Explosive Weapons in Populated Areas:

Technical considerations relevant to their use and effects

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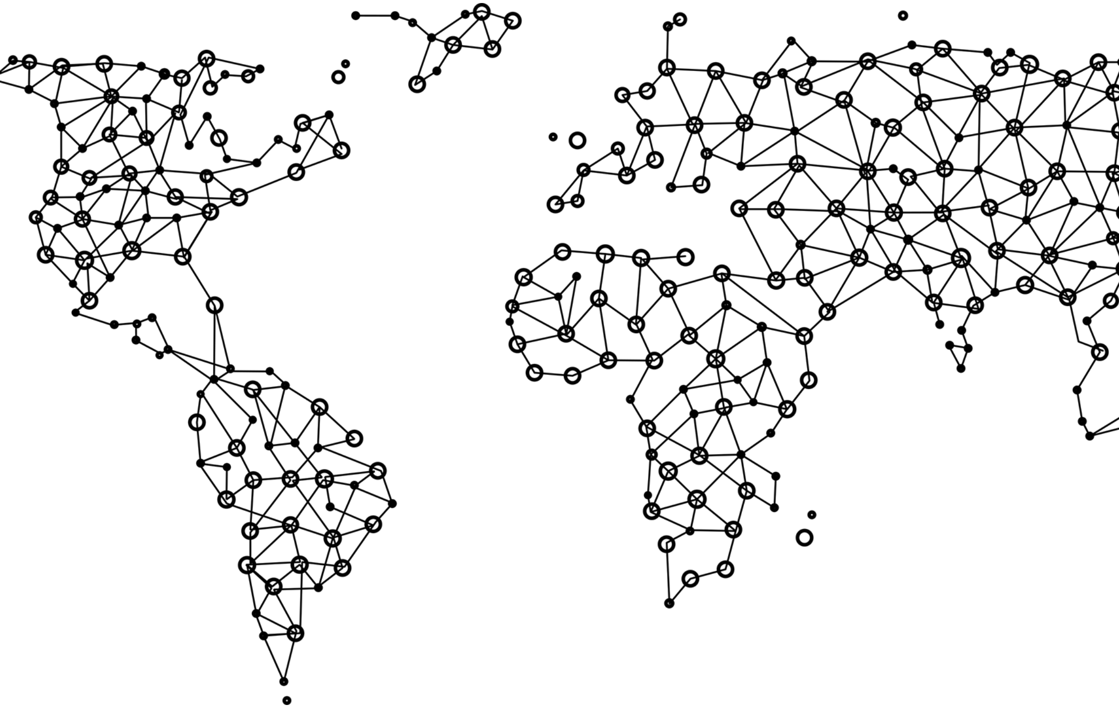

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ABOUT THIS REPORT

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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SAFETY INFORMATION

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 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.

The views expressed in this report are those of the authors and do not necessarily represent the views of the International Committee of the Red Cross.

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ABBREVIATIONS AND ACRONYMS

ADW
Air-delivered weapons

AFV
Armoured fighting vehicle

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ASM
Air-to-surface missile

ATGM
Anti-tank guided missile

BAE
Behind armour effects

BD
Base detonating

BDA
Battle damage assessment

CBN
Circular bivariate normal distribution

CBRN
Chemical, biological, radiological and nuclear

CCIP
Constantly computed impact point

CCW
Convention on Certain Conventional Weapons

CDE
Collateral damage estimate

CDM
Collateral Damage Methodology

CEP
Circular error probable

DIME
Dense inert metal explosive

DPICM
Dual-purpose improved conventional munition

EFP
Explosively-formed penetrator

ERA
Explosive reactive armour

ET
Electronic time

FAE
Fuel-air explosive

FFR
Free flight rocket

FMJ
Full metal jacket

GPS
Global Positioning System

HE
High explosive

HEAT
High explosive anti-tank

HE-FRAG
High explosive fragmentation

HEP
High explosive plasticised

HESH
High explosive squash-head

HFD
Hazardous fragment distance

HUD
Heads-up display

ICRC
International Committee of the Red Cross

IED
Improvised explosive device

INS
Inertial navigation system

IR
Infra-red

IRAM
Improvised rocket-assisted munitions

LSA
Land service ammunition

MBT
Main battle tank

MET message
Meteorological message

MPI
Mean point of impact

MSD
Minimum safe distance

MT
Mechanical time

MTSQ
Mechanical time super quick

NEW
Net explosive weight

NSL
No-strike list

PD
Point detonating

PGM
Precision guided munition

PI
Percent of incapacitation

PID
Positive identification

PTT
Powder train time

RED
Risk estimate distance time

RF
Radio frequency

RTL
Restricted target list

RV
Re-entry vehicle

TBE
Thermobaric explosives

TSQ
Time super quick

UAV
Unmanned aerial vehicle

VBIED
Vehicle-borne improvised explosive device

VT
Variable time

INTRODUCTION

Explosive weapons with wide area effects are prone to cause harm beyond the targeted military objective and put civilians at grave risk of death or injury when used in areas containing concentrations of civilians due to scale of explosive force, inaccuracy of delivery or use of multiple warheads. This report will examine weapons that are frequently encountered on contemporary battlefields, or else commonly held, that may fall within one or several of these three categories.

Part 1 of this report examines the design and effects of explosive munitions. Weapon effects are the result of the weapon's design and the context in which the weapon is used. The context refers to 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 therefore vital to understand how explosive weapons function, 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. The damage mechanisms of explosive weapons are introduced, followed by a brief introduction to explosive munitions design, supported by examples of common warhead types, including an examination of thermobaric and related munitions. Part 1 also addresses the cornerstones of protecting civilians from collateral damage – positive target identification, correct weapon choice to achieve only the desired military effect, and sufficient operator training. Specific attention will be paid to thoroughly explaining important concepts such as accuracy, fuzing, the targeting process (including so-called 'targeteering' or 'weaponeering'), collateral damage estimations (CDE), battle damage assessments (BDA), and more.

Part 2 of this report will consider the broad categories of weapon systems which deliver explosive payloads – mortars, rocket artillery, unguided aerial bombs, and other types. Generic information for each of these broad categories is included. For each weapon category identified, Part 2 provides a description of the technical features relevant to the effects of the weapon. In particular, it includes, where available, estimated blast and fragmentation radius for munition types, estimated circular error probable (CEP) figures, and other measureable effects. The weapon types in this section have been chosen because they are either in common use or because they are representative of their class of weapons that may raise concerns when used in populated areas, although not all of the weapons covered in this part will necessarily raise concerns in every instance of use in populated areas.

This report was written without prejudice to any particular weapon, manufacturer, or user. **While all weapon effects are contextual, certain weapons may foreseeably cause harm beyond a specific**

1 In this report, the term "concentration of civilians" is used as a synonym for "populated area". See ICRC, "Challenges Report", 2015, p. 49.

2 The International Committee of the Red Cross (the ICRC) has stated that "due to the significant likelihood of indiscriminate effects and despite the absence of an express legal prohibition for specific types of weapons, the ICRC considers that explosive weapons with a wide impact area should be avoided in densely populated areas." (ICRC, 2011). The United Nations Secretary-General has "called upon parties to conflict to refrain from the use of explosive weapons with wide-area effects in populated areas", UN Security Council, Report of the Secretary-General on the Protection of Civilians in Armed Conflict (2015) (S/2015/453). For further reading on the humanitarian, legal, technical and military aspects of explosive weapons use in populated areas, see (ICRC, 2015).

target when used in areas containing concentrations of civilians due to how the weapons are designed even though precautions to limit those effects are taken.

There are three broad categories of explosive weapons that are prone to having wide area effects when used in populated areas, with some weapons in this report having varied levels of concern in one or more categories, and some only having concern with certain warheads or other contextual circumstances. The three categories of concern are:

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 tend to 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 (especially when using unguided munitions), and unguided air-delivered bombs.

Weapons designed to deliver a wide area effect are weapons typically fired en masse or in salvos, although individual munitions used may not necessarily have a large blast and fragmentation radius. This includes artillery barrage systems such as multiple-barrel rocket systems[3].

[3] Sometimes called 'multi-barrel rocket launchers'.

PART 1

The Technology of Explosive Weapons, Their Use, and Effects

1.1The Design & Effects of Explosive Weapons

1.1.1 The Damage Mechanisms of Explosive Weapons

The first step in understanding explosive munitions[4] is to look at how they damage a target and the surrounding area. An explosion is a rapid release of energy which takes the form of light, heat, sound, and a shock wave (FEMA, 2003). A rapid chemical process breaks the bonds of explosive compounds, occasioning a chemical recombination into different compounds (principally gases) which results in a release of thermal energy. This, in turn, causes a rapid expansion of these gases, which reinforce the detonation shock wave and provide the energy to produce the destructive effect of an explosive warhead (NSWC, n.d.).

There are three ways an explosive weapon can cause damage: through blast, fragmentation, and heat. The transfer of energy from these three mechanisms will produce the primary effects of deaths or injuries of persons and damage or destruction of structures, and other materiel, and may also produce secondary effects such as penetration, ground shock, cratering, secondary fragmentation, and firebrands (described below). Primary and secondary effects can be tailored and mitigated to minimize damage to non-combatants and to civilian infrastructure that surround the target.

The use of any explosive munition will result in the presence of each of these three damage mechanisms, in varying degrees, even when they are tailored to deliver a specific effect. For example, an anti-tank projectile is designed for maximum penetration of armour. They typically feature characteristics such as dense metals, high impact velocity, or a shaped-charge explosive to pierce the target armour (see section 1.1.2 for further discussion of munitions design). Nonetheless, there will also be some effects on target which result directly from an explosive detonation's blast, fragmentation, and heat mechanisms. All of these effects must be considered when a munition is used, especially in a populated area where there is a significant risk of harm to civilians and civilian infrastructure.

Table 1.1 shows the distances at which various common explosive weapons affect personnel under training and combat conditions. The table draws on two US military concepts, minimum safe distance (MSD) and risk estimate distance (RED); the former is intended for use under training (peacetime) conditions, whilst the latter is intended for use under combat conditions. At the MSD, risks to personnel from the munition in question's point of impact are considered negligible. The RED is expressed in terms of expected 'percent of incapacitation' (PI) to unprotected personnel, with .1 PI representing one in one thousand soldiers being incapacitated, and 10 PI representing 1 in 10 soldiers (10%) being unable to continue fighting (DA, 2007). The table provides a useful reference for common types of explosive munitions, and whilst the table expresses MSD and RED for US munitions types, these are largely analogous for other munitions of the same type and calibre.

Table 1.1 – Safety and incapacitation distances from point of impact for common explosive weapons[5]

Weapon system	MSD (training)	RED (combat)[6]	
		.1 PI	10 PI
60 mm Mortar	250 m	175 m	65 m
81 mm Mortar	350 m	230 m	80 m
120 mm Mortar	600 m	400 m	100 m
105 mm Artillery	550 m	275 m	90 m
155 mm Artillery	725 m	450 m	125 m
155 mm Artillery DPICM[7]	725 m	475 m	200 m

Source: DA, 2007

[4] See note 9 for the distinction between 'high explosives' and 'low explosives'.

[5] All tables in this report, unless stated otherwise, assume the use of point detonating (PD) fuzes (where applicable). Additionally, as per industry standard, figures given for area effects assume munitions use in an open area unless otherwise indicated.

