opposing indirect-fire and direct action. For this reason, a typical battery of six to eight guns or mortars will occupy a position in which they are dispersed and camouflaged to avoid detection, and in order to minimise casualties if hit by enemy fire. Ammunition is protected by being dug in or sand-bagged, and weapons are often dug into gun pits to further enhance survivability (British Army, 2015). Although most artillery units possess an organic ability to defend themselves with attached weapon systems and personnel, it is not the role of artillery units to become decisively engaged in close quarters combat.

Sustainability is also a key consideration for artillery units, and they are often supported by sophisticated logistics infrastructure in modern military forces. In common with other arms and

⁵³ In addition to maintenance, security and battery survivability are other factors that might leave individual weapons systems in a unit out of action. Since artillery units are meant to be self-sustaining, they do not draw extra manpower for security from supported units. In certain situations, such as when emplaced at fire bases, infantry and artillery elements can have a mutually-supporting relationship, with infantry or other manoeuvre elements providing fire base security or local security through patrols, while the artillery provides the required fire support for manoeuvre operations. Where security from other elements is not available, a firing battery may be forced to operate with fewer artillery systems in order to free up manpower to provide their own local security. For this purpose, many artillery units are outfitted with crew-served weapon systems – generally medium and heavy machine guns and automatic grenade launchers and light anti-tank weapons. These complement the unit's light tactical vehicles and may be employed for static or convoy operations, as required.

⁵⁴ Often high-value targets.

⁵⁵ Determining the adjustments made to the weapon system in order to fire accurately and precisely at the target.

services in a military force, indirect-fire assets will require fuel and spares, as well as rations and water to sustain their assigned manpower. Artillery units differ from other parts of the force in that ammunition is not only the most crucial resupply item, but also the most problematic, due to its significant weight and the high rates of consumption typical of indirect-fire systems. In a NATO force, artillery ammunition can occupy up to 75% of the effort of a logistic resupply organisation in some operations⁵⁶. This also imposes a significant storage requirement, with artillery ammunition dumps occupying large areas that are frequently vulnerable to interdiction. It is often easier to counter a force supported by mobile and effective artillery and mortars – which are hard to detect and engage – by hunting the ammunition supply chain and attacking the more vulnerable convoys and dumps.

Effective maintenance and an accurate record of use history can be vital to maintaining weapon systems' performance, including their expected level of accuracy. Poor storage of weapons, support systems, or their ammunition, or the improper maintenance of such, can reduce the effectiveness of artillery systems and introduce operational limitations, notably in terms of reliability and accuracy.

Training

In common with direct-fire weapons, indirect-fire weapons are meant to be controlled by qualified operators who are trained and tested to ensure that they are capable of assessing the risks posed to civilians and applying ROE and the other restrictions in combat; they have to be trained, qualified, competent and current – sometimes referred to as 'TQC2'⁵⁷. However, in practice, this is not always the case. Different armed forces have different standards and requirements for training personnel, and non-state armed groups will often differ substantially from conventional forces.

In most military forces, officers tend to supervise the direction of artillery and, though they are qualified to control, they will often delegate this to non-commissioned officers in the fire control team – most often, an air force observer will direct air and aviation assets in direct-fire aerial attack, an artillery observer will direct artillery gun and rocket systems, and a mortar fire controller will direct mortars. Each will contribute to the targeting process carried out at the tactical level, with the team commander (often a captain in NATO militaries) making decisions concerning collateral damage, battlespace management, and weapon-target matching. The team commander is in turn supervised and directed by his superior, who commands the fire element of combat support for an armoured or infantry formation. This command and control process is replicated at the different levels up the military chain of command (MOD, n.d).

Training goes beyond simple target practice and seeks to improve a firing element's proficiency to 'shoot, move, and communicate', and everything in between. In many militaries, observers attend career courses in the discipline with which they are associated, furnishing them with training, qualifications, and competency. Currency is maintained with a logged requirement to conduct a set number of exercises replicating the various engagements that they may meet on operations; these are carried out live on firing ranges, and in simulated environments throughout the training year.

Echoing the complex training required of the observer, sophisticated armed forces require the crews delivering artillery fires as well as those supplying and maintaining them to be highly skilled. Gunners

⁵⁶ Authors' experience.

⁵⁷ Various terms are used by different armed forces, including suitably qualified and experienced person (SQEP), and others.

are individually and collectively (as a team) trained to operate their weapon safely and quickly on career courses, with extra responsibility coming with rank. In a gun, rocket, or mortar team most personnel are handling ammunition to sustain the weapon; the soldier operating the sight who also fires the round will have typically risen from this job via attendance at a course and promotion. At the top of this crew will be the weapon commander. He will check the fuzing of the projectile and the alignment of the weapon before giving the order to fire (British Army, 2015).

This whole process is drawn together in collective training exercises, often replicating the conditions expected to be encountered on operations. These exercises integrate the teams in dry and live firing manoeuvres which will culminate in a full rehearsal exercise in conjunction with relevant infantry and armour elements. Such exercises require large training areas and are complex. They will often include assessment in accordance with the Training and Readiness (T&R) standards required by the national force. T&R is a process that is followed at all levels and is audited in the manuals and drill books that underpin individual and collective training.⁵⁸

⁵⁸ Much of the discussion in this report draws from these publications, including both US and UK sources, as well as NATO publications. Several are listed in the bibliography.



SECTION 3

Accuracy & Precision

Ove S. Dullum

Overview

Unguided indirect-fire artillery projectiles and rockets follow a ballistic trajectory upon being fired, governed by the propellant charge or rocket motor and the physical characteristics of the barrel and projectile or rocket. The accuracy of indirect-fire systems is therefore a combination of these ballistic parameters and environmental factors.

When discussing accuracy, a number of different, specific terms can be used, and sometimes these terms can differ by nation, or in different environments.

Within this report we use the following terms and definitions with regards to accuracy of indirect-fire systems:

Accuracy: the measure of mean point of impact (MPI) deviation from the desired MPI.

Aim point: the desired mean point of impact.

Bias: the distance (inaccuracy) and direction between the actual MPI and the desired MPI.

Error: A source of bias or imprecision, such as gun tolerance, ammunition variance, or meteorological conditions.

Error Budget: total cumulative expected error, which may or may not be acceptable for a given scenario.

Mean point of impact (MPI): the average impact position of a number of rounds.

Precision: the measure of MPI consistency or 'dispersion'.

These terms are illustrated in Figure 3.1, below.

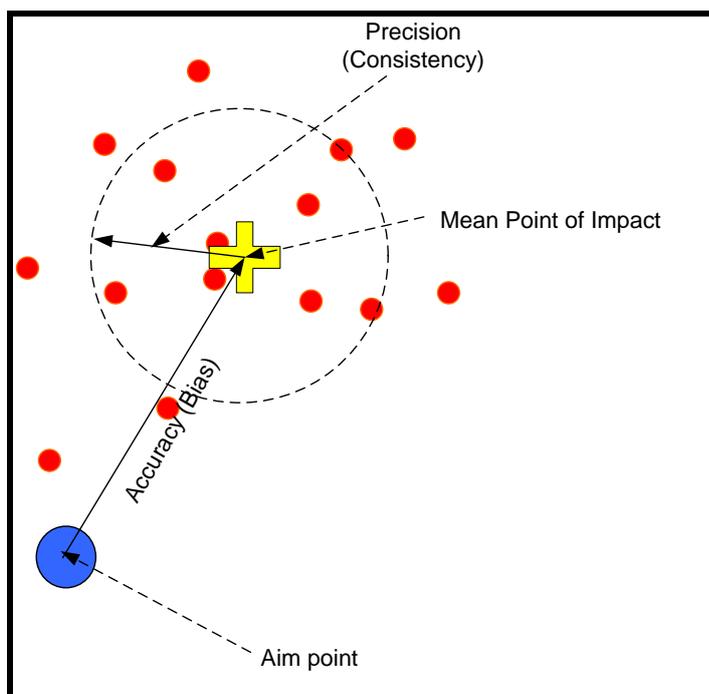


Figure 3.1 The relation between the different terms describing accuracy (source: ARES).

The combination of ammunition and indirect-fire system is modelled and then test fired to calculate the path of the projectile at a given barrel angle; known as gun elevation. This means that for a given distance from gun to target an elevation is set for the gun to achieve a desired range. In artillery parlance, these firing solutions are known as firing tables and they are often produced in paper format, as well as being encoded in ballistics computers and fire control systems (FCS). These can prove particularly useful in situations where speed is critical, such as emergency or hasty firing. To point the gun in azimuth (the direction in the horizontal plane) it is necessary to determine the direction from gun to target in order to apply the correct bearing to the gun. It is critical that both the coordinates or relative positions of both the artillery system and the target are known. The accuracy of this information will affect the deviation from desired mean point of impact (error) for the first projectile fired.

In broad terms, environmental factors describe the characteristics of the environment at both the indirect-fire system and in the projectile flight path, and some non-ballistic influences on the platform. The external ballistics of a projectile are determined by many factors, and when firing at long ranges some geophysical and environmental factors become particularly important. Foremost amongst these are meteorological factors, which almost invariably have the greatest influence on the flight of a projectile or rocket through the atmosphere. Pressure, wind and temperature are examples of these factors. Other factors that are considered include the temperature of the propellant, drift caused by the spin of the projectile in flight (the Magnus Effect), the Coriolis Effect, and muzzle velocity (see below). Barrel wear is the principal reason for variations in muzzle velocity, which may cause projectiles to fall short or long of their desired mean point of impact.

This section will describe errors which are present for the three indirect-fire systems discussed within this report; artillery guns, mortars, and rocket artillery. Meteorologically-induced errors are discussed broadly as they dominate the error budget for long range fire. Finally, we will briefly examine the technical characteristics of these three indirect-fire systems, and how these characteristics can affect accuracy.

Circular Error Probable

One common measure of weapon system precision is known as **circular error probable (CEP)**. The actual calculation used to determine the CEP for a weapon system is complex and requires substantial modelling, field testing, and statistical analysis of fall of shot data under known conditions, however, it can be approximated to the radius of a circle, centred about the MPI, whose boundary is expected to include the impact points of 50% of the munitions in question (Sheedy, 1988). In simple terms this means half of the munitions fired at a target would fall within the CEP of the weapon system, 93.7% will fall within 2 CEP, and 99.8% will fall up to 3 times the CEP radius from the MPI (see Figure 3.2)⁵⁹. A larger CEP therefore denotes more uncertainty as to the precision of the weapon system⁶⁰.

⁵⁹ Figures given for CEP assume munitions employed under standard testing circumstances unless otherwise indicated. These figures are found in national publications.

⁶⁰ The original concept of CEP was based on a circular bivariate normal distribution (CBN) with CEP as a parameter of the CBN just as μ and σ are parameters of the normal distribution. Munitions with this distribution behaviour tend to cluster around the aim point, with most reasonably close, progressively fewer and fewer further away, and very few at long distance. That is, if CEP is n meters, 50% of rounds land

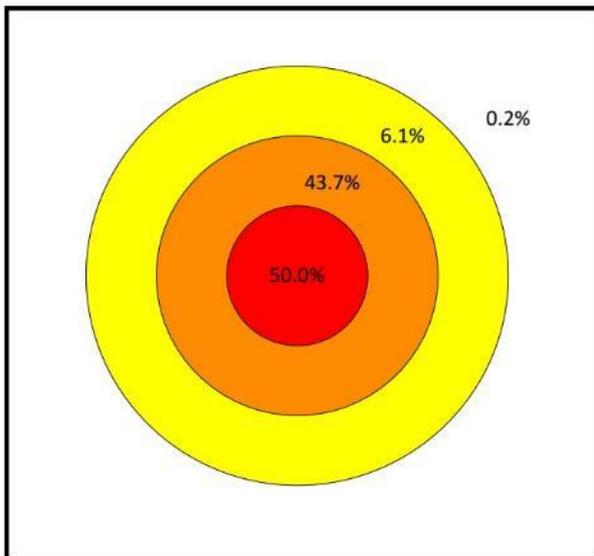


Figure 3.2 Circular Error Probable circular distribution diagram (source: ARES)

As outlined earlier, this kind of circular distribution behaviour is rarely exhibited by artillery, especially in the indirect-fire role. Munitions often have a larger standard deviation of range errors than standard deviation of azimuth (deflection) errors, resulting in an elliptical confidence region. CEP can be relevant when discussing the dispersion (precision) of a salvo of fire from artillery systems, but is not very useful for describing accuracy⁶¹. Nonetheless, the term is commonly used by some manufacturers and militaries, and by policymakers and other stakeholders.

Table 3.1 gives some indicative accuracy figures for 105 mm and 155 mm artillery guns, expressed in CEP.

Table 3.1 – Indicative accuracy of 105 mm and 155 mm artillery guns

105 mm Artillery Accuracy	
Range	CEP
5 km	60 m
10 km	97 m
15 km	120 m
20 km	163 m
155 mm Artillery Accuracy	
Range	CEP
15 km	95 m
20 km	115 m
25 km	140 m
30 km	275 m

Sources: Hill, 2007; Hill, 2011; Dullum, 2010

within n meters of the target, 43.7% between n and $2n$, and 6.1% between $2n$ and $3n$ meters, and the proportion of rounds that land farther than three times the CEP from the target is around 0.2% (Cross et al., 2016).

⁶¹ Precision guided munitions follow the same statistical laws as unguided munitions, but their CEP is much smaller. PGMs generally have more 'close misses' and so do not follow a Gaussian (normal) distribution (Cross et al., 2016).

Error Classification

The bias and imprecision induced by the total cumulative error is practically impossible to predict. What is more predictable is the distribution of the error budget by class, depending upon the range and other parameters, detailed under the relevant sections below.

There are two classes of errors; systematic errors and random errors. **Systematic errors** result in a bias (affecting accuracy), and **random errors** result in imprecision. Systematic errors repeat themselves from round to round, resulting in a mean point of impact that deviates from the aim point. If time permits, and impact points are observed, these can be largely compensated for by adjusting the firing parameters in successive salvos. Random errors are random from round to round. They are mostly related to variances in the projectile or rocket or the weapon system, but short term variation in the wind conditions are also of importance (Cross et al., 2016).

The relationship between systematic and random error is important, as the concept of dispersion can be critical for artillery effectiveness. An ideal error budget will be dominated by random error. Significant systematic error will result in low accuracy, however sufficiently high random error may result in a limited effect on the target area (see Fig. 3.3, no. 1). The ideal scenario is that a predictable random error results in a dispersion of impact points which delivers the desired effect over the target area, with minimal systematic error resulting in high accuracy (Fig. 3.3, no. 5).

If random errors are acceptable but systematic errors are not accounted for, the desired mean point of impact is missed with high precision (Fig. 3.3, no. 2). With more random error than budgeted and low systematic error, the imprecision may result in only a few impacts delivering the desired effect on target, despite high accuracy (Fig. 3.3, no. 3). With less random error than budgeted and low systematic error, the dispersion of impact points may be such that the entire target area is not affected as desired (Fig. 3.3, no. 4).

The importance of accuracy and/or precision can vary widely based on the weapon system, projectile type, rules of engagement, collateral damage estimate, environment, geography, and other factors.

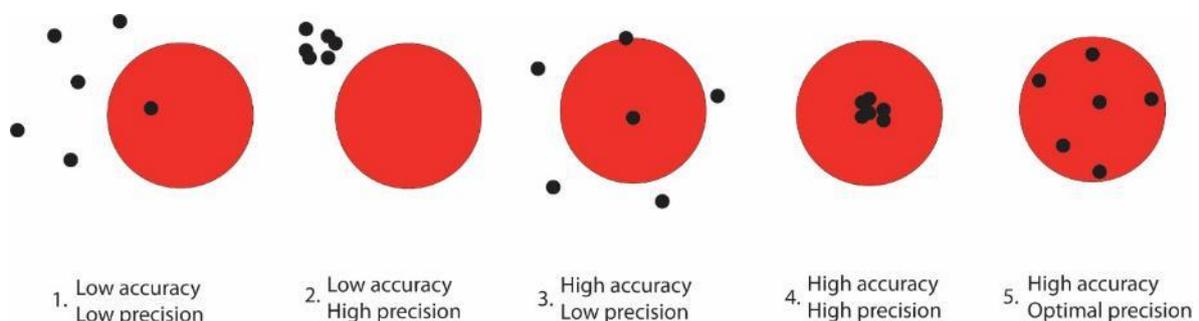


Figure 3.3 Accuracy and precision as affected by systematic and random errors. Red circle represent the desired area of effect (source: ARES)

Systematic Errors

Systematic errors are errors that remain approximately consistent shot to shot. Systematic errors can therefore be compensated for. After observing and measuring the MPI's bias, this information can be used to update the ballistics model (via a ballistic computer or manual gunnery techniques) to achieve higher accuracy. However, as systematic errors are observed conflated with random errors, the extent to which a systematic error can be compensated for depends upon how readily it can be identified.

Meteorological errors

These comprise a very complex group of errors that depend on several factors. With the increasing range of artillery guns, rocket artillery, and to some extent mortars, meteorological (MET) errors, both systematic and random, tend to dominate the error budget, particularly at ranges beyond 15 km. The modern emphasis on 'first-round fire for effect' (see *Fire for Effect*, above) often means meteorological data is more crucial than ever. MET errors can be reduced by analysing the atmosphere through which the projectile is to be fired. This information is a prerequisite for using these systems effectively.

A ballistics meteorological report may be conducted to determine atmospheric conditions at altitude intervals up to the predicted apex of ballistic trajectories. This data will then be used to alter the azimuth and elevation, either from firing tables or as determined by a ballistics computer. Such meteorological surveys will depend on the availability of equipment, manpower, and time.

Data on atmospheric conditions is commonly collected using meteorological balloons released from the rear area of the artillery battalion. Up to the turn of the century, these balloons contained a light-weight radar reflector, and the operator had to track the balloon with a radar unit up to the desired altitude. By measuring the horizontal drift of the balloon, the speed and direction (i.e. velocity) of the wind can be calculated. In addition, a sensor measuring pressure and temperature is also carried by the balloon. This technique is still in use, but the radar has been replaced with a GPS-unit, which makes the data collection far easier and typically more accurate.

Within NATO militaries, meteorological data requests are commonly issued as meteorological-computer (MET:CM) or meteorological-target acquisition (MET:TA) messages⁶², or in other formats. Data elements used by most systems may include:

- Relative humidity⁶³
- Temperature
- Barometric pressure
- Altitude of MET data station (relative to weapon system)
- Wind speed
- Wind direction

⁶² Sometimes known more broadly as simply 'meteorological messages' (MM).

⁶³ Oftentimes, humidity is not explicitly included in artillery MM. The temperature term used is 'virtual temperature' which is the actual temperature corrected for humidity in such a way that the air density is accounted for (Dullum, 2005).

This set of data is given for each 'meteorological zone'. Zone 0 is at ground level for the artillery meteorological station (AMS), zone 1 is from 0 to 200 m altitude, and so on, up to 30 km altitude and 32 zones (Blaha, Potužák & Šilinger, 2014). This data is entered into the ballistics computer. From this, positional data for the firing unit and the desired mean point of impact, the azimuth angle, the elevation of the gun, and the propellant charge (where variable) is determined.