[6] REDs do not represent the maximum range at which fragmentation from a munition poses a danger, nor do they account for so-called 'rogue fragments' (DA, 2007; DODESB, 2006).

[7] Dual-purpose improved conventional munition; a projectile that airbursts and dispenses small HEAT/FRAG sub-munitions, designed to attack both armoured fighting vehicles and personnel.

Primary Damage Mechanisms

Blast refers to overpressure[8] caused by a high explosive[9] detonation. The overpressure creates a shockwave of compressed air traveling faster than the speed of sound. The air-blast shock wave is usually the most significant damage mechanism in an explosion; as the energy of the wave is transferred it damages whatever it comes into contact with. The blast effect is usually relatively short in range and duration, though this depends on explosive weight and munition type. It is often the primary damage mechanism in large bombs. A blast warhead uses a high explosive detonation to damage a target at the point of detonation and a shockwave emanating from the detonation creates a pressure variation potentially spreading the damage. Some structures, for example, may collapse or be damaged from external pressure while others are able to resist damage. Detonating a blast warhead above ground in an airburst sometimes creates a reflective shockwave where the wave reflects off the ground and is reinforced thus greatly increasing the effective radius of the weapon (see section 1.1.7 Fuzing, below).

Whilst the human body can withstand relatively high blast overpressure without experiencing significant trauma (for example, according to some sources, a 5 psi blast overpressure will only rupture eardrums in approximately 1% of subjects), the significant blast winds that accompany this overpressure are often more damaging, leading to fatalities and injuries (Zipf & Cashdollar, n.d.). Table 1.2 shows the effects on structures and the human body from various blast overpressures and their accompanying blast wind speeds.

Table 1.2 – 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[10]
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%

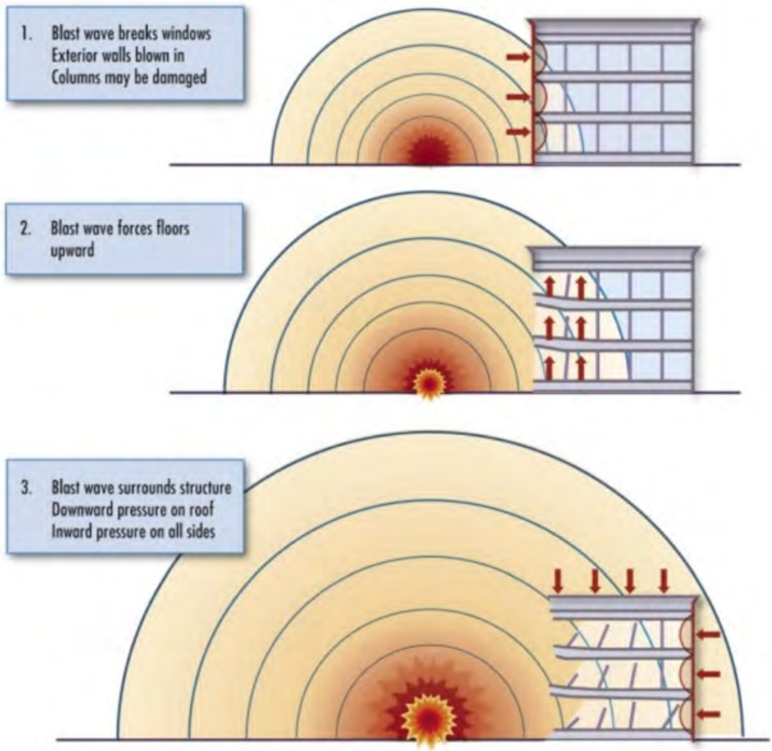
Source: Zipf & Cashdollar, n.d.

[8] 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.).

[9] So-called 'high explosives'; a high explosive is one which detonates (the chemical reaction moves through the material faster than the speed of sound), whilst a low explosive is one which deflagrates.

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

Figure A – The effects of an air-blast shockwave on a structure



Source: FEMA, 2003

The pressures the air-blast shockwave exerts on a structure's surfaces may be orders of magnitude greater than the stresses the structure has been designed to sustain[11]. The shock wave may also act in directions that the building has not been designed to resist. Figure A shows the effects of an air-blast shockwave on a structure. The pressures associated with explosive detonations decay very rapidly as distance from the source increases[12]. As a result, direct primary 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).

Fragmentation. There are typically both primary and secondary fragmentation effects resulting from the detonation of an explosive munition. The munition casing (body) and warhead breaking up upon detonation results in primary fragmentation. The fragments can be pre-formed, such as steel balls or cubes, they can be uniform metal fragments created by a controlled fragmentation warhead specifically designed to create fragments, and they can be non-uniform, often jagged, naturally occurring parts of the weapon 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 velocity (thousands of feet 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).

[11] Subsurface blasts may also produce impact stresses which a structure has not been designed to sustain.

[12] 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).

Fragmentation may be assessed as part of estimates such as the MSD and RED models described above. Another model is used by the US military to estimate the hazardous fragment distance (HFD) of a sample munition with a known net explosive weight (NEW[13]). The HFD is defined as the distance at which the density of hazardous fragments becomes 1 per 600 ft2 (55.7 m2) (AFSC/SEW, 2011)[14]. At this distance, there is approximately a 1% probability of a person being struck by a lethal fragment (USATCES, 2011). Note that the HFD is not the maximum range of fragments resulting from the detonation of an explosive munition. Table 1.3 shows the calculated HFD for sample munitions of varying NEW (DA, 2013).

Table 1.3 – 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: DA, 2013

Thermal energy is the final damage mechanism. The detonation of an explosive munition results in the 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). Detonating explosions produce extremely high temperatures of a very limited duration, often described as a short-lived 'flash'. 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 detonation of explosive weapons or by projected firebrands (see below), producing significant secondary threats. In contrast to explosive munitions, true incendiary munitions deflagrate, or burn, as opposed to detonate and are not explosive weapons per. See section 1.1.4 for further discussion of incendiary munitions.

Secondary effects of blast, fragmentation, and thermal energy effects

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 on civilians and civilian objects, particularly in built-up areas.

[13] The Net Explosive Weight (NEW) is the actual weight of explosive mixtures compounds (including the TNT equivalent of energetic material) contained in a munition, expressed in pounds (JCS, 2010). When expressed in kilograms, this figure is known as the net explosive quantity (NEQ).

[14]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 report will use the US DoD definition.

Secondary fragmentation is comprised of fragments of objects affected by a munition's detonation, generally those in close proximity to the explosion. These objects commonly include structural materials from buildings or vehicles, such as concrete, glass, and metal debris[15]. 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).

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. 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).

Penetration refers to piercing damage delivered to a target, typically achieved through kinetic energy. Some weapons are designed with penetration as their primary effect, such as anti-armour weapons, while others use penetration to deliver their explosive effects, such as penetrating bombs. For example, deep-penetrating air-delivered bombs are designed to burrow into the ground or structure prior to detonation so their explosive effects reach their targets such as bunkers. Many penetrating weapons, such as anti-tank munitions, do not have wide area blast or fragmentation effects as they contain little or no high-explosive[16]; such weapons will not be examined in detail herein.

Penetrating warheads are designed to penetrate armour, earth, and masonry to deliver an explosive effect to the target. Penetrating, or armour-piercing, warheads on air-delivered bombs act in a similar manner to large masonry nails, using the kinetic energy of descent to burrow deep into the target before a time-delay fuze causes the munition to detonate[17]. A shaped-charge warhead uses an inverted metal cone that is explosively collapsed and accelerated to high velocities to drive it through metal.

Ground shock results from energy imparted to the ground by the detonation of explosive charges under, on, or close to the surface of the ground. This energy is imparted through both direct-induced ground shock and air-induced ground shock. Air-induced ground shock results when the blast wave above ground compresses the surface of the ground, stressing the ground underlayers (de Silva, 2005). Ground shock may cause structural damage to adjacent structures as ground reverberates from the blast. It can also cause damage to subterranean structures including sewage, water, electricity or gas networks (see, for example, ICRC, 2015).

Cratering is the deformation of the ground and projection of material from the point of explosion, and is influenced by both direct-induced ground shock and air blast (DOD & ERDA, 1977)[18]. A crater is a secondary effect of the use of explosive weapons; however, cratering may be the desired primary intent of a weapon such as munitions that are designed to create holes in runways to render them useless to aircraft. If deep enough, cratering can cause substantial damage to underground structures, as with ground shock described above. Wide, deep craters are formed when air-delivered bombs detonate, particularly underground. Craters typically refill to some extent with material from an explosion that has fallen back to earth.

[15] They may also include fragments generated from biological targets, including teeth, bone, and wood.

[16] Note there may be minor fragmentation effects such as fragments caused by spalling inside of an armoured target. This is when internal elements of an armoured target break off due to impact from an anti-armour weapon and act as secondary fragments.

[17] Of note is the practice of some militaries to replace explosive fill with inert materials such as cement and use kinetic energy to achieve desired effects with minimal collateral concerns.

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

1.1.2 Explosive Munitions Design

All explosive munitions[19] are designed to destroy, damage, kill, injure, or incapacitate the intended target. The designer will take into account the nature of the target, be that human, animal, equipment or structure. They will also consider the effect that is required on the target and the range from which the effect is expected to be delivered. These 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'. The vulnerabilities of the target must be understood as fully as possible if the explosive munition is to be designed and used to create the predictable levels of damage required.

Each target presents specific challenges; warheads[20] with specific properties (damage mechanisms) are developed and selected to provide the desired effects on the target and overcome these challenges. For example, defeating armoured targets requires penetration, infantry in open terrain may be engaged with fragmentation, and some targets require multiple effects to defeat. Warheads carry the explosive 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. The warhead types below use various methods to transfer the energy of the detonation of the explosive to the target based upon the fuze type and warhead design.

All warhead types contain the fuze, the explosive fill, and the warhead case. As with the design of any piece of equipment, the final product is always what is considered to be the best compromise to meet the design constraints which might include: overall weight, dimensions, materials, legal restrictions, cost, the working environment (hot/cold, dry/wet, fresh/salt water, etc.), firing platform (ship, aircraft, vehicle, person), and other factors. All of these variables contribute to the potential for collateral effects (increased or decreased) in populated areas and help determine the scale of the weapon's impact area.

A major factor in the design and production of a munition is the way that it is intended to be used. To take a simple example, a 7.62 x 51 mm ball (full metal jacket; FMJ) cartridge intended for specialist marksman or sniper use might appear to the casual observer to be identical to that produced for the general infantryman. In actual fact, whilst the physical composition and design of these two cartridges may be similar, the sniper round is produced adhering to higher tolerances than the general service round because the sniper is required to provide a highly accurate, long-range capability, whereas the infantryman will often be fighting as part of a group at shorter ranges. Compared with a 'traditional' warfare requirement to destroy an enemy military command headquarters (composed of structures and armoured fighting vehicles (AFVs) dispersed over a wide area) and the more modern phenomenon of targeting a non-state armed group's headquarters facility located close to, or embedded within, a concentration of civilians, it is clear that the very different natures of these targets require different designs. The 'traditional' headquarters is an area target which lends itself to the employment of, say,

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[19] Most munitions are described by the terms 'bomb', 'projectile', 'rocket', and 'missile'. There is some overlap between technical terminology (both within and across different fields), and lay terminology. For example, the term 'missile' may be used to refer to any self-propelled munition, or to any object forcibly propelled at a target. In military terms, a 'bomb' is generally accepted to be a guided or unguided munition with no method of propulsion (such as an aerial bomb, or emplaced IED). A 'projectile' refers to a munition which is propelled under power from a weapon, such as a gun. A 'rocket' is generally accepted to be an unguided munition propelled by a rocket engine, whilst a 'missile' is generally accepted to be any self-propelled guided munition. Guided munitions which employ rocket propulsion may sometimes be termed 'guided rockets'; however some missiles may use forms of propulsion other than rocket propulsion.