Weather can be volatile. MET data sampled four hours ago may not be representative of the current conditions. Consequently, the MET data has to be refreshed quite frequently, typically at least every four hours, and if possible, hourly. Another source of error is that the MET data cannot be sampled near the desired mean point of impact, unless the balloon drifts towards that location and survives. The meteorological conditions may be different at the firing position relative to the desired MPI, especially if the weapon is operating in terrain with significant topographical variances; the weather in two neighbouring valleys may differ significantly. Passages of fronts or abrupt weather change in wind velocity, pressure, and temperature, are particularly disruptive to MET data and can constitute significant error.

Weather prediction for indirect-fire is a developing field, and standards exist for applying such information. The potential of this technique is promising, and may substantially reduce the error induced by the weather.

Wind

For unguided long range artillery, the wind induced error is the most significant contributor, and the factors involved are quite complex. Typically, wind is variable over an area and can be volatile. The degree of variation is a function of height above the ground, the average wind speed and time⁶⁴:

- If the average wind speed is doubled, the wind variation increases by 152%.
- If the altitude is halved, the variation decreases by 26%
- If the age of the MET data is doubled, the wind variation increases by 26%.

Terrain can have a significant effect on wind below the Ekman layer⁶⁵, about 2 km above ground level. Above the Ekman layer, the atmosphere is not affected by terrain, but the wind speed increases at constant rate until the tropopause⁶⁶ is reached at around 10 – 12 km above sea level. At this level, the wind speed may be very high however, the air pressure is quite low and therefore the impulse induced by the wind is limited. At this altitude, jet streams may also be present⁶⁷. (Sedunov et al., 1991). Inside the Ekman layer, and especially below 1km, wind can be very volatile and the velocity may vary significantly in a matter of minutes. This can have serious consequences for rockets as they have their boost phase inside this layer.

⁶⁴ These figures originate from a formula used in Norwegian Army field artillery computer which predicts the expected value of wind speed change as a function of time, altitude, and current wind speed. See Dullum, 2005 for a fuller explanation.

⁶⁵ The Ekman layer is that in which flow occurs as the result of a balance between pressure gradient, Coriolis Effect, and turbulent drag.

⁶⁶ The tropopause is the boundary in the earth's atmosphere between the troposphere and the stratosphere. It occurs somewhere between 9 km at the poles and 17 km at the equator (Sedunov et al., 1991).

⁶⁷ These are currents of air in the atmosphere moving at very high speed, from west to east, which may exceed 150 knots.

The error induced by the wind depends on the relative air force acting on the projectile in flight. Ballistic projectiles will be affected by the air resistance as a function of the resultant force vector of wind against the projectile's relative speed. A longitudinal wind (headwind or tailwind) will result in a deviation at the impact point according to the direction of the wind. For a lateral wind (sidewind or crosswind), the situation is more complicated. A projectile without propulsion will deviate in the direction of the wind, such that a wind from the right will deflect the projectile to the left. On the other hand, rocket propelled projectiles, which have an additional force component caused by the propulsion, will accelerate the projectile during the boost phase causing deflection in the opposite direction, such that a wind from the right will deflect the rocket to right. However, when the rocket motor ceases to function, the deflection will be consistent with other ballistic projectiles, though with different aerodynamic properties resulting in a different proportional wind error (Dullum, 1993; 2005).

Temperature and pressure

Temperature and air pressure both affect the density of the air. Speaking generally, an increase in temperature makes the density lower; an increase in pressure makes it higher. The temperature normally decreases with altitude, around 6.5°C for each kilometre above sea level. This is called the lapse rate. Upon reaching the tropopause, the temperature remains constant with height. A couple of kilometres higher, the temperature begins to increase again (Cavcar, 2014). Air pressure is a measure of the weight of air above a given point in the atmosphere, thus it will always decrease with altitude. The pressure will vary by a few percent depending on the presence of low-pressure or high-pressure areas in the weather-pattern. A pressure change near the ground will affect the whole column of air above (Sedunov et al., 1991).

Temperature and pressure have consequences for the air resistance that a projectile experiences. In addition, the temperature also affects the speed of sound and the air viscosity, having an impact on the C_D -curve⁶⁸.

Aiming error

As previously mentioned, units providing indirect-fire do not have a direct line-of-sight to their target area. The operators are dependent on coordinates, aligning the weapon system with a virtual point based on an azimuthal bearing and elevation determined by ballistics calculations. With the long range fires typically involved, even a small error can result in a much larger inaccuracy than with direct-fire systems. If the weapon system's azimuthal and elevation parameters are not correct, inaccuracy can be larger than imprecision, resulting in total lack of effective fire on target.

This aiming process was traditionally based on maps, compass, and range measurement of geographical landmarks or points of interest. In some militaries, positions can be determined far more accurately by modern positioning technology such as GPS or relative positioning systems such as laser range finding. However, accuracy of positioning data does not translate directly into accuracy and precision for the firing unit. Additionally, determining the height above sea level by GPS alone is still subject to technical limitations. Accurate GPS determination of altitude requires timing the relay time of the signal between satellite and GPS unit.

⁶⁸ The C_D -curve is a curve for the air drag coefficient, and represents expected drag (see *Air Resistance*, below).

The precise coordinates of the target are less easy to determine, especially in flat terrain without known landmarks. Forward observers are tasked with overcoming these limitations by employing traditional methods and incorporating relative positioning systems such as laser range finding. Forward observers can be air-, sea-, or land-based and may be capable of entering enemy territory and communicating the coordinates of an object of interest to the firing element or a battlefield management system via various technologies, in order to greatly reduce target positioning error. With any positioning technology, regular calibration is required to ensure that errors inherent in the aiming systems are identified and eliminated wherever practicable.

Propellant temperature

Another potential source of systematic error is variation in propellant temperature. Whether the munition in question is a mortar or artillery projectile or a rocket, temperature may affect the burn characteristics of the propellant. This effect is more or less pronounced for different propellant formulations, geometries, and densities. At low temperature, the propellant burns slower, generating a lower pressure and lower muzzle velocity. This effect will be, to some extent, compensated for by an elongated burn time. Some propellants have characteristics that may minimize the temperature variance effects on propellant burn errors, however that is beyond the scope of this report.

Model errors

Computational systems for ballistic calculations (ballistics computers) contain a ballistics model which in itself may constitute systematic error, due to limitations of the model. A ballistics model is a mixture of mathematical calculation, simulation and empirical data derived from testing. Models are limited by the ability for empirical data to account for all variables in a real system (as some cannot be determined), and theoretical calculations are only able to account for the variables that are included. In addition, the data which provides parameters for the ballistics computer may be inadequate.

Air Resistance

In the ballistics model, air resistance is characterised by a curve for the air drag coefficient, also called the C_D -curve. The C_D -curve represents expected drag, neglecting air density and projectile size, as a function of the Mach number, which is a ratio of projectile speed to the ambient speed of sound⁶⁹. A typical C_D -curve is shown in Figure 3.4, below. The air resistance is low in the subsonic regime (Mach number less than 1), and rises sharply in the transonic regime (around 1 Mach). It then decreases with increasing speed in the supersonic regime (Mach number greater than 1). This shows that supersonic projectiles experience lower air resistance proportional to a Mach number in excess of 1.

⁶⁹ The speed of sound is usually approximated to 340 m/s, although this can vary based on altitude, temperature and meteorological conditions. In addition, the speed of sound is in reference to the medium, thus the projectile may be faster or slower relative to the wind velocity. This may or may not be accounted for by the ballistics model.

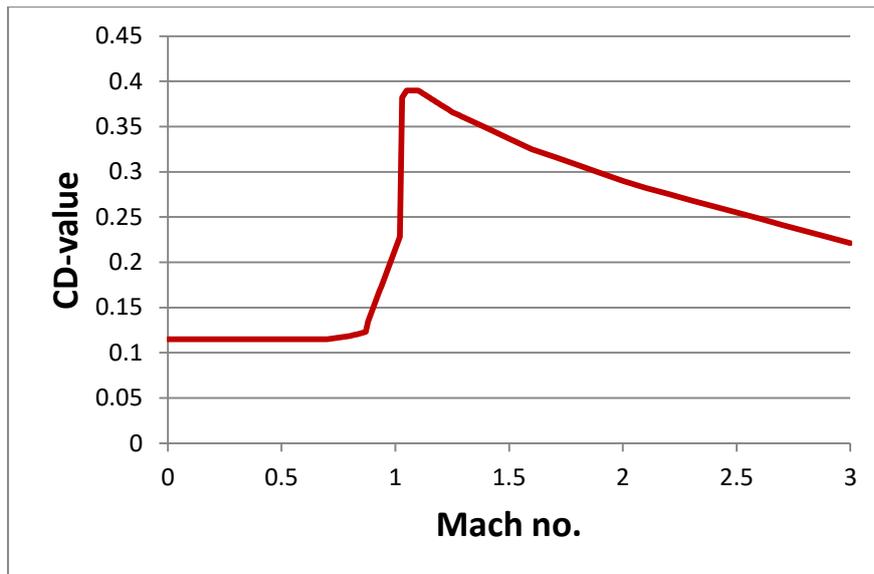


Figure 3.4 A typical C_D -curve for an artillery projectile (source: ARES).

In the ballistics computer, a C_D -curve is represented by a piece-wise linear function, as shown in Figure 3.4 which is an approximate adaption to empirical data and interpolation between data points⁷⁰. In addition to the C_D -curve, a ballistics model for a projectile contains other aerodynamic parameters determining the forces and moments⁷¹ induced by the air. These parameters will also affect the trajectory and may lead to error.

Coriolis Effect

Coriolis Effect error may result from the fact that both the firing unit and the target are situated in a coordinate system that rotates around the Earth's axis. In the northern hemisphere the Coriolis force will drive the projectile to the right respective to its vector of travel; and to the left in the southern hemisphere. Firing a projectile at a range of 30 km will typically result in a Coriolis drift of around 300 m, depending on latitude. This force is predictable and is included in modern ballistics computers. At a range of less than 5 km, the effect is negligible (Longdon, 1987).

Drift

Many projectiles are spin-stabilised, with stabilisation often imparted by a barrel's rifling. This results in a ballistic drift in the direction of the projectile's spin. This is caused by the differences in air flow pressure between the upper and lower side of the projectile. The deflective force on the projectile is a reaction to the deflection that the body imposes on the air-flow due to its spin; this known as the Magnus effect (Longdon, 1987). This should be included in the ballistics model.

⁷⁰ The 'true' curve would be smooth. The difference between the true function and the piece-wise curve represents a systematic model error, as it is an approximation. However, this contribution is usually minor, though care should be taken in the transonic region where the approximation may be less accurate.

⁷¹ In this respect, 'moments' are combinations of forces that tend to turn the projectile around any axis.

Random Errors

By definition, random errors are those that do not remain consistent between rounds. The point of impact is random, with Gaussian (or Normal) distribution around the mean point of impact (see Fig. 3.5).

Typical sources of random errors are⁷²:

- Projectile speed and weight. Some projectiles are produced via a forging process, and both the dimensions and weight of projectile can be inconsistent. For artillery projectiles, a final product check may include classification into weight 'classes' which may cover an interval of some 1.0kg. This interval, a tolerance of 0.5 kg, may result in a muzzle velocity variance of up to 20m/s, muzzle velocity variance may also result from differences in propellant mass which is a distinct error.
- Propellant mass. The actual mass of propellant may vary individually or between production batches. The deflagration characteristics and the energy content of the charge may also vary⁷³.
- Auxiliary propulsion. Some artillery munitions include rocket-assisted or base-bleed auxiliary propulsion systems. These are implemented by some kind of incorporated propellant and nozzle or engine. Like any propellant, the burn characteristics will vary based on the propellant mass and ambient temperature. The time of ignition and extinction of the unit may vary resulting in a random error.
- Elevation. During firing, the elevation of the barrel may shift due to recoil or barrel vibrations from a previous firing. The crew may not have time to identify and correct this error.
- Meteorological factors. Short term meteorological effects can constitute random errors. Temperature and pressure change usually occurs over a long enough time scale to be considered systematic error, however, low altitude wind may be volatile and present as random error.

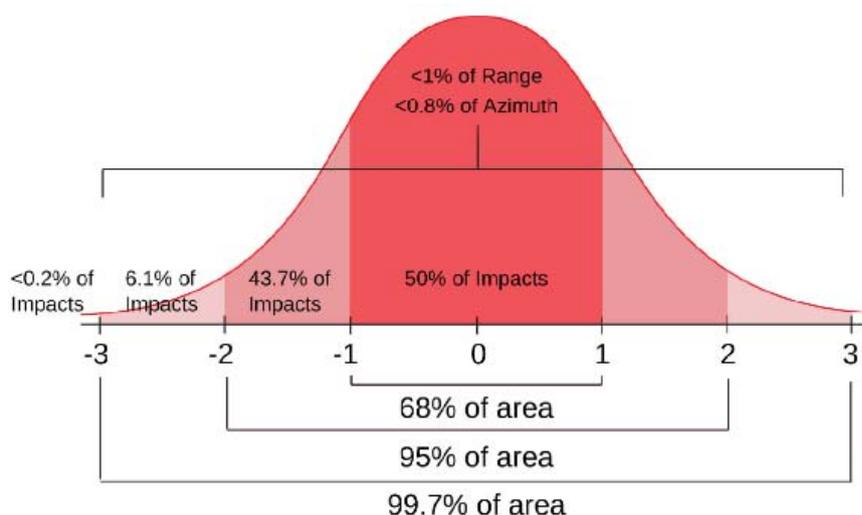


Figure 3.5 Error around the point of impact – Gaussian distribution (source: ARES).

⁷² Other random errors may include minor differences in the form of the rotating band; variations in the ramming of the projectile; variations in the temperature of the bore from round to round; play (looseness) in the mechanisms of the carriage; non-uniform reactions to firing stress; etc. (USMC, 1999).

⁷³ This may be influenced by factors including: moisture content and temperature of the propellant grains; variations in the arrangement of the propellant grains; differences in the rate of ignition of the propellant; etc.

Cumulative Error Summation

In the previous section, various distinct errors were defined. An individual error may contribute bias, imprecision, or both, over a number of impacts. Systematic errors will combine to form a resultant vector which determines the overall bias. In this way, multiple systematic errors may mitigate each other. This can occur with random errors, though it is unlikely for more than one projectile. Random error will combine in the same manner.

Whether an error component is systematic or random may in some cases be hard to determine as it will depend on the rate of fire. When firing a at rate of 10 rounds per minute, for example, most wind errors become systematic; firing one round every ten minutes will render the error caused by low level wind random.

It is often useful to express the error in two orthogonal component vectors in a coordinate system with the axis defined by the line of fire, and using the desired mean point of impact as the origin. Using this concept, each point of impact may be described as deviating from the desired mean point of impact by a term along each axis - along the line of fire, and across the line of fire. That is, the error can be described succinctly as 'error along' and 'error across' (see Figure 3.6).

Over a number of impacts, the distribution along each axis will form a normal distribution, offset by the component bias. If the coordinate system is then redefined to remove the offset (both component biases) such that the MPI is the origin, then the circular error probable, or proportion of shots which fall within a certain distance from the MPI, will conform to a Gaussian probability distribution in one dimension (see Figure 3.5), or a Weibull or Rayleigh distribution in two dimensions.

For gun and mortar projectiles, the normal distribution along the line of fire will almost certainly have a larger variance, but if the variance is equal and the errors are uncorrelated, it conforms to the Rayleigh distribution. For rockets, the error across may sometimes be larger than the error along. The longitudinal dispersion for projectiles without propulsion may be 3 - 7 times larger than the transversal, depending on the vertical angle of firing. A shallow angle (low angle) gives the highest longitudinal dispersion, resulting in impacts far from the aim point⁷⁴.

⁷⁴ The concept of quadrant elevation (QE) is discussed in more depth in US Army FM 6-50 (US Army, 1996).

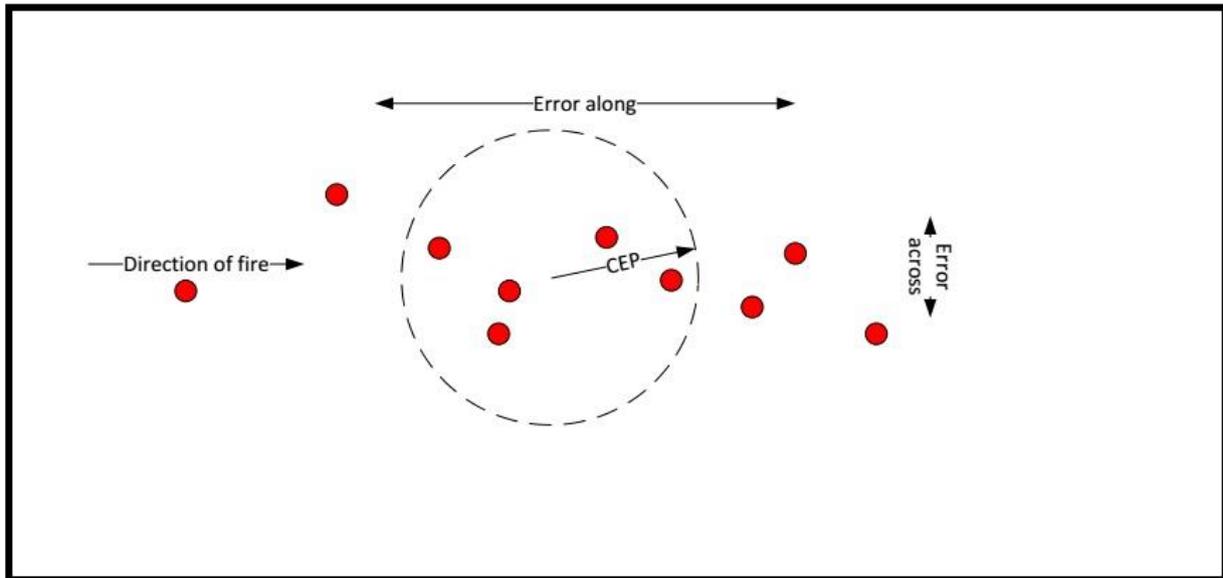


Figure 3.6 Error across and along the firing line (source: ARES).

One error usually, but not always, occurs independently of another error. As an example; an error in the aiming device will be completely uncorrelated to the error caused by an inaccurate projectile weight. Such terms cannot be added in a linear fashion, but rather the squares of the contributions should be added⁷⁵.

Some error terms are, to differing extents, interdependent. An example is an error caused by variation in air temperature and an error caused by a change in pressure. A change in temperature will, to some extent, induce a pressure change, and vice versa⁷⁶. It is beyond the scope of this report to go deeper into error correlation, but this should indicate the complexity of error handling.