[20] In general usage, the term 'warhead' refers to the portion of a munition containing the payload. This distinction is blurred when referring to munitions with submunition payloads, or less-lethal or non-lethal payloads.

conventional artillery rockets, whereas the ‘embedded’ target might be considered a point target, and require a precision guided munition (PGM) with sophisticated fuzing[21] (see section 1.2.1 for a fuller discussion of point and area targets).

Explosive ordnance is optimized according to its primary purpose. Some examples are described below:

Artillery projectiles. These munitions are primarily designed to produce fragmentation, and are often used against personnel and vehicles. Thus, the casing is quite thick. A thick projectile is also required for structural reasons due to the extremely high acceleration during firing. The explosive filling may be less than 20% of the total mass of the projectile.

Mortar projectiles. These are generally intended for use against personnel and light vehicles. The casing is thinner than that of an artillery projectile, and made of more brittle material creating smaller and more numerous fragments.

General purpose bombs. While mortar and artillery projectiles are subject to enormous acceleration during launch, bombs dropped from an aircraft are only exposed to the airstream in the vicinity of the aircraft. Thus, air-delivered munitions do not require the structural rigidity of projectiles fired from the ground. Therefore, they can be made with a relatively thin casing compared to artillery projectiles.. General purpose bombs achieve their intended effects through a combination of blast and fragmentation.

Armour piercing explosive projectiles are designed to penetrate a target before detonation. As a result, the front part of the projectile is solid and the explosive fill is located towards the rear of the munition. This allows it to penetrate a structure or armoured vehicle before exploding within.

Shaped charge (e.g. HEAT) munitions. These munitions are designed to perforate armour. The explosive filling has a conical cavity in the front that is lined with a thin metal (typically copper) sheet. Upon detonation, this metal is converted to a thin jet with an extremely high velocity that is able to penetrate armour up to ten times the calibre of the warhead. The casing of this projectile is usually thin as fragmentation properties are secondary considerations.

[21] Alternative methods of warfare may also be employed.

The mode of delivery also significantly affects the design of the warhead. Warheads delivered at long distances through the air must have an aerodynamic shape that is able to maximise their potential range, within some constraint on size and mass.

Land mines vary significantly in design according to their use. Some are intended to work primarily by blast from a buried emplacement. Others are placed above ground and achieve their effects primarily through fragmentation. Some are designed to penetrate the under-armour of vehicles and make use of a shaped-charge design. Land mines may also be distributed from cargo munitions.

Cluster munitions are cargo munitions which carry and disperse smaller munitions (submunitions). The container must contain one or more ejection devices that ensure an ample dispersion of the submunitions. This is usually achieved by a combination of an explosive charge and the spin of the container. The density of submunition impacts on the ground should be relative to the effectiveness of a single submunition.

Anti-personnel landmines and cluster munitions are prohibited by international conventions. However, not all states have adhered to these conventions. Still, these weapons remain as a threat to populated areas, and are in use in some current conflicts. Given the widespread attention these types of munitions have received, landmines and cluster munitions are not covered in this report.

1.1.3 Common Types of Explosive Munition Warheads

The warhead of a munition is its primary component, responsible for effecting the damage or destruction of the target. As mentioned in the previous section, warheads are generally considered to consist of three components; the fuze (including any safety, arming, and disarming devices; see section 1.1.7 Fuzing, below), the warhead case, and the explosive fill. The vast majority of explosive munition warheads can be categorised as one of the types described below, or as thermobaric warheads. Thermobaric munitions are discussed in section 1.1.4.

The warhead design determines the mechanisms used to achieve destruction of the target, and thus their suitability for use against a given target. Some warheads may utilise a combination of these effects.

Blast warheads

Blast warheads are designed to achieve target damage primarily through the effects of a shock wave, producing overpressure and high temperature resulting from the detonation of high explosives. As described in section 1.1.1, this detonation causes a compression wave to propagate outwards, causing a near-immediate rise from normal atmospheric pressure to peak overpressure, followed by a slower drop back to, and below, normal atmospheric pressure, in objects it passes through. See table 1.2 for details on the effects of blast overpressure on the human body and structures.

Typically, warheads that rely on blast for target destruction are designated as high explosive (HE). HE warheads are common amongst explosive weapons of all types, including rockets and artillery projectiles. HE munitions are most often employed in conjunction with point-detonating fuzes, and typically fuzed in the nose of the munition. Common sizes range from 12.7 mm to ≥240 mm.

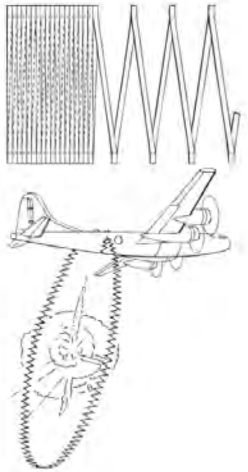
Fragmentation warheads

As described in section 1.1.1, fragmentation warheads are designed to cause target damage through the creation of high velocity fragments. The weight of individual fragments varies depending on the purpose of the munition, and commonly range from tenths of grams up to around 16 grams[22] (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.). Generally speaking, the radius of effective fragment damage exceeds the radius of blast damage, as air friction slows the blast wave much more effectively than the dispersed fragments (NSWC, n.d.).

A distinct subset of HE warheads, high explosive fragmentation (HE-FRAG) warheads are designed to produce more lethal fragments than a standard blast warhead. This is generally achieved through enhancing the natural fragmentation characteristics of their materials, by designing for controlled fragmentation, or by the inclusion of preformed fragments. The fragmentation behaviour of a warhead is influenced by its chemical composition, metallurgy, shape and configuration, and explosive fill (Beetle & Schwartz, 1976). HE-FRAG warheads are typically constructed of different materials than blast warheads, and often feature heavier metal construction or have a supplemental fragmentation sleeve integrated or affixed to the munition body. Many fragmentation warheads undergo a thermal, chemical, or mechanical treatment in order to make the metal more brittle and more susceptible to uniform fragmentation (Beetle & Schwartz, 1976). A fragmentation sleeve is a metal sleeve that contains pre-formed fragments or has been scored to encourage fragmentation. Fragmentation sleeves are most

[22] In specialized literature, the "grain" is the common unit of measurement in ballistics. One gram consists of approximately 15.43 grains.

Figure B – The design and function of a continuous rod warhead



Source: Naval Education and Training Professional Development and Technology Center (NETPDTC)

often used in conjunction with conventional HE warheads. Fragmentation warheads are often chosen for employment against personnel and light vehicles.

Another type of fragmentation warhead is the continuous rod warhead. Warheads of this type use a long rod 'folded' (connected end-to-end) in a bundle surrounding the high explosive filler. When the warhead functions, these rods expand to form a complete 'hoop' centred at the munition's axis. This circle expands as a continuous rod until its circumference is approximately equal to the length of the unfolded rod, after which it will fragment. This is distinct from the multidirectional fragmentation pattern associated with sleeved munitions. Figure B shows the design and function of a continuous rod warhead. The ring of fragmentation is highly effective against aerial targets, and as a result continuous rod warheads are often found in anti-aircraft munitions (Reynolds, 1965). While these warheads are predominantly used against aircraft, they have also seen limited applications on the ground, especially in an obstacle clearance role.

Dense inert metal explosive (DIME) warheads are a novel design intended to develop a highly lethal munition with lower collateral damage potential. One experimental DIME munition features a carbon fibre warhead casing containing a homogeneous mixture of a phlegmatised explosive compound and fine tungsten alloy particles. The tungsten alloy displaces explosive material which reduced the NEW of the munition, and contributes to a highly lethal but localised area of effect (Engle, 2005). Despite the claimed effectiveness of these warheads, there are concerns that wounds from DIME weapons are particularly difficult to treat surgically, and may have ongoing health impacts (Kalinich et al., 2005; Wolf et al. 2009).

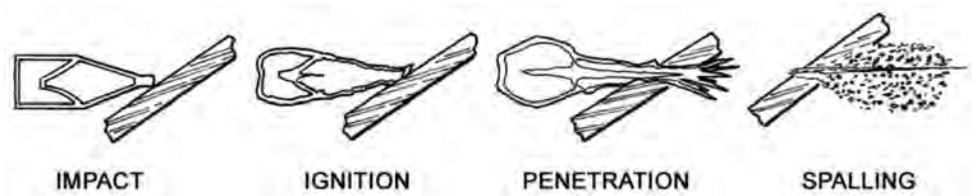
Anti-armour warheads are those specifically designed to engage armoured fighting vehicles. Whilst anti-armour warheads generally will not have a 'wide impact area' when employed individually, especially in the direct-fire role, the employment of such munitions in quantity, especially by untrained or uninformed personnel, may constitute a threat to civilians.

Explosive anti-armour warheads are known as chemical energy penetrators, in contrast to kinetic energy penetrators, which rely upon energy imparted during the firing process and act in much the same way as a conventional small calibre projectile fired by an infantry rifle. Chemical energy penetrators, on the other hand, use the energy of an explosive detonation generated when the munition functions on approaching or reaching its target (Meyers, 1994). Examples include shaped charge (including high explosive anti-tank, or HEAT, and HESH warheads will be considered below.

Shaped charge warheads, the most common of which are termed HEAT warheads, are characterised by a hollow metal liner (often copper or aluminium) which formed in a conical or hemispherical shape, and typically bonded to the explosive fill on the convex side. When the HEAT warhead functions, the explosive composition is detonated from the rear of the warhead at its apex, collapsing the metal liner at its apex and projecting a jet of metal in a state of superplasticity. This phenomenon is known as the Munroe effect (Kennedy, 1990). The jet is followed by approximately 80% of the liner's mass, which forms a slug, and the immense velocity of this molten stream is highly effective at cutting through steel armour (Dawe, 2008; NSWC, n.d.). The liner is effectively converted into a kinetic energy penetrator, however typical impact velocities are significantly higher than kinetic energy penetrators (around 7 km/s as opposed to 1 – 2 km/s) (Sandstrom, 1989). Shaped charge warheads are designed to effect armour penetration, and are often employed against armoured fighting vehicles.