A consequence of total or partial lack of correlation is that improving or eliminating a minor error may have a limited effect on the total error. For example, if one error results in an inaccuracy of 100 m and another error results in an inaccuracy of 10 m, the total error becomes 100.5 m, provided that they are uncorrelated. Eliminating the smaller error will reduce the total inaccuracy by only 0.5 m. By comparison, reducing the larger error by 50 per cent will reduce the total inaccuracy to 51 m. Thus, if the objective is to improve the accuracy of a system, the major sources of error contributions should be prioritised.

⁷⁵ As an example, two contributions, here with magnitude a_1 and a_2 , respectively, adds up to a total error of

$$a_{total} = \sqrt{a_1^2 + a_2^2}$$

⁷⁶ In that case, the equation above becomes complex:

$$a_{total} = \sqrt{a_p^2 + a_T^2 + \text{correlation term}}$$

Time of flight

Many of the most significant sources of inaccuracy, such as meteorological conditions and aiming errors, are proportional to the projectile time of flight (varying with range to the target area). As an example, an aiming error in the azimuthal direction will be magnified proportionate to the distance travelled, and the time of flight will generally increase in proportion to distance. Likewise, an error in the muzzle velocity will also increase with range. However, the correlation between the velocity error and the aim point error may be quite complicated.

Rocket Artillery Errors

Error terms for rocket artillery include some terms that are not present for the other systems. Random and the systematic errors must be treated separately.

Random errors

There are many kinds of random errors, but the so-called 'tip-off' error usually has the largest impact on accuracy. This error is caused by the movement of the launching unit. In many cases, the rocket is initially attached to the launcher by a series of shear bolts that are intended to break when the propulsive force of the motor exceeds a certain limit. Before the bolts break, the launcher is subject to a force that will try to move it in the direction of launch. As the bolts break, the launcher will recoil, causing the launcher to move in an unpredictable manner. This movement will depend on the firing direction relative to the vehicle axis, and on the mass of the launcher, which will depend on the number of rockets left on the launcher.

Figure 3.7 shows the relative significance of some of these random error contributions for a fin stabilised-rocket firing at near maximum range.

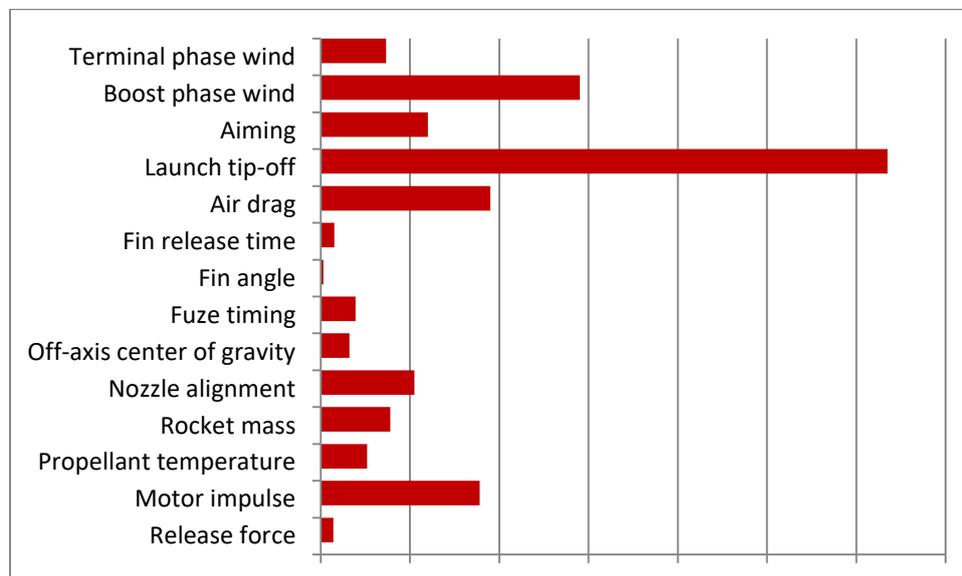


Figure 3.7 An example of relative error contributions for a fin-stabilised rocket fired at 90% of its maximum range (Source: ARES; Dullum, 1993).

Systematic errors

Systematic errors of rockets are typically dominated by meteorological causes. Figure 3.8 shows a typical error distribution.

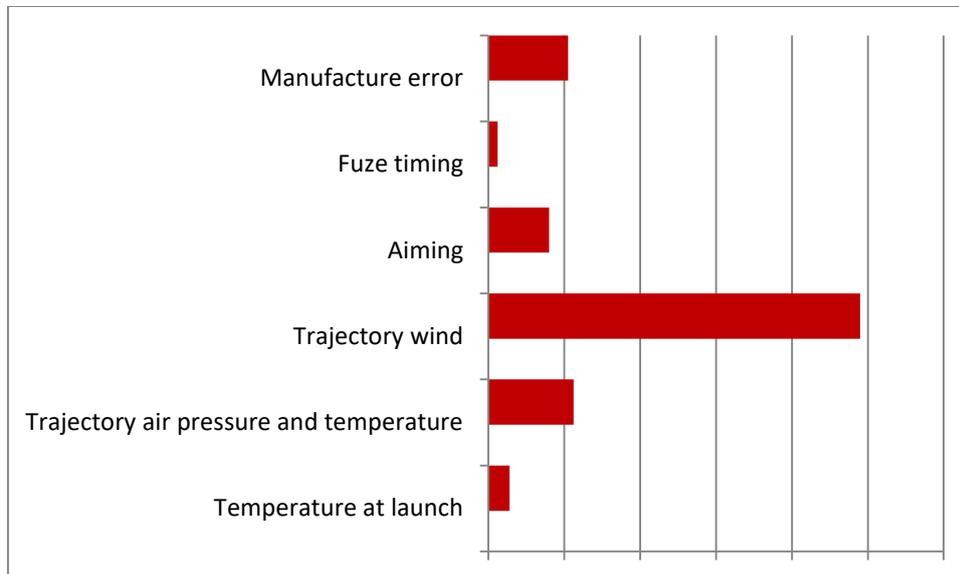


Figure 3.8 A typical relative error budget for systematic error for fin-stabilised rockets (Source: ARES; Dullum, 1993).

The accuracy of rockets is often given separately as the error along and across the line of fire. It is often expressed in mils⁷⁷ and as a fraction of the firing distance. These latter two representations suppose that the error is proportionate to the firing distance (Cross et al., 2016). Examples of rocket artillery accuracy, as given by the producer or user, are given in Table 3.2.

⁷⁷ One *mil* is approximately equal to a *milliradian* which is an angle spanning out one meter at a distance of 1000 m – there are 6400 mils in a circle. An error measured in mils can be converted to meters by multiplying the given error (in mils) by the firing distance (in kilometres).

Table 3.2 - Accuracy of selected rocket systems⁷⁸

Accuracy of selected multiple-barrel rocket launchers (assumed values)					
Values given as deviation in mils <i>across x along</i> the line of fire					
System	Calibre (mm)	Firing distance (km)	Random error (mils)	Systematic error (mils)	Total error (mils)
227 mm	227	12	4.0 x 9.5	4.2 x 5.7	5.8 x 11.1
		20	4.0 x 9.2	3.3 x 6.3	5.2 x 11.1
		32	5.0 x 11.3	3.8 x 7.5	6.3 x 9.4
107 mm	107	8	8.8 x 12.5	5.6 x 11.3	10 x 16.3
122 mm	122	19	5.8 x 8.5	6.0 x 12.0	8.3 x 14.7
122 mm (modernized)	122	20	4.9 x 7.6	Data not available	-
220 mm	220	30 -35	5.0 x 5.6	Data not available	-

Sources: Chaplin, 1990; Dullum, 2010; Гуров, n.d.(a); Гуров, n.d.(b)

Summary of errors

The three systems considered here - artillery guns, mortars, and rocket artillery - are all susceptible to both random and systematic error. Many types of error, like aiming error, wind error, and mass variations, are common across all systems.

Rocket artillery is subject to a number of error contributions not found in other systems, like tip-off due to launcher motion, and wind during the boost phase. Unguided rockets are thus generally less precise and less accurate than the other systems.

Mortars are used at short ranges, but mortar projectiles are fired at a high angle. This means that mortar projectiles may have flight times three to five times longer than an equivalent artillery projectile fired at the same range. As most errors are proportional to flight time, and the error budget will increase in proportion to the time of flight, mortars will generally be less accurate and precise than artillery guns at comparable distances.

In relative terms, artillery guns are generally the most accurate and precise of these three systems. However, like rockets, artillery projectiles are still subject to error caused by wind. At ranges beyond 15 km, wind factors will comprise most of the error budget. The ability to mitigate meteorological

⁷⁸ In the table, the MBRL values are based on the MLRS ballistic simulation software (Chaplin, 1990). The values for a spin-stabilised 107 mm rocket are determined from simulations using the same software. The others are based on data apparently given by the producer. However, they fit very well with the assumed values in the Rocket Artillery Reference Book (Dullum, 2010).

errors is dependent on the accuracy and age of the meteorological parameters provided to the ballistics computer.

Due to the difficulty in quantifying and accounting for all variables which could contribute error, it is virtually impossible to produce an exact error budget. An indicative measure is indicated in Table 3.3, showing typically errors as a percentage of firing range.

Table 3.3 – Typical errors along and across the line of fire

System	Typical error (%)	
	<i>Along line of fire</i>	<i>Across line of fire</i>
<i>Artillery guns</i>	1.5	0.5
<i>Mortars</i>	3.0	2.5
<i>Rocket artillery</i>	1.5	1.0

Data given for artillery projectiles, mortars bombs, and rocket artillery, as a percentage of the firing distance⁷⁹ (source: ARES).

As the inaccuracy and imprecision resulting from errors are proportional to projectile time of flight, the actual accuracy in metres may be comparable at the different ranges these systems are employed. In addition, it is important to note that compensation for systematic error is typically only possible for artillery and mortar indirect-fire systems, where sustained fire accuracy may improve over multiple shots or salvos.