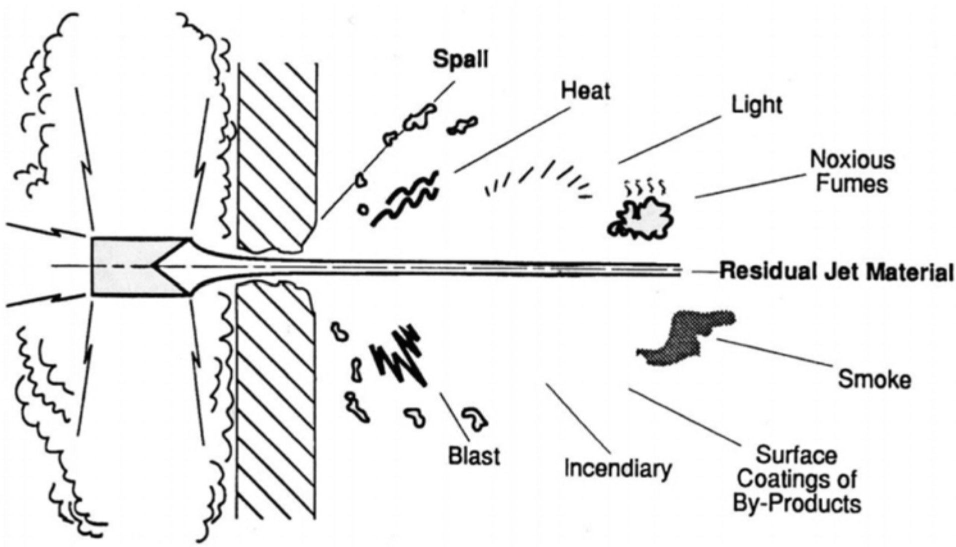
Figure C illustrates how the explosive wave converges on to the liner in a HEAT warhead, inverting it, forming a jet, and driving this into the target's armour. Figure D shows the behind armour effects (BAE) of a shaped charge. The primary damage mechanisms are the residual jet material and spall. The blast wave, thermal energy, smoke and light may also pose a threat under certain circumstances (Held, 2008). HEAT warheads can be commonly found in rockets and missiles as well as recoilless rifle and direct-fire artillery projectiles (see Part 2 of this report).

Figure C – The functioning of a shaped charge munition



Source: (DA, 2006)

Figure D – Behind armour effects of a shaped charge

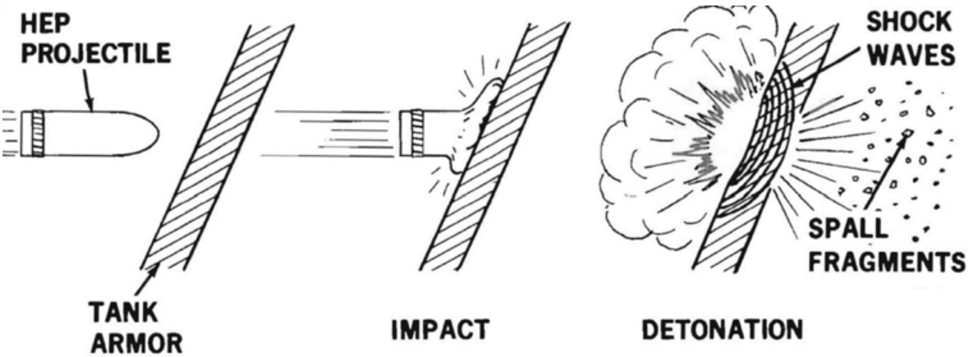


Source: Kennedy, 1990

Unlike kinetic energy penetrators or HEAT warheads, *high explosive squash head* (HESH)[23] warheads, do not necessarily need to penetrate the target's armour in order to inflict damage. This is achieved through the use of a thin-walled projectile, filled with a plastic explosive. Upon impact with the target, the explosives flatten out into a disc, or 'pad', before the fuze at the base of the munition detonates (Goad & Halsey, 1982).

This large contact area results in a shock wave being transmitted through the target material, causing secondary fragmentation known as spall to be produced and projected from the side opposite to impact (DDC, 1964) (see Figure E). Damage to the target is primarily effected through blast and secondary fragmentation. Munitions of this type have been historically employed against armoured fighting vehicles, producing spall inside the vehicle crew cabin, and against structures. Whilst they are used less commonly against armoured fighting vehicles in modern warfare (having been replaced by HEAT munitions), HESH munitions remain in service in many countries in an anti-structure or multipurpose role. HESH warheads are most common with recoilless gun and direct-fire artillery gun projectiles.

Figure E – Functioning of a HESH (HEP) projectile



Source: US Army

[23] Sometimes known as high explosive plasticised or high explosive plastic (HEP).

1.1.4 Thermobaric and Fuel-Air Explosive Munitions

It is important to understand the difference between incendiary, fuel-air explosive (FAE), and thermobaric (also referred to as volumetric or enhanced blast) munitions, as well as the differences between these munition types and conventional high explosive munitions. The wide range of terminology applied to these weapon types, and the inaccurate ways such munitions are defined, has led to some confusion and hyperbole in reporting on the use of incendiary, thermobaric, and FAE weapons.

Incendiary weapons, devices or bombs are designed to start fires or destroy sensitive equipment, using materials such as napalm, thermite, chlorine trifluoride, or white phosphorus. Whilst incendiary weapons are not explosives, and thus fall outside of the scope of this report[24], it is important to distinguish between incendiary munitions as opposed to thermobaric and FAE munitions. The former deflagrate, whilst the latter detonate[25].

Incendiary weapons are primarily intended to provide sufficient heat and fuel to ignite, and possibly sustain, a fire at the target[26]. The intention of a thermobaric or fuel-air-explosive weapon is to create a gross overpressure, combined with very high temperatures, such that the target suffers severe physical damage almost instantaneously.

Thermobaric Munitions

Thermobaric weapons[27] have been likened to mini-nuclear devices or referred to as vacuum bombs that 'suck the air from the lungs'. In fact, the effects are akin to those of gas- or dust-explosions that occur from time to time in industrial accidents. The 'usual' effects of an explosion, i.e. blast wave, overpressure, negative pressure and heat are of the same nature as those expected from a conventional high explosive, except that the duration of each effect is likely to be greater, increased from a few milliseconds to tens of milliseconds.

An agreed definition of 'thermobaric weapon' is not easily found, primarily because the term has been used for a variety of different weapon systems and effects over the years. In etymological terms, the term thermobaric is derived from the Greek words for 'heat' and 'pressure': thermos, meaning hot + baros meaning weight or pressure. This origin efficiently describes the effects of such weapons, but it is the mechanism and duration of these combined effects that directly relate to the types of damage caused. 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. Fuel-air explosives are one of the most well-known types of thermobaric weapons (see below).

"The detonation of high explosive (HE) can be viewed in three stages. The first, an anaerobic stage, is measured in microseconds and breaks down the explosive by a shock wave. The subsequent exothermic molecular reactions go on to propagate the detonation wave. The second stage, measured in hundredths of microseconds, is also anaerobic. This involves reactions between any products that were too large to be involved in the main detonation event. The third stage is aerobic and lasts milliseconds. In this stage more, previously unreacted, fuel particles react with the surrounding air.

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[24] Protocol on Prohibitions or Restrictions on the Use of Incendiary Weapons, 10 October 1980, in force 2 December 1983, 1342 UNTS 171. See also ICRC, Customary International Humanitarian Law Study, Rule 84-85, https://www.icrc.org/customary-ihl.
[25] Note that some incendiary munitions may also contain high explosive bursting/anti-handling charges.
[26] The Protocol on Prohibitions or Restrictions on the Use of Incendiary Weapons defines an "incendiary weapon" as such: "any weapon or munition which is primarily designed to set fire to objects or to cause burn injury to persons through the action of flame, heat, or combination thereof, produced by a chemical reaction of a substance delivered on the target.", Article 1(1).
[27] Sometimes called 'thermobaric explosives', or TBE.

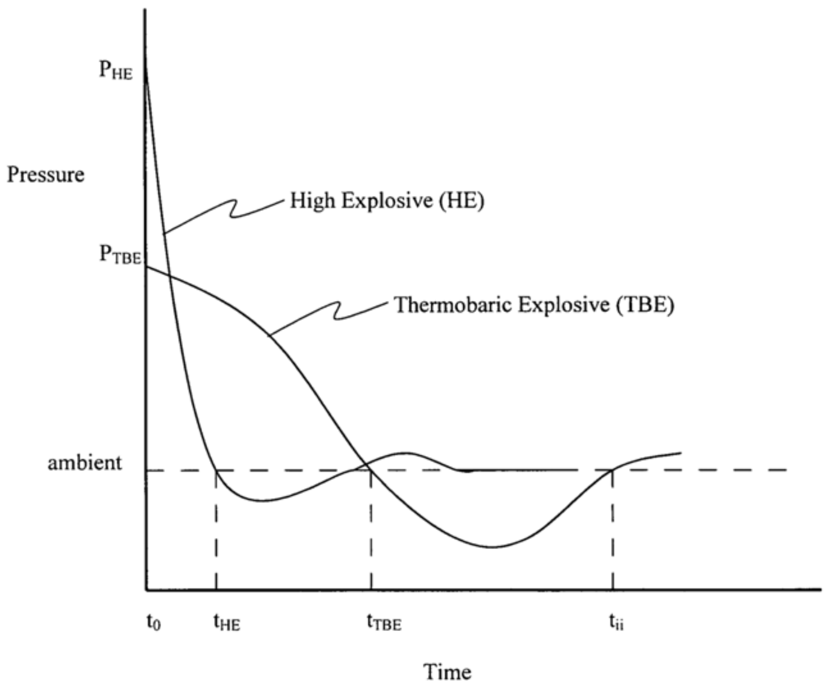
Stage One defines the HE's high-pressure shock effects (such as propelling a metal liner or fragments); Stage Two prolongs the high-pressure blast pulse, giving a useful heaving effect needed in building or bunker defeat; and Stage Three produces a long-duration, lower-pressure pulse that can also have a high thermal output, both of which are useful for materiel and personnel defeat.

Stages Two and Three are enhanced in thermobarics. This is accomplished by the addition of various fuels and additional oxygen-carrying chemicals to the explosive. By carefully selecting the HE, fuel and oxidiser, the multiple-target defeat effects of blast, fragmentation and thermal pulse can be brought into effect.

Blast enhancement is mainly due to two reasons. The first is the fact of the wide dispersion of the fuel before combustion, making the initial combustion zone very large in comparison with a standard high explosive (metres compared with millimetres). The second is that although the peak pressure produced is lower, the duration is far longer. This is effective as the ability of buildings and people to survive a given pulse pressure level decreases with increasing pulse duration [See Figure F]. The thermal effects of such warheads also dwarf those of classical HE, the temperature of the fireball, the heat flux produced and its duration all being several times larger (some an order of magnitude greater)."

Source: Gibson & Pengelley, 2004

Figure F – Comparative pressure pulse of thermobaric and high explosive munitions



A typical thermobaric weapon consists of a container packed with a fuel substance, in the center of which is a small conventional-explosive bursting charge, or 'scatter charge'. Fuels are chosen on the basis of the exothermicity of their oxidation, ranging from powdered metals, such as aluminium or magnesium, to organic materials, possibly with a self-contained partial oxidant. The most recent development involves the use of nanofuels, which are described as being a new geometric form of stable solid hydrogen and oxygen clusters formed from water which induce a strong catalytic reaction inside the combustion chamber[28] (Sheridan et al, 2009; Nanofuel, n.d.).

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. The principles of thermobaric explosives are similar to those which underlie accidental unconfined vapour cloud explosions, such as those encountered in flour mills and coal mines.

Fuel-Air Explosive Munitions

Fuel-air explosive (FAE) munitions are sometimes considered a sub-type of thermobaric munitions, however their operating principles are distinct. FAE devices generally consist of two separate explosive charges and a fuel container, with their initial charge designed to function at a predetermined height, dispersing a cloud of fuel from the container. Certain hydrocarbons and their oxides form detonable aerosols, and this fuel cloud, mixing with atmospheric oxygen, can surround and penetrate objects and structures. The second charge detonates this cloud, causing a massive blast wave that damages or destroys structures, equipment, and personnel. The performance of a FAE munition depends largely on droplet size, minimum energy for initiation, and the chemical behaviour of the fuel, and can also be affected by additives to the fuel mix (Rao, 1987).

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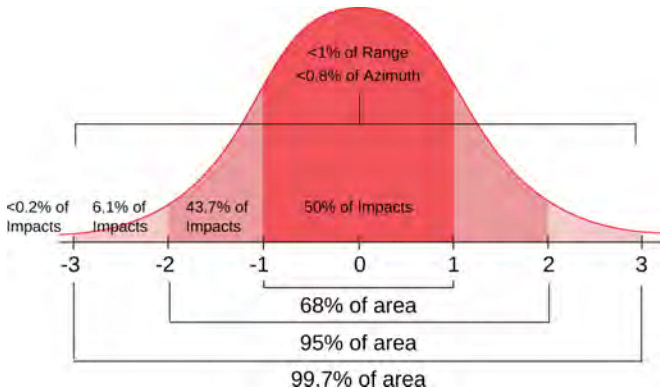
[28] Optimising a thermobaric munition's effective yield requires the combination of a number of factors, including the dispersal of fuel, how rapidly and efficiently this fuel mixes with the surrounding atmosphere, the initiation of the igniter, its position relative to the container of fuel, and the micro- and macro-geometry into which the fuel-oxidiser mix flows. In some designs, the munitions casing allows the blast pressure to be contained long enough for the fuel to be heated up well above its auto-ignition temperature, so that once the container bursts, the fuel will auto-ignite progressively as it comes into contact with atmospheric oxygen.

1.1.5 Accuracy

For the purposes of this report, 'accuracy' is defined as a weapon's ability to strike a specific aim point[29]. Not all militaries have access to precision-guided munitions[30]. Accuracy is one factor that contributes to a weapon's potential wide area effects, precision is another, see Dullum et al., 2016 for a more thorough discussion of accuracy, especially as it applies to indirect fire artillery systems. Accuracy does not strictly affect the weapon's potential wide area effects per se. However, in order to obtain the desired effect on target, an inaccurate weapon must be delivered in greater quantities in order to ensure that the operation results in a destruction of the target. In an extreme case, a ten-fold improvement in the precision may result in a hundred-fold reduction in the number of explosive units that have to be delivered in the target area to achieve desired effect on all targets. Because of this, inaccurate or imprecise weapons usually have a wide area effect in order to compensate for the miss distance (or 'error') and to ensure that at least some desired effect may be inflicted on the target. For example, some surface-to-surface missiles have their accuracy measured in hundreds of metres or more, and may carry several hundreds of kilos of high explosives, creating a large and potentially uncertain area of effect.

There are a number of measures of accuracy and precision used for explosive weapons. The most well-known is circular error probable (CEP). CEP is a measure of precision used for some weapons, including some air- delivered munitions and artillery. The actual calculation to determine the CEP for a weapon system is rather complex and requires extensive 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 mean point of impact (MPI)[31], 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 weapons dropped on a target will fall within the CEP, the rest may fall up to 3 times the CEP radius; the larger the CEP, the larger the uncertainty of where the munitions will detonate (see Figures G & H)[32].

Figure G - Circular Error Probable & Normal Distribution



[29] A more technically correct term would be 'desired point of impact', or 'desired mean point of impact' in the case of weapons firing in salvos.

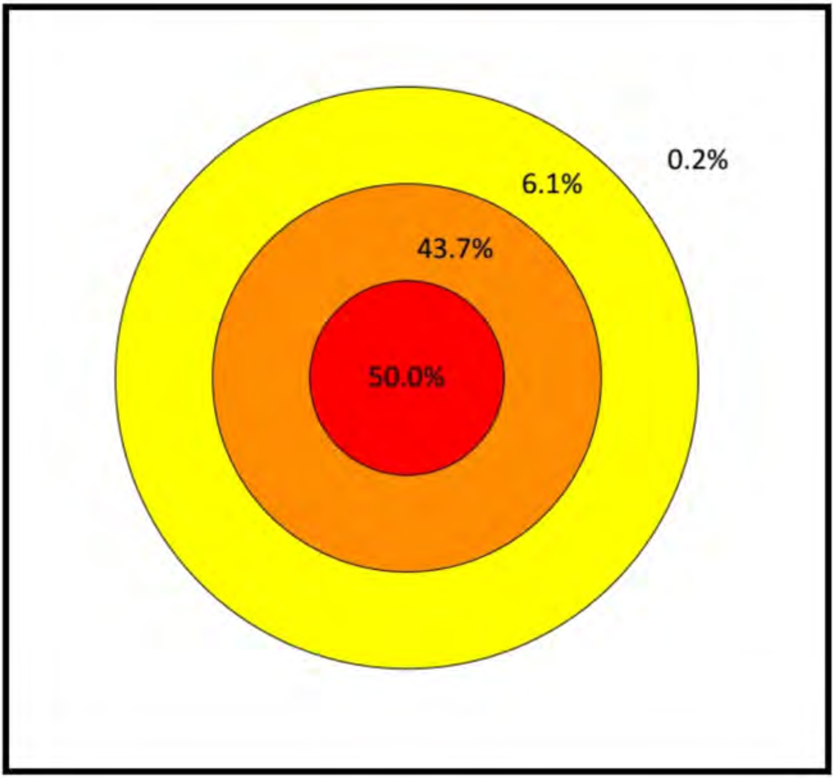
[30] Precision is the mneasure of mean point of impact (MPI) consistency, or 'dispersion' (Dullum et al., 2016).

[31] Note that the MPI will usually deviate consistently from the "aim point" or "desired MPI". The distance of this is the inaccuracy, the coordinate difference is called the "bias". Successive salvos will observe the MPI and compensate for bias to achieve optimal effect on target. See Dullum et al., 2016 for further details.

[32] Figures given for CEP assume munitions employed under standard testing circumstances unless otherwise indicated.

Circular Error Probable is derived from a circular bivariate normal distribution (or Rayleigh Distribution) with parameter σ (standard deviation), which directly informs the CEP (~1.4 standard deviations from the MPI is 50% population). Munitions with this distribution behaviour tend to cluster around the MPI, with most reasonably close, progressively fewer and fewer further away, and very few at long distance. Indirect fire systems, over a large number of shots, produce impact patterns that will trend towards a normal distribution. That is, if CEP is n meters, 50% of rounds land 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%. See circular distribution chart, below.

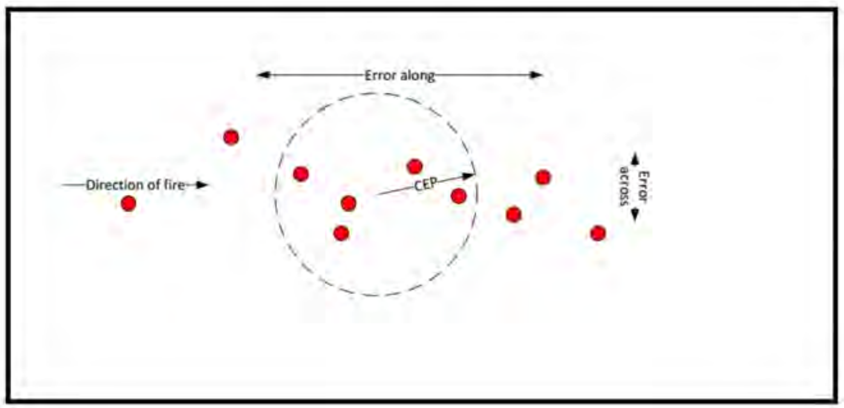
Figure H - Circular Error Probable (circular distribution)



Source: ARES

This kind of circular distribution behaviour is often not met. Circular distributions are not typical for precision guided munitions, which deviate by less random amounts. Munitions often have a larger standard deviation of range errors than standard deviation of azimuth (deflection) errors, resulting in an elliptical confidence region. The centre of this pattern is generally off the point of aim. This is referred to as bias. For an effective delivery, the bias should not exceed 1.5 – 2.0 CEPs, or the majority of impacts will have no effect on target. For long range indirect fire, the CEP concept is less likely to apply as the dispersion may be quite different along and across the line of fire. The longitudinal dispersion 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 more impacts far from the MPI[33]. Thus, it is sometimes considered more useful to differentiate between the errors along these axes using the concept of separate probable errors along and across the firing line (see Figure I). This can also be modelled by the application of an ‘elliptical error probable’, see Dullum, et al., 2016 for more information.

Figure I – Error across and along the firing line for indirect-fire weapons



Source: ARES

For aerial bomb delivery and long range artillery fire, the CEP concept is useful for describing precision (dispersion), however it is not useful for describing accuracy. However for artillery fired at a low angle, typical of rocket artillery at short range, CEP is less applicable and an elliptical model accounting for separate error along and across the firing line should instead be used.

For projectile (gun) artillery, the CEP is relevant when discussing the precision of a salvo but is not useful for describing accuracy, which is the ability to have an MPI col-located with the aim point. Precision is determined by random errors or variations in parameters like muzzle velocity, projectile mass and low altitude meteorological conditions. Accuracy, on the other hand, is determined by systematic error sources, like errors in gun and target positioning, alignment of the gun, and, most significantly, meteorological parameters like wind and air resistance (Dullum et al., 2016).

Meteorological parameters dominate the error budget, or estimated inaccuracy and imprecision, when firing at ranges beyond 15 km. The most important environmental parameters that affect accuracy are temperature, air density and wind, of which the latter is the most significant. The table below shows some estimated figures, based on the assumption that a meteorological profile of the wind was made 2 hours in advance of the firing (FFI, 1993). Under typical wind conditions, the wind speed would likely vary by approximately 5 kts in that time. In the case of 95% wind percentile (a wind condition exceeded only 5% of the time; ‘strong wind’, below), the change in wind speed would be approximately 8 kts. In terms of error along and across the line of fire under these conditions, Table 1.4 would apply.

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

Table 1.4 – Sample precision of artillery projectiles by firing distance and wind effects

Firing distance (km)	Precision with average wind		Precision with strong wind	
	Along (m)	Across (m)	Along (m)	Across (m)
6	40	5	50	6
12	85	39	123	57
18	119	66	178	101
24	150	118	251	200
30	176	124	322	230

The quality of meteorological sampling is essential to the accuracy of all artillery, and especially to rocket artillery. Meteorological sampling is traditionally conducted by launching a balloon equipped with a temperature and pressure sensor that transmits the data back to the launching unit at regular intervals. The wind velocity, which is the most important factor, is calculated from the change in location of the balloon over time from a GPS unit that transmits its position. This information is then converted to a standard meteorological message (MET message) that is input to the ballistics computer in the gun or rocket battery (DND Canada, 1992). For many less-developed militaries and non-state armed groups, meteorological data is based purely upon observation at the launching site, or is not considered at all.