⁷⁹ This is a very broad 'rule of thumb', showing that, for example, an artillery gun may have an error of 1.5 x 0.5 % of range – i.e. 150 x 50 m at 10 km.



SECTION 4

Effects

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Effects and Damage Mechanisms of Indirect-fire Munitions

Indirect-fire weapon systems achieve their intended battlefield effects by employing a range of munitions. These include high explosive (HE), high explosive fragmentation (HE-FRAG), thermobaric, anti-personnel, smoke, illumination, and other types. The battlefield impacts of massed fire delivered by indirect-fire artillery systems executing a fire for effect mission can be devastating. Primarily employing HE and HE-FRAG munitions, indirect-fire artillery systems are often capable of engaging a range of enemy manpower, armoured vehicles, and structures. As the most common munition types employed by indirect-fire weapon systems are of the high explosive and high explosive fragmentation types, these are dealt with in the most detail herein.

Whilst the effects of all munitions are context dependent – affected by the composition of the target area, which is determined by factors such as building density and construction, topography, soil type and density; weather, angle of attack, delivery platform; and fuze type and setting – there are foreseeable, design-dependent effects that can be assessed.

Munitions employed by indirect-fire weapons are primarily classified by the ‘type by function’ of the munition. This utilitarian measure considers the primary function and its effect upon the battlefield. To be able to classify and evaluate hazards and mechanisms of damage it is first essential to understand the utility, functions, and effects of artillery munitions.

Explosive Damage Mechanisms

The damage mechanism most commonly associated with all munitions is that of an explosive effect. Explosions are a rapid release of energy which takes the form of light, heat, sound, and a shock wave (FEMA, 2003). Though other types of explosions exist, the type most closely associated with conventional munitions is the chemical explosion. Chemical explosives react to the application of sufficient heat or shock by initiating a rapidly propagating exothermic decomposition into gases, resulting in an extreme pressure and temperature change. This results in a rapid expansion of these gases, which reinforce the detonation shock wave and provide the energy to produce the destructive effects of an explosive (NSWC, n.d.).

The primary mechanisms of effect employed by conventional explosives are: blast – the shockwave and blast wind; fragmentation – projected materials; and heat – fires and secondary effects. Energy transfer via these mechanisms will produce the primary effects of human casualties and damage or destruction of structures and other materiel, and in differing ratios contribute to secondary explosive effects such as penetration, secondary fragmentation, and firebrands. All explosive munitions occasion effects resulting from the three primary damage mechanisms, but through design may limit or enhance their magnitude to achieve a specific result (Cross et al., 2016).

Blast refers to overpressure⁸⁰ caused by a high explosive detonation. High explosive detonations create a ‘shockwave’, a high energy overpressure wave which propagates through air at supersonic speed. A shockwave will impart energy into any material that it comes into contact with,

⁸⁰ Overpressure is pressure above normal atmospheric pressure caused by an explosion’s shockwave. Depending on the pressure it may cause internal and external injuries and damage/destruction of structures. For further discussion of these concepts, see (Zipf & Cashdollar, n.d.).

this interaction and transfer of energy is the most significant destructive mechanism in an explosion and usually results in additional reflections that cause incident overpressures larger than the original shockwave to occur as the resultant blast waveforms overlap. Shockwaves incident upon a material cause a compressive propagation followed by a rarefaction which stresses the material, generating shear forces and heating. Some proportion of the wave, depending upon the material, will reflect internally and externally, imparting separate energy modes which interfere constructively and destructively to cause pressure and temperature discontinuities, potentially shattering the material along structural weaknesses where the shear forces will be concentrated.

Since the energy of an explosion is spread in all directions, pressures associated with explosive detonations decay and dissipate very rapidly as distance from the source increases⁸¹. As a result, direct air-blast damages tend to be more localised and may be, for example, significantly more severe on the side of a structure facing an explosion than the opposite side (FEMA, 2003).

Whilst the human body can withstand relatively high blast overpressure without experiencing significant trauma the significant blast winds that are a result of this overpressure are often more damaging, leading to fatalities and injuries (Zipf & Cashdollar, n.d.). Table 4.1 shows the effects on structures and the human body from various blast overpressures and their accompanying blast wind speeds. Generally, peak overpressure is greatest close to the point of detonation, however it is affected by factors such as explosive composition, explosive quantity, altitude, and the environment.

Table 4.1 – Effects of blast overpressure and blast wind on structures and the human body

Peak overpressure	Maximum wind speed	Effects on structures	Effects on the human body ⁸²
1 psi	38 mph	Window glass shatters	Light injuries from fragments occur
2 psi	70 mph	Moderate damage to houses (windows and doors blown out and severe damage to roofs)	People injured by flying glass and debris
3 psi	102 mph	Residential structures collapse	Serious injuries are common, fatalities may occur
5 psi	163 mph	Most buildings collapse	Injuries are universal, fatalities are widespread
10 psi	294 mph	Reinforced concrete buildings are severely damaged or demolished	Most people are killed
20 psi	502 mph	Heavily built concrete buildings are severely damaged or demolished	Fatalities approach 100%

Source: Zipf & Cashdollar, n.d.

⁸¹ The Hopkinson-Cranz Scaling Law states that peak overpressure is directly related to the energy of the blast and inversely proportionate to the cube of the distance from the blast epicentre. See the IATG 01.80 *Formulae for Ammunition Management* for details (UNODA, 2013).

⁸² For a fuller discussion on the effects of explosive weapons on the human body, see (Brevard et al., 2012).

Fragmentation is the projection of materials propelled by the blast wave of an explosion. If the fragment is part of the munition and is propelled by its explosive force then it is referred to as 'primary fragmentation'. If the fragment is generated from another source then it is referred to as a 'secondary fragment' (see below). Fragmentation can be pre-formed, such as steel spheres or cubes held in a matrix; pre-fragmented as the result of scoring or moulding of the munition body; or non-uniform, often jagged, naturally occurring parts of the munition casing or body. Controlled fragmentation is caused when a pre-fragmented warhead or fragmentation sleeve is ruptured by the blast of a high explosive detonation. The fragments initially travel at high speed⁸³ (thousands of metres per second) away from the point of detonation causing damage to personnel, structures, and materiel, typically at a much greater distance than blast effects (AFSC/SEW, 2011).

Fragmentation hazards may be assessed using a range of models, but one of the most effective is used by the US military to estimate the hazardous fragment distance (HFD) of a sample munition with a known net explosive weight (NEW⁸⁴). The HFD is given as the distance at which the density of hazardous fragments becomes 1 per 600 ft² (55.7 m²) (AFSC/SEW, 2011)⁸⁵. At this distance, there is approximately a 1% probability of a person being struck by a lethal fragment (USATCES, 2011)⁸⁶. Note that the HFD is not the maximum range of fragments resulting from the detonation of an explosive munition. These fragments, known as **rogue fragments** travel past the HFD and may fly in excess of 10,000ft (3,048 m) farther than what would be normally predicted (DOD,2008). Table 4.2 shows the calculated HFD for sample munitions of varying NEW (US Army, 2013).

Most militaries will physically test munitions prior to their acceptance into military service. In some cases, the testing will be significant and will provide hazardous area data specific to the munition in question. Sample munitions may be detonated within a series of concentric layers of diagnostic material and the number of penetrations at a given distance recorded to determine the lethal and hazardous zones for a given projectile or rocket. Simpler tests may focus solely on observed effects in an impromptu testing area.

⁸³ The initial speed of these fragments is predicted using Gurney's Equation, developed during World War 2 using a combination of geometry, mass, and specific energy of the explosive filler (ABRL, 1943).

⁸⁴ The actual weight of explosive mixtures or compounds (including the TNT equivalent of energetic material) contained in a munition, expressed in pounds (DoD, 2010a). When expressed in kilograms, this figure is known as the net explosive quantity (NEQ).

⁸⁵ According to the US Air Force Safety Center, a hazardous fragment is one having an impact energy of 58 ft-lbs (79 J) or greater (AFSC/SEW, 2011). The US Department of Energy classifies hazardous fragments into two classes; those with an impact energy between 11 ft-lbs (15J) and less than 58 ft-lbs are considered capable of causing 'serious injury', whilst fragments having an impact energy of 58 ft-lbs or greater are considered capable of causing 'severe injury or death' (DOE, 2012). This paper will use the US DoD definition.

⁸⁶ To put this number in perspective, this equates to a single hazardous fragment in an area equal to three standard football goals.

Table 4.2 – Hazardous fragment distances (HFD) for a given net explosive weight (NEW)

NEW (lbs)	HFD (ft)	NEW (lbs)	HFD (ft)
1	291	25	546
2	346	50	601
3	378	75	633
5	419	100	658
10	474	250	1014

Source: US Army, 2013

Thermal energy is the final primary mechanism of an explosion. The detonation of an explosive munition results in the exothermic breakdown and recombination of various chemical compounds, occasioning a release of thermal energy which heats the combustion gases and ambient air to a high temperature (NFPA, 1998). Explosive detonations cause extremely high temperatures of a very limited duration, often described as a short-lived ‘flash’ of thermal radiation. Detonations may also result in the formation of a fireball, the momentary ball of flame present during or immediately after the explosive event as a result of the ignition of flammable vapours (NFPA, 1998). Whilst the thermal energy released is capable of causing very severe burns, the limited duration and radius of these phenomena means that, generally, the primary thermal hazard posed by an explosive weapon is less significant than the blast and fragmentation threats (AFSC/SEW, 2011). However, flammable materials such as stored fuel may be ignited by the momentary thermal energy released by detonation of explosive munitions or by projected firebrands (see below), producing significant secondary effects. In contrast to explosive munitions, true incendiary munitions deflagrate, or burn, as opposed to detonate (Cross et al., 2016).