Unguided air-delivered bombs, also known as gravity bombs, do not have a measurable or calculable CEP. Their accuracy is a product of the aircraft, altitude, speed, competence (a combination of knowledge, skill, experience, and attitude/behaviours) of the pilot, weather and other factors and as such, varies greatly. Many aircraft use an on-board computer linked to the heads-up display (HUD; the display the pilot observes the target through) to create a calculation called the 'constantly computed impact point' (CCIP). The CCIP is displayed on the HUD as a moving crosshair where the computer predicts the bomb will strike (CNATRA, n.d.). Under optimal conditions, a well-trained pilot can hit a tank-sized target with a gravity bomb, though not all militaries are equipped appropriately, or able to train to this level of aptitude.[34]

When firing a projectile or rocket against a target, there are two classes of error that appear:

Systematic errors

These errors are consistent from round to round (provided the rate of fire exceeds the volatility in meteorological conditions, see Dullum et al., 2016), resulting in a mean point of impact that deviates from the aiming point, or bias. If time permits, and the error or errors are correctly identified, these can be largely compensated for by adjusting the firing parameters in successive salvos. Typical sources for systematic errors are:

- The difference between the actual meteorological state, and that which is measured, predicted, or assumed;
- Deviation between the properties of the actual batch of ammunition, and the standard properties of such;
- Errors in the aiming device;
- Errors in the target acquisition data
- Errors in the launcher position and orientation; and
- Incomplete ballistic models.

[34] Interview with USAF pilot, July 15, 2014. Name withheld.

Random errors
These errors are inconsistent from round to round. They are mostly related to variability in the projectile/rocket or the launcher, but short term variation in the wind conditions are also of importance. The typical sources are:

- Variations in projectile/rocket mass;
- Variations in propellant mass;
- Temperature dependent propellant burn characteristics
- Errors in the manufacture of rocket/projectile (fins, body, shear bolts, etc.);
- Fuze timing inaccuracy (for cargo and certain other payloads);
- Thrust misalignment (for rockets);
- Gun/launcher movement and vibrations; and
- Short term wind variation in the boost phase (for rockets).

An important tenet of accuracy is that systematic errors should not exceed the random errors. A salvo for which there is a certain systematic error in excess of munition area of effect, but no random errors, will not achieve desired effect on the target area, as all projectiles/rockets will hit at the same inaccurate point. The estimated systematic and random error, or error budget, is essential input when calculating the expected number of rounds required to neutralise targets in an area. However, the size of the target, as well as the area than an individual round will affect, are also important in this determination.

Rocket artillery accuracy
There are a number of additional considerations that are important when discussing rocket artillery system accuracy. Table 1.4 is not indicative of rocket projectile inaccuracy due to the different and larger meteorological error characteristic of these systems. For rocket artillery these values could be up to twice as large. The majority of artillery rockets are known as ‘free flight rockets’ (FFR) because they are unguided. Precision of these weapons is not generally listed as a CEP, although the published accuracy may be expressed in terms of CEP or in terms of an area expressing an elliptical confidence region (see above). Precision and accuracy are strongly influenced by the range to target, making statements on the precision of these often imprecise weapons difficult. For example, the published accuracy of some 122 mm rockets is 168 m in length and 80 m in azimuth at maximum range, giving a large elliptical area in which they may function. Traditionally, rocket artillery has been intended for salvo fires with multiple rockets impacting a targeted area to compensate for the imprecision of the weapon, thus creating a large potential area of effect (Dullum, 2010).

The accuracy of rocket artillery is more complex than for most other systems, as there are more sources of error and several of these contributions are hard to quantify. For rocket artillery the two major sources of error are:

Inaccuracy in launch direction

This is mainly caused by movement and vibration in the launcher unit after ignition of the rocket, but before the rocket has left the launcher rail or tube. In order to minimize the variations in launch velocity, the launcher releases the rocket when the rocket force has reached a certain level. This is typically achieved by attaching the rocket to the launcher using so-called ‘shear bolts’ that will break when exposed to a certain force. Before that event, the rocket will exert forces which try to move the launcher, and when the bolts break, the launcher will recoil. This movement will not be consistent from shot to shot. The vibration of the launcher unit will change as its mass and moment of inertia will decrease for each rocket that is fired. This is an example of a random error that has a minor cumulative influence on the mean point of impact, but notably affects the precision of a salvo of rockets, especially in the direction across the line of fire.

Wind

Artillery rockets usually have a rather short burn time, with the propellant often consumed after 1 – 2 seconds, in which time the rocket accelerates from zero to, for example, 800 m/s. After that, the rocket flies like any other ballistic projectile with the same shape. The aerodynamic properties of the rocket ensure that the rocket will line up into the relative wind (typically in the direction of travel except in strong opposing/cross wind). During the acceleration phase (also called the boost phase), which may extend to a trajectory length of around 1000 m, the rocket will deviate into the wind; after the acceleration has ceased, it will deviate with the wind. The amount of deviation is determined by the duration of the boost phase, the amount of acceleration or deceleration, and the impulse (which is affected by air density and velocity) of the ambient air. This type of error is essentially of a systematic nature, but the wind during the boost phase may also have some random character if the salvo is fired over some time. All effects taken into account, the error induced during boost phase may in the worst cases be comparable to the error caused by wind in the ballistic phase. Another important factor is that light rockets are more subject to wind-induced error than heavy rockets.

The precision of rockets is often given separately as the error in meters along and across the line of fire. As an example, 180 m x 140 m means that the deviation of impact is 180 m along the line of fire and 140 m across the line of fire. It may also be given in mils[35] and as a fraction of the firing distance. These latter two representations suppose that the error is proportionate to the firing distance. Examples of rocket artillery accuracy, as given by the producer or user, are given in Table 1.5.

Table 1.5 - Accuracy of selected rocket systems[36]

Accuracy of selected multiple-barrelled rocket systems Values given as deviation in mils *along* x *across* 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
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 x14.7
122 mm (modernized)	122	20	4.9 x 7.6	unknown	-
220 mm	220	30 -35	5.0 x 5.6	unknown	-

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

It is important to note that, when comparing projectile artillery to rocket artillery, the latter has larger error, but in addition, rockets deviate far more to the side than ordinary projectiles. It is reasonable to say that the most typical error values are:

- Fin-stabilised rockets have a random error of around 5 x 9 mils
- Spin-stabilised rockets have a random error of around 9 x 12 mils
- Light rockets (commonly 100 - 130 mm) may have an indicative systematic error of 6 x 12 mils
- Heavy rockets (more than 200 mm) may have an indicative systematic error of 4 x 6 mils

35 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).

36 In the table, the values are based on the ballistic simulation software (Chaplin, 1990). The values for a spin-stabilized 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).

However, the major part of the systematic error may be compensated for in practice if the operating force has ways and means to observe the MPI, and then adjust for the subsequent salvos. The errors are typically independent of the payload, but payloads that require a time delay fuze introduce additional error sources in the fuze timing, and due to the unknown wind in the terminal phase. However, the error contribution from this phase will, in most cases, be insignificant in comparison to other errors.

An additional source of error for rocket artillery is how the atmospheric conditions along the flight trajectory are affected by the rockets themselves. When a high number of rockets are fired within a short interval of time, a significant quantity of warm gasses are emitted to the air column in which the rockets burn. The energy will change the wind field and the temperature in the air and create significant turbulence. This will contribute to the random error; however, this effect has not yet been examined in the available scientific literature.[37]

[37] As of May 2015.

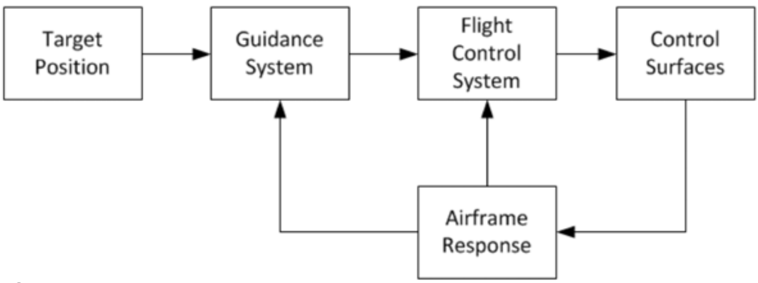
1.1.6 Precision Guided Munitions

Precision guided munitions (PGMs) are a class of munitions, both powered and unpowered, which can alter their flight paths to more accurately strike a target. PGMs offer increased accuracy, a wider array of fuzing options, lower ammunition consumption (and relief of associated logistics burdens), may allow for the ability to strike moving targets with greater ease, and may allow the employing force to minimise the likelihood of collateral damage (Jenzen-Jones, 2015a).

The definition of precision can be broad. For example, 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 10 meters (Sine, 2006). Meanwhile, the United States Army quotes their small and ‘precise’ guided rockets as having a CEP of 1.3 meters (Cavalier, 2010). 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.

At the heart of a PGM is a control loop comprised of several key components (Zarchan, 2007). As shown in Figure J, there must be a mechanism to receive target position. This information, along with the munition’s position, is used to generate guidance commands which are sent to a flight control system. The flight control system, or autopilot, then generates commands to control surfaces which in turn generate forces on the munition to change its motion. Control surfaces typically employ aerodynamic forces via wings and fins, but some munitions also possess the capability to alter the propulsion force which is known as thrust vectoring.

Figure J – A sample PGM control loop.



Source: ARES

All parts of this loop play a role in the accuracy of a PGM, but the guidance system is the most critical contributor. A variety of guidance system designs exist, but they can all be categorised as external, non-homing or homing (Siouris, 2004). Within each of these categories are several sub-types, each with their own distinct functionality and performance.

External guidance, as the name indicates, is an approach which employs an external guidance source such as an operator or fire control system. A common type of external guidance is command guidance where steering commands are sent directly to the munition over a control link such as a radio. Another type of external guidance, known as beam riding, uses a beam of energy pointed towards the target by the launcher. The munition attempts to stay on this beam until the munition and target’s paths cross. In both cases, the external source must remain present throughout the flight for the munition to have a chance at a successful engagement.

Non-homing guidance is an approach where the munition is given the target position and it flies there via some navigation method. The most popular form is inertial guidance which has traditionally been associated with ballistic missiles. Eventually, however, it found its way into smaller tactical weapons as electronics performance increased and size decreased. Today, probably the most recognised form of this guidance is in ‘satellite-guided’ (often GPS) weapons. In this case, the munition is not actually being guided directly by the satellite navigation signals, but rather by an inertial navigation system (INS) which is being aided, or updated, by the satellite navigation signals. The INS gets its name by the use of accelerometers and gyroscopes which measure inertial acceleration and rotational speed onboard the munition. When combined with software in an onboard microprocessor, these systems are able to determine position within a specified accuracy for a certain amount of time. The addition of high precision satellite navigation signals increases the overall accuracy of the INS and counteracts the natural tendency of the INS to lose accuracy over time. Non-homing guidance is restricted to stationary targets.

The position is loaded into the munition before launch and cannot be changed afterwards unless the munition has a live datalink capability. Non-homing guidance is also referred to as mid-course guidance in some longer range munitions which use a homing guidance method in the terminal phase of the engagement.

Homing guidance uses some form of energy from the target for tracking. The energy is typically radio-frequency (RF), light, or thermal. RF energy can be emitted from the target as in the case of a radar unit targeted by an anti-radiation surface-to-air missile system. It can also be reflected from the target when it has been illuminated by targeting radar. Light energy comes primarily in the form of lasers and visible light. Laser energy must come from a man-made source while visible light simply comes from the target’s environment. The final form of energy, thermal or infra-red (IR) energy, is the heat given off by the target. The heat comes from the target’s absorption and reflection of ambient heat as well as target heat generated by machinery, power generation, and electronics (Siouris, 2004).

There are three common forms of homing guidance. Active guidance occurs when the munition transmits the energy, typically RF, used for tracking. Semi-active guidance, on the other hand, only receives energy transmitted by another participant in the targeting chain using either radar or a laser. The source of the energy could be the launch platform or a third party. Finally, passive guidance relies on receiving energy already present in the environment, such as a target’s thermal signature. Both active and passive guidance provide a ‘fire-and-forget’ capability, meaning the launch platform is no longer needed for targeting once the munition is released. Contrarily, semi-active guidance requires targeting throughout the engagement (Zarchan, 2007).

Homing guidance is set apart from other types of guidance by the use of a seeker, a word which has also become synonymous with precision guided munitions in general. A seeker is a component, usually on the nose of the munition, which receives, and transmits in the case of active guidance, one of the aforementioned types of energy. A seeker is equipped with a mechanism to move itself relative to the body of the munition to resolve target position. It also has one or more of the following types of sensors:

- RF antenna with receiver (and transmitter);
- IR scanner or imager; and
- Visible light video camera or imager.

Precision guidance is not a panacea to minimising collateral damage. In addition to warhead effects and tactics, PGM technology itself can play a role in how close these weapons can be employed to protected objects or persons. The same technology that makes PGMs more accurate also has drawbacks that can cause them to lose accuracy or possibly become unguided. For example, due to their increased complexity, PGMs will be prone to more equipment failures than unguided munitions. Their guidance systems can also be degraded or disabled in a number of ways by both man-made and natural elements (NATO AGARD, 1997). Just a few of these possible elements include:

- Weather
- Low light
- Navigation satellite signal jamming[38]
- Target signature[39] reduction
- Smoke

Weapons designers have a selection of tools to counteract these effects as well as the inherent limitations of any given guidance type. One approach is to use multiple types of guidance during the course of a munition's flight. As noted, some munitions rely on inertial guidance with some form of homing guidance in the terminal phase of the engagement. The inherent inaccuracies associated with inertial guidance over time can then be overcome by employing a precise homing method during the terminal (end) phase of flight. Still another, more recent approach, is the use of multiple types of homing guidance by employing a tri-mode seeker capable of exploiting RF, laser and IR energy (US Army, 2012). Here, the simultaneous use of multiple forms of energy offsets several elements which would otherwise lower accuracy or render the munition useless.

[38] Other cyber and electronic means may also affect the guidance system of a munition. Other systems may also be affected, not just navigation satellites; this is a non-exhaustive list.

[39] How the target appears in various types of energy.

1.1.7 Fuzing

A fuze is a mechanical or electronic initiating device designed to initiate the function of munitions (King, 2011). The weapon is chosen to deliver the effect to target, primarily through a combination of munition and fuzing, with the effect being the primary consideration. The choice of fuzing options can greatly affect the impact of explosive weapons by mitigating or enhancing certain munition effects. There are three common categories of fuze that are defined by their firing function: impact, time, and proximity.

Most fuzes must be chosen at the time they are mounted to the munition by the operator or munitions specialist[40]. 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[41] (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 function the munition approximately 8 m above ground level, in order to optimise fragment spread (Ness & Williams, 2011). The fuze incorporates an impact backup capability, should the main fuzing method fail to function. This design also incorporates 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 departs from standard flight parameters.

When considering how a fuze influences collateral effects, take the example of a multi-story building targeted by a 1,000 lb. air-delivered PGM. 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, depending on the nature of the target and the surrounding infrastructure. Thus the choice of fuze is critical in understanding how militaries make choices in tailoring a weapon's effects during the targeting process.

Impact Fuzes

The most common fuze typically used with high explosive munitions is the impact fuze, also known as a point (or base) detonating fuze or an "all ways contact" fuze[42]. When used with different types of ordnance, these fuzes are often referred to by different terms. Impact and impact inertia[43] 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 ADW and LSA: the direct impact or rapid deceleration (caused by impact) along a munition's trajectory. While the effect is to detonate upon impact, impact fuzes often incorporate a delay of milliseconds or more upon

[40] This varies by munition type, and could range from prior to aircraft take-off, in the case of some air-delivered munitions, to immediately before firing, in the case of some land service ammunition.

[41] Variable fuzing is common in modern air-delivered bombs and missiles. Electronic fuzes allow a pilot, for example, to change fuzing from the cockpit to tailor weapon effects to the needs of the force to be supported.

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

[43] Some impact fuzes feature mechanisms which rely on impact inertia ('shock') to function the munition. This can prevent the munition from functioning until it hits a 'hard' target, allowing it to pass through foliage or other light cover.

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 (subsurface[44]). 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) fuze[45] (King, 2011). Some weapons require a base detonating fuze to be used on contact so that the warhead will function properly. For example, a HEAT warhead often has an initiator in the nose with the fuze located behind the charge; fuzes such as this are known as point initiating, base detonating (PIBD) types. 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. Contact fuzes were previously used with incendiary bombs that tumble in flight. Regardless of the distinct features of each design, impact fuzes as a group account for the largest portion of ADW and LSA fuzing systems used in modern combat.

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, respectively[46]. 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 also 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[47]. Time fuzes may also be used to achieve an airburst effect, detonating a munition above a target after a calculated, pre-set period of time from launch.

Proximity Fuzes

Proximity, or 'variable time' (VT), fuzes function a munition at a specific distance from the target. A proximity fuze generally uses radio waves[48] 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 munition 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.). Proximity fuzing has also become the preferred fuze for use in air-delivered cluster munitions. While a time fuze fulfilled this role in the past, the precision of having a regular dispersal height afforded by a large proximity fuze is essential to the usage of more advanced submunition models. Additionally, proximity fuzes have been incorporated in to a subset of submunitions known as sensor-fuzed weapons (DOT&E, 2001).

[44] These 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.
[45] 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.
[46] Additionally there are chemical and material fatigue delay mechanisms, but these have fallen out of favor with modern militaries due to reliability issues.
[47] 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).
[48] Optical, acoustic, magnetic influence, infrared, and other types have also been developed.

1.2 The Targeting Process

The targeting process is a systematic series of actions taken by a combatant prior to, during, and after the use of force. This process is undertaken, with varying degrees of doctrine, discipline and understanding, by military forces and non-state armed groups alike. It is summarised in US military use as follows:

"Targeting is the process of selecting and prioritizing targets and matching the appropriate response to them, considering operational requirements and capabilities." (JCS, 2007).

The targeting process enables the selection of the most appropriate and efficient use of force required for the task at hand. When properly employed, the targeting process can greatly reduce the risk of collateral damage when undertaking military action. This is especially true when choosing means and methods of warfare in populated areas.

For some groups, especially state armed forces, the targeting process is formalised and dependent upon military doctrine and the chain of command. This is beyond the scope of this report, and this section instead seeks to provide the fundamental elements of the targeting process. These elements, in order of action, are:

- Target identification and development
- Determining desired effects on target
- Weaponeering
- Collateral damage estimate
- Battlefield damage assessment

1.2.1 Target Identification and Development

The first step in the targeting process is to ensure the positive identification (PID) and development of a target. "Development" refers to the necessary analysis and assessment of a target, such that it satisfies the requisite criteria for an action to be taken. Considerations for what constitutes a viable target may vary depending on which group is making the assessment, but must comply with international humanitarian law, as well as any established rules of engagement. It is also dependent on the characteristics of the target, including the consideration of physical, functional, and environmental factors. The correct identification and development of a target is integral to compliance with international humanitarian law (law of armed conflict) requirements. Improper identification or understanding of a target can lead to mistakenly attacking an unlawful target, extensive civilian harm and a loss of military advantage.

Targets can typically be classified as either 'area targets' or 'point targets'. An area target is one which is spread over an area which comprises multiple aim points. Examples may include formations of enemy personnel or vehicles, or a string of enemy-held buildings or fortifications. A point target, on the other hand, is one which has a specific location with a single aim point, such as an enemy combatant or vehicle, or a particular structure or piece of equipment (DA, 2007). Some weapon systems are limited in the types of targets they can engage, whilst others are capable of engaging both area and point targets.

Certain militaries maintain lists of targets which may not be targeted in the course of normal operations, or which require specific authorisation to target. The United States, for example, maintains a no-strike list (NSL) and restricted target list (RTL). An NSL prevents person, place, or thing from becoming a target (for example, avoiding the targeting of a world heritage site) whilst an RTL exists to prevent unintended effects (for example, significant damage to critical civilian infrastructure) (JCS, 2014). US Army doctrine requires commanders balance the military benefit of engaging a target with "the possibility that the targets are occupied by or in close proximity to civilians, that destroying such targets will unduly harm civilians, or that their destruction will create long-term effects such as contaminating the environment" (DA, 2012).

1.2.2 Desired Effects on Target

At the most fundamental level, munitions are selected based upon the general and specific effects military planners wish to impose on a given target. Desired effects might include the exertion of psychological influence, warning the target, incapacitation or wounding the target, or outright destruction, and will depend on the nature of the target, be it personnel, structures, vehicles, or otherwise. The choice of effect will also be based upon the political, strategic, or tactical motivations for the engagement, to the extent that these are compatible with international humanitarian law (the law of armed conflict). Effects are often articulated using words such as destroy, delay, deny, neutralise, suppress, or influence (JCS, 2014).

Psychological effects are beyond the scope of this report and will not be considered further. Physical effects are brought about by the manifestation of the damage mechanisms discussed in Section 1.1.1. Combinations of those damage mechanisms, applied at different stand-off distances from the target, will exhibit different effects on the target – for example, the blast overpressure and radiant heat caused by a high explosive warhead will be greatest within a few metres of the explosion and reduce to nothing over several tens or hundreds of metres. Primary fragmentation from the detonation of a high explosive warhead will spread over a predictable area, however secondary and tertiary fragmentation also need to be considered. Similarly, the penetration capability of an armour-piercing or anti-structure munition must also be considered.

1.2.3 Weaponeering

Once the target has been selected and identified, and the desired effect/s on the target have been determined, the next step is to choose the appropriate quantity and type/s of weapon and attack parameters to achieve the desired effects, taking into account concerns regarding incidental harm (or "collateral damage"). Here the combatant will decide if an explosive weapon is most appropriate for the target and, if so, how such a weapon will be employed in a manner which mitigates foreseeable incidental harm. Weaponeering is defined as, "The process of determining the quantity of a specific type of lethal or nonlethal means required to create a desired effect on a given target" (JCS, 2007). The mitigation of incidental harm is a key element of weaponeering.

The effects of the weapon chosen may depend on a number of variables, including but not limited to: target composition and construction, population density, soil type and density, time of attack, angle of attack, weather, number of munitions employed, warhead, and fuze setting. Variables controllable by the attacker, such as fuze setting, may be altered to reduce potential incidental effects predicted by a collateral damage estimate (see section 1.2.5) (JCS, 2009a).