Secondary effects of blast, fragmentation, and thermal energy⁸⁷

The following types of damage are occasioned as a result of one of the three main damage mechanisms of blast, fragmentation, and thermal energy. These secondary effects are often achieved or enhanced by the design features of the munition in question. These effects may pose a significant risk of harm to civilians and civilian objects, particularly in built-up areas.

The reflections and absorptions of blast energy create another type of blast effect called **ground shock**. Ground shock may be directly induced by an explosion on or in the ground (such as by certain types of piercing munitions⁸⁸), or through the transfer of energy from an air shockwave (Cross et al., 2016). As with air shock, ground shock may cause structural damage to adjacent structures as the ground conducts the shockwave from the blast into other materials. It can also cause damage to subterranean structures including sewage, water, electricity or gas networks (see, for example, ICRC, 2015).

Secondary fragmentation is comprised of fragments of objects affected by a munition’s detonation, as opposed to the munition itself. Most secondary fragments are formed by the shearing or spallation of solid objects as they fail to withstand the air or ground shock wave. These objects

⁸⁷ This section is adapted from Cross et al., 2016.

⁸⁸ Colloquially called ‘bunker busters’.

could include structural materials from buildings or vehicles, such as concrete, glass, and metal debris, or fragments generated from human or animal targets, including bones and equipment. These fragments are generally larger than primary fragments and typically do not travel as far or at as high a velocity as primary fragments (often at hundreds, rather than thousands of feet per second) (AFSC/SEW, 2011). This effect may be exploited by artillery observers engaging targets in forested environments, with the correct impact angle able to generate significant secondary fragmentation effects⁸⁹ (Roponen, 2015).

Firebrands ('embers') are projections from an explosive detonation which are either burning or very hot, and which may transfer thermal energy to their surroundings. Firebrands may occur when an explosive munition detonates in close proximity to solid flammable materials such as wooden structures or packaging, forests, or ammunition and associated packaging, or when the casing of the munition has been specifically designed to behave in a pyrophoric manner⁹⁰. One such example is the inclusion of Zirconium cubes as part of a pre-formed fragmentation sleeve. Firebrands can act in a similar manner to incendiary munitions and ignite fires well beyond the distance at which primary thermal effects pose a threat (AFSC/SEW, 2011).

Cratering is the deformation of the ground and projection of material from the point of explosion, and is influenced by both direct induced ground and air shock (DOD & ERDA, 1977)⁹¹. Cratering is a secondary effect of the use of explosive munitions, but ejecta from craters has been determined to also present a hazard as secondary fragmentation (DODESB, 1975). Cratering may additionally be an intended effect of munitions, rendering avenues of approach, runways, or subterranean structures useless.

Psychological impact

In addition to the raw physical damage that artillery can visit upon an opposing force's equipment and personnel, the use of artillery can have a profound psychological effect. This is well captured in E.B. Sledge's World War II account *With the Old Breed*:

"To be under a barrage or prolonged shelling simply magnified all the terrible physical and mental effects of one shell. To me, artillery was an invention of hell. The onrushing whistle and scream of the big steel package of destruction was the pinnacle of violent fury and the embodiment of pent-up evil.... To be killed by a bullet seemed so clean and surgical. But shells would not only tear and rip the body, they tortured one's mind almost beyond the brink of sanity. After each shell I was wrung out, limp and exhausted.

During prolonged shelling, I often had to retrain myself and fight back a wild, inexorable urge to scream, to sob and to cry. As Peleliu dragged on, I feared that if I ever lost control of myself under shell-fire my mind would be shattered. I hated shells as much for their damage to the mind as to the body. To be under heavy shell-fire was to me, by far, the most terrifying of combat experiences. Each time it left me feeling more forlorn and helpless, more fatalistic, and with less confidence that I could escape the dreadful law of averages that inexorably reduced our numbers. Fear is many-faceted and

⁸⁹ According to one model, up to 50% more casualties may be inflicted with lower angles of fire from indirect-fire weapons in forested environments (Roponen, 2015).

⁹⁰ This secondary explosive effect contributes greatly to the overall incendiary effect of a munition, this allows military planners flexibility in weapon selection for effects against explosively hardened but thermally sensitive targets such as munitions or aircraft bunkers or underground fuel containment facilities.

⁹¹ Cratering is highly dependent upon the munition, fuze, target, soil/ground composition, and several other factors.

has many subtle nuances, but the terror and desperation endured under heavy shelling are by far the most unbearable.” (Sledge, 1981)

Heavy ‘saturating’ fire is particularly effective in delivering psychological effects; one former British general noted that in addition to the destructive effects on personnel and materiel, “the most potent effect of [these types of fires] is the shock and psychological effect created by sheer weight of explosive” (Bailey, 2009). Some studies have suggested that munitions delivered from a high angle, such as air-delivered weapons or mortar projectiles, are more frightening than low-angle attacks. The most frightening elements in the bombardment were assessed to be the “destructive power of the weapon” and the noise intensity (Dayan & Gal, 1992).

Common Indirect-fire Munition Types

All munitions utilise one or more of the three primary mechanisms discussed above to produce effects in combat. All munitions are designed for specific types of targets. The designer will take into account the nature of the intended target, and consider the effect that is required and the range from which the effect is expected to be delivered. During the design process, these essential factors will be analysed in detail and specified as precisely as possible so that the weapons and munitions are designed within acceptable, attainable, and affordable limits; to achieve the desired effect but without ‘overkill’.

Each target presents specific challenges; warheads⁹² with specific properties are developed and selected to overcome these challenges and provide the desired effects on target. For example, defeating armoured targets requires penetration, infantry in open terrain may be engaged with fragmentation, and some targets require multiple effects to defeat (Cross, et al., 2016). The warhead of a munition is its primary component, often lending its nomenclature and type to the entire system. Warheads carry the payload to the target and are designed to deliver the effects of the munition to the target in the most efficient manner possible. There are numerous types of warheads, as well as warheads that combine two or more different effects; this analysis will look at the most common.

Common Types of Explosive Munition Warheads

Explosive warheads are responsible for delivery of a primarily explosive effect to a target and include the majority of munitions employed in modern conflict. Explosive warheads can further be classified by the primary damage mechanism resulting from their use. Their design determines the mechanisms used to achieve effect on target, and thus their suitability for use against a given target. Some warheads may utilise a combination of these effects. These warheads are commonly employed with point detonating (PD) or proximity fuzing so that the maximum application of the desired explosive effect is utilised against the target. Common sizes range from 30 mm to 300 mm.

High Explosive

Standard high explosive (HE) warheads are designed to achieve target damage primarily through the effects of blast, producing overpressure and thermal effects resulting from the detonation of high explosives. As described above, this detonation causes a shock wave to propagate outwards, causing a near-immediate rise from normal atmospheric pressure to peak overpressure, followed by a

⁹² The term “warhead” is used here and throughout this section to refer to a payload section of a munition. This term applies primarily to munitions such as rockets and missiles. Artillery projectiles and mortars are not typically referred to as warheads but the context and methodology remain the same for this purpose.

slower drop back to, and below, normal atmospheric pressure in objects it passes through. See Table 4.1 for details on the effects of blast overpressure on the human body and structures. HE warheads are often constructed with a heavy casing, producing lethal primary fragmentation in an uncontrolled or semi-controlled fashion. HE warheads are used as a standard baseline for fragmentation and blast damage when selecting munition effects. They are one of the most commonly used explosive warheads for all types of targets due to the balance of blast and fragmentation effects.

High Explosive Fragmentation

High explosive fragmentation (HE-FRAG) warheads are primarily designed to cause target damage through the creation of high velocity fragments as opposed to blast energy. This is generally achieved through enhancing the natural fragmentation characteristics of the warhead materials, by designing for controlled fragmentation, or by the inclusion of preformed fragments. HE-FRAG warheads are typically constructed of different materials than blast (HE) warheads, and often feature heavier metal construction or have a supplemental fragmentation sleeve integrated or affixed to the munition body. A fragmentation sleeve is a metal sleeve that contains pre-formed fragments or has been scored to encourage fragmentation. The weight of individual fragments varies depending on the needs of the munition, and commonly range from a few grains up to around 250 grains⁹³ (Goad & Halsey, 1982). Typically, fragmentation warheads utilise approximately 30% of the energy released by the explosive detonation to separate and disperse these fragments, with the rest of the energy causing blast effects as described above (NSWC, n.d.). Fragmentation warheads are often chosen for employment against personnel and light vehicles.

Thermobaric

A thermobaric munition is a type of explosive munition that utilises ambient oxygen from the surrounding air to fuel an exceptionally high temperature explosion, which results in an enhanced blast effect of longer duration but lower peak pressures. When a thermobaric weapon functions, a flame front accelerates to a large volume producing pressure fronts first within the fuel-oxidant mixture, and then in the surrounding atmosphere.

These munitions usually feature very light casings and produce no appreciable primary fragmentation, relying on the sizable blast effect to inflict damage. The strong blast effects of thermobaric warheads are reflected and magnified through wave interaction if employed in urban areas against personnel and structures. For further information regarding the design and employment of thermobaric munitions, see Cross et al., 2016.

⁹³ Grains are an important unit of measurement used in conjunction with ammunition and ordnance. One grain is defined as exactly 64.79891 mg (Butcher et al., 2011).

Fuzes & fuzing⁹⁴

A fuze is a mechanical or electronic initiating device designed to function a munition. The role of the fuze is:

- To ensure that the crew can safely handle the munitions during the loading process;
- To arm the munition at a given time or position; and
- To function the munition at a given time or position.

The choice of fuzing options can greatly affect civilian harm from explosive weapons by mitigating or enhancing certain munition effects (Cross et al., 2016). In particular, area effects may be constrained or enhanced by the selection of different fuze types, and hence fuze and fuzing mode selection is of primary importance when evaluating the use of explosive munitions in populated areas.

There are three common categories of fuze that are defined by their firing function: impact, time, and proximity. When indirect-fire weapon systems are employing HE or HE-FRAG munitions, impact fuzes are most commonly used. Most fuzes must be selected at the time they are mounted to the munition by the operator or munitions specialist. Some modern fuzes available to some militaries have a variety of fuzing options, giving more latitude in selecting the effects required for the target immediately prior to use (King, 2011). Some fuzes have multiple-function capability, such as a combination of mechanical time delay and point detonating. Note that nearly all fuzes have an arming sequence governed by launching forces which ensures arming and subsequent initiation only after the weapon has travelled a safe distance from the launching party.

Fuzes often incorporate backups and failsafe devices. For example, some 122 mm artillery rockets use a radio proximity fuze to detonate the warhead approximately 8 m above ground level, in order to optimise fragment spread (Ness & Williams, 2011). This fuze incorporates an impact backup capability, should the main fuzing method fail to function, as well as a complex safety system, wherein an air-driven turbine spins as the rocket flies, mechanically arming the rocket some 300 m from the launcher. The fuze is typically operational 12 seconds after launch and has a failsafe that will not allow the rocket to detonate if it falls off-axis due to departure from standard flight parameters.

Unexploded ordnance (UXO) most commonly occurs as a result of a munition failing to arm or failing to function – typically directly influenced by the munition's fuze. In some cases, a cause or contributing factor is the presence of multiple safety mechanisms, which result in a munition which is safer to transport or handle, but may increase the chance of failure due to overlapping mechanical, electrical, or human inputs required to complete arming. Another cause or factor may be poor production tolerance causing mechanisms to jam or only partially arm the munition. UXO may also result due to environmental effects before, during, or immediately after impact, which fail to produce the forces or signals required to function an armed munition. This can include the presence of soft earth, vegetation, water, or oblique impact angles. Other significant factors include the age of the munitions (some compounds and mechanisms can degrade over time) and improper employment (which may not provide the required forces or inputs to arm or function a munition).

⁹⁴ This section is derived from Cross et al., 2016.

Stated and reported failure ('dud') rates can range from as low as 0.1 per cent to more than 30 per cent, depending on munition type, testing parameters, and data gathering methodology. Figures given by organisations working in the field, for example, are often much higher than manufacturers' estimates, as munitions may have been affected by the various environmental, age, and employment factors mentioned above.

When considering how a fuze influences collateral effects, take the example of a multi-story building struck by an indirect-fire munition. If the intent is to neutralise a specific target by destroying the top floors of the building, an instantaneous impact fuze will be used. This will leave much of the building intact, sparing lives in lower floors, though potentially rendering the building structurally unsound. Blast and fragmentation damage will also affect areas adjacent to the point of impact. If, however, the intent is to destroy the building entirely, an impact fuze with a delay element may be used, causing the building to implode as the weapon detonates at the foundations (subsurface) after travelling from the initial point of impact deep into the structure. This will completely destroy the building but may also minimize surrounding collateral effects. Thus the choice of fuze is critical in understanding how militaries make choices in tailoring a weapon's effects during the targeting process (Cross et al., 2016).

Impact fuzes

The most common fuze typically used with high explosive munitions fired by artillery systems is the impact fuze, also known as a point- (or base-) detonating fuze or an all-ways contact fuze⁹⁵. When used with different types of ordnance, these fuzes are often referred to by different terms. Generally speaking, impact and impact inertia fuzes are used with air-delivered weapons (ADW), such as guided missiles, bombs, and submunitions. Point-detonating (PD) and base-detonating (BD) fuzes are used with land service ammunition (LSA) such as projectiles and rockets. The mechanism for fuze functioning is the same for both groups: the direct impact or rapid deceleration (caused by impact) of the munition. While the outcome is to detonate upon impact, impact fuzes often incorporate a delay of milliseconds or more upon functioning (USAFAS, 2004). This is caused by inevitable requirements for movement of fuze components as part of functioning, or as part of a short delay option. A short delay option is used when the weapon is intended to explode inside or underneath the target (subsurface⁹⁶). Fuzes with an impact delay such as this are commonly used with penetrating weapons. If a point-detonating fuze is designed for an instantaneous explosion it is known as a 'super quick' (SQ) fuze⁹⁷ (King, 2011). A final variety of impact fuze is the 'all-ways impact' (or contact) fuze. This specific type of fuze functions without regard to the orientation of the munition during impact. This type of fuze is most commonly found in use with submunitions, where the likelihood of a predictable impact trajectory is low. Regardless of the idiosyncrasies of individual design, impact fuzes as a group account for the largest portion of ADW and LSA fuzing systems used in modern combat.

⁹⁵ When used with air-delivered munitions, the term 'impact' is generally used rather than PD.

⁹⁶ Fuzes for this purpose will typically be fitted in the tail or base of the munition. The nose will typically be a solid nose, or a dense aerodynamic plug will be installed.

⁹⁷ Many common PD fuzes for projectiles allow the operator to select either the super quick action, or a short delay. This allows the projectile - typically a high explosive projectile - to penetrate the target prior to detonating.

Time fuzes

Time fuzes utilize a predetermined delay as their primary firing function, rather than relying on a physical input such as impact. The delay mechanism may be mechanical, electronic, or pyrotechnic in operation, known as mechanical time (MT), electronic time (ET) or powder train time (PTT) fuzes, respectively⁹⁸. Each allows the munition to function at a pre-set time after launch. This type of fuzing is primarily used in cargo-carrying ordnance, although time fuzes are known to be used in conjunction with explosive and smoke munitions. Time fuzes can be designed to operate on the scale of seconds and minutes (as for projectile or rocket time fuzes) or in hours and days (aerial dropped bombs and submunitions), which are orders of magnitude larger than the delay options found in impact fuzes. When used with unitary HE or HE-FRAG munitions, time fuzes are typically employed to achieve an airburst effect, detonating a munition above a target after a calculated, pre-set period of time from launch. Some sub-types of time fuzes are 'time super quick' (TSQ) and 'mechanical time super quick' (MTSQ), which incorporate an impact backup fuzing option (USAFAS, 2004).

Proximity fuzes

Proximity, or 'variable time' (VT), fuzes function a munition at a specific distance from the target. A proximity fuze generally uses radio waves⁹⁹ to detect when the munition is at the proper height and distance from a target before functioning. Ordnance items designed to engage aircraft usually make use of proximity fuzes to function the warhead and increase the chance of successful hit by fragmentation, rather than requiring a direct impact. When employed against ground targets, proximity fuzes are most often used to 'airburst' a munition (USAFAS, 2004). Employing a weapon in an airburst manner will function the munition at varying heights above ground, in order to enhance the effects of the blast and fragmentation damage. Employing munitions in an airburst fashion can be useful when attacking a large concentration of infantry in the field or when targeting multiple comparatively fragile structures, such as communication dishes, in an open area. Generally speaking, fewer weapons can be employed to effect similar results. An above ground explosion may create a ground reflected blast wave that can reinforce or follow the original shock wave and typically disperses primary fragments over a larger area than an impact explosion. An airburst weapon can increase area effect up to 100% of a weapon's design (NSWC, n.d.).

Precision Guided Munitions

Precision guided munitions (PGMs) are those which can alter their flight paths to more precisely strike a target. PGMs may be either guided or unguided, and offer significantly increased accuracy and precision over conventional, unguided munitions. They may also present the user with a wider array of fuzing options, result in lower ammunition consumption (and relieve associated logistics burdens), allow for the ability to strike moving targets with greater ease, and allow the employing force to minimise the likelihood of collateral damage (Jenzen-Jones, 2015a).

PGMs are increasingly common amongst major militaries, however comparatively high per-munition cost and other factors restrict their use amongst the armed forces of developing nations.

Additionally, PGMs are not suitable for all traditional artillery roles. PMs may also require sophisticated battlefield management systems, storage and transport considerations, and

⁹⁸ Additionally there are chemical and material fatigue delay mechanisms, but these have fallen out of favor with modern militaries due to reliability issues.

⁹⁹ Optical, acoustic, magnetic influence, infrared, and other types have also been developed.

specialised training. PGMs are not available to all military forces, and remain in relatively limited use despite their advantages. The use of PGMs may dramatically alter the role of indirect-fire weapon systems and are often incompatible with some of the core roles of artillery units. In practice, PGMs typically offer a supplementary capability even in the most modern of armed forces.

The definition of precision can be broad; the United States Air Force Fighter Weapons School has taught a 'precise' weapon is that which has a CEP of less than three meters while an 'accurate' weapon has a CEP less than ten meters, for example¹⁰⁰ (Sine, 2006). The degree of precision, therefore, has to be considered in the context of the type of weapon as well as how it will be employed on the battlefield (see Section 3). The increasing prevalence of highly-targeted fire missions, comprising extensive planning phases including CDE, and the increased adoption of PGMs has created something of an 'identity crisis' for artillery units in some armed forces, with commanders and their personnel rapidly learning about new and altered capabilities. As a result, it is essential that liaison officers provide proper guidance to supported units to ensure a thorough understanding of the nature and utility of artillery systems. For further information on the design and employment of PGMs, see Cross et al., 2016).

¹⁰⁰ See Section 3 for the definitions of 'precision' and 'accuracy' used herein.

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