Weapon selection is the most fundamental element of weaponeering. It is the choice of the proper weapon in order to attain the desired effects against a target with minimal potential for civilian harm. The effects may range from nonlethal or less-lethal through to the damage or destruction of the target. Weapon selection is affected by the availability of particular munitions, fuzes, platforms, or other enabling systems. If the optimal weapon is not available but another is, then that weapon may be substituted even if it is not the most favourable method of achieving the desired effect. It may have properties that decrease the possibility of destroying the target, for example, but damaging the target may be preferable to allowing the target to continue to function, so long as the substitute weapon can be used in compliance with international humanitarian law. Weapon selection also refers to the number of munitions selected for a particular attack on a target. Harm to civilians and civilian objects may be affected by the use of either more munitions, or fewer.

Method of engagement is integrally tied to weapon selection, as the desired method of engagement may restrict the choice of weapons available, or the selected weapon may restrict available methods of engagement. For further discussion of the various considerations involved regarding methods of engagement, see section 1.2.4.

Accuracy of a given weapon system is also a key consideration in weaponeering, and can be dependent on multiple factors, as discussed in section 1.1.5.

Target composition and construction will often have a significant impact on the type of munition employed. Different materials require different weapons; for example, efficiently destroying an armoured fighting vehicle often calls for specialised anti-armour munitions (see section 1.1.2 and 1.1.3 for a discussion of munitions design and common types). The composition and construction of the target and its surroundings also influences weapon choice regarding wide area effects and the potential for civilian harm. For example, an adobe structure will require significantly less explosive force to destroy than a reinforced concrete building. Quality of construction is also a key factor, with buildings in different regions and of different types often varying significantly in this regard. The composition of the target is also critical in assessing the likelihood of secondary blast and fragmentation effects[49]. The location of the target relative to its surroundings is also important when modelling how blast and fragmentation damage are likely to propagate. For example, the effects of reflected blast waves may amplify the impact of a munition if a weapon explodes in a densely built-up urban area, causing damage further from the point of impact than may be reasonably expected in a remote area.

Population density describes the number of people living in a given space. Population density will strongly relate to the potential for civilian harm, and may influence weapon choice. If there are more people living in a given area, there is generally a greater chance for civilian harm. For example, targeting a military objective located in a large city would require extreme care, due to the significant population density. Conversely, targeting a military objective in a remote desert location might involve little to no potential for civilian harm. Population density statistics are often used in collateral damage estimates (see sections 1.2.5 and 1.2.6).

Soil type and density are factors for both weapon choice and collateral damage analysis. Crater size is influenced by the soil as is potential damage to adjoining structures from propagation of the blast wave. If a fuze with a delay element is to be selected, the relative importance of soil type and density may be greater (see subsection 1.1.7 for a discussion of fuzes and fuzing).

Time of attack has the potential to greatly reduce civilian harm under certain circumstances. The time a target is in a position where an attack is possible may not be fixed. For example, targeting a military objective located next to a market in the daytime may increase the risk of civilian harm, whereas targeting it at night - when the market is closed - may reduce such risk.The time of attack will prove crucial, as not only must the target be in a position to be attacked, the time of day selected for the attack may mean more or fewer civilians are in the area, potentially complicating targeting and affecting the collateral damage estimate.

Angle of attack describes the angle and direction of the attack. The CDE will be directly affected by considerations of attack vectors, as damage and debris from an attack will typically be projected in the direction of the attack. For example, an air-delivered munition striking a ground target from west to east will typically result in increased damage to the east side of the target as the debris spreads in that direction. By adjusting the attack angle, the spread of damage may be shaped and mitigated. Additionally, in urban centres where tall structures abound, the angle of attack may need to be adjusted to ensure the ballistic trajectory of the munition is almost vertical, ensuring it does not strike adjacent buildings or bounce off structures.

Weather is a factor in weapon selection, where it may limit the visibility of operators for certain weapon systems, or prevent the use of weapons which do not function well under certain conditions such as snow. Climatic conditions may also have adverse effects on certain warhead seekers, such as laser-guided bombs, although there is a movement towards multi-mode seekers to mitigate weather as a factor.[50]

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[49] These may include the presence of explosive or flammable materials, the projection of materials such as glass as secondary fragmentation, and so on.

[50] Multi-mode seekers are precision-strike weapons that combine multiple seekers such as GPS and laser. For more information see (Whitney et al, 2006).

Warhead type for a given munition can significantly alter the impact of a strike (as discussed in sections 1.1.2 and 1.1.3). Different warhead types, or different designs or payload weights within one type, can have different effects on a target, and can drastically alter the effects of munitions. For example, an air-to-surface missile with a HEAT warhead has a directed explosion that is intended to ensure penetration of armoured targets, and has relatively minimal area effects. The same weapon with a thermobaric warhead may have widespread effects in relation to the target, as described in section 1.1.4.

Fuze type and setting (as discussed in 1.1.7 above) determines how and when the munition functions (detonates) in relation to the target. It has a significant effect on blast and fragmentation damage and how widespread it is. For example, the same air-delivered bomb may be fitted with either a time delay fuze or a proximity fuze. This may result in a munition which detonates once partially embedded subsurface, containing the blast and fragmentation effects, or a munition which explodes with an airburst effect, allowing the spread of blast and fragmentation damage over a wider area.

Weaponeering speaks to the context of the use of explosive weapons as it deals with the many variables involved in an attack and how those variables may influence wide area effects and collateral damage. A US Army study of the effects of weapon damage reinforces the idea that context is a central aspect of the use of explosive weapons. It found that "[c]onfined-space (closed-space) explosions generally have more primary blast injury and penetrating injuries than explosions in open areas (open-space). The pressure wave associated with high-order explosive detonation reflects off doors, ceilings, and walls in confined spaces, lasts longer, and comprises what is termed a "quasi-static" exposure to overpressure effects" (Brevard et al., 2012). Therefore even a weapon that does not have "wide-area effects" per se may have augmented lethal effects depending on where and how it is employed.

1.2.4 Methods of Engagement

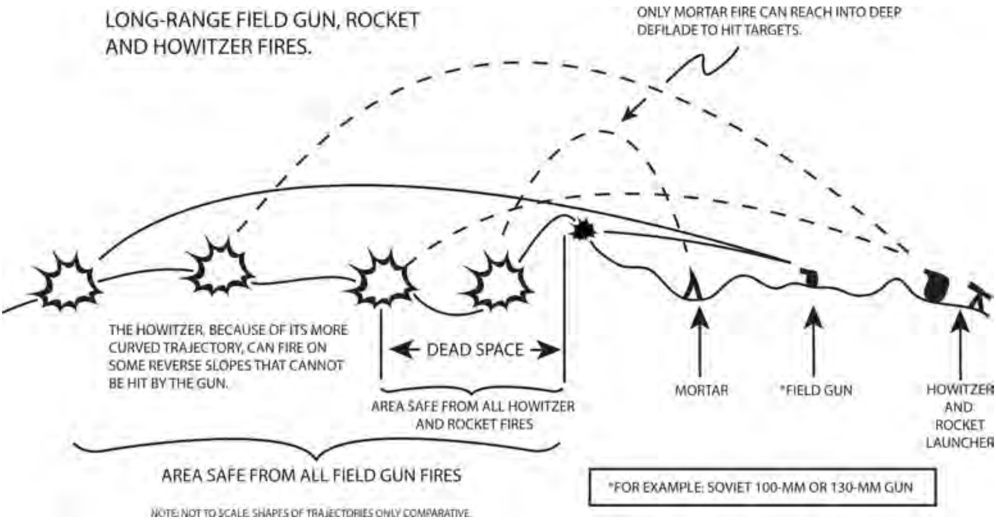
The basic method of engagement selected determines how the munitions are physically employed, and is often referred to as the 'lay' of a weapon (DA, 2007). Different methods will be selected based on a number of variables including access and physical proximity to the target, geography, weather, available systems, and collateral damage considerations. There are three common ways in which targets are engaged with explosive weapons: direct fires, indirect fires, and air-delivered fires, and these are overwhelmingly the most common methods of engagement[51].

Direct fires are employed when the target is visible and the weapon is aimed directly at the target. In these cases, the weapon used are most often systems such as tanks, field guns, shoulder fired weapons, and similar. Typically, weapons employed in this manner demonstrate better accuracy than weapons employed in indirect fire roles, but the accuracy of a given system remains dependent upon the competence of the gunner or person firing the weapon, among other factors. The strength of a direct fire weapon is its responsiveness to changing combat conditions (DA, 2007). Direct fire weapons often have limited range and/or may not be capable of delivering as substantial a payload as indirect fire systems, as a result of volume and weight constraints on such weapons. Explosive munitions fired from tanks, some gun systems and shoulder fired rockets commonly include HE, HE-FRAG, HEAT, HESH, and other types.

Indirect fires are most commonly employed when the target cannot be observed visually, is located a significant distance away, and/or is protected by geographic or structural features in deep defilade. Weapons systems which typically operate with this method of engagement include artillery guns/howitzers, mortars, rocket systems, and guided missiles. Explosive munitions commonly employed by indirect fire systems include HE, HE-FRAG, various cargo (cluster) types, and other types. Naval fires are employed and coordinated in much the same way as land-based indirect fires.

[51] Other methods of engagement, such as subsurface launches of missiles and emplaced munitions will not be covered herein. The latter includes items such as demolition charges and improvised explosive devices (IED). Vehicle-borne IEDs (VBIED) and other 'directed placed munitions' are also not covered herein.

Figure K – Examples of indirect fire types and restrictions



Source: (USAFAS, 2004)

Air-delivered fires share characteristics with both direct and indirect fires, and these can vary significantly depending on munition type and platform. While the engagement methods are very similar to direct fires, the methods of fire control are much more similar to those associated with indirect fires. Air-delivered fires require the greatest coordination between the fire control elements, delivery platforms, and other parties (JCS, 2014). When air-delivered fires are requested by a commander on the ground, the fire control system is similar in many respects to calling for an artillery strike. However, if an aircraft's pilot is on a combat patrol he or she may engage targets in a similar manner to a direct fire engagement. Aerial and surface fires need to be deconflicted, to ensure friendly units are not endangered (DA, 2001).

1.2.5 Collateral Damage Estimation

A collateral damage estimate (CDE) is part of the targeting process for some military forces. It aims to predict the incidental (or collateral) civilian casualties and damage to civilian objects, such as buildings and infrastructure[52], likely to be inflicted by an attack. By understanding how a military determines the collateral effects of a strike we can consider how they attempt to mitigate these effects, especially when explosive weapons that may have wide area effects are used. This will help inform when such certain types of explosive weapons are or are not appropriate for use in populated areas. Note that such an assessment will also take into account the military importance of striking a particular target. The 'acceptable' level of collateral damage may change with the importance of the target.

Some militaries conduct a CDE during the proportionality analysis of a target when they ensure the use of force will achieve a direct and concrete military advantage (US Army, n.d.a). The CDE uses a methodology to predict and mitigate collateral damage from attacks with lethal munitions. In some contemporary conflicts certain militaries may require a CDE for every target[53].

[52] Carrying out such an assessment is required by international humanitarian law.
[53] Interview with former US targeting personnel, name withheld.

During operations where troops on the ground come under fire ('troops in contact' situations) and targeting to support them is therefore time-sensitive, it is not uncommon for the ground commander to undertake a rapid, or field CDE[54]. A field CDE is done for immediate targeting such as a target of opportunity or for a troops-in-contact situation. This is a less rigid model due to time constraints. With it the ground commander tries to determine if any non-combatants are in danger from an intended strike. Visual observations and requests from forces in the field about the location of non-combatants are conducted. For weapons such as air-delivered bombs the pilot may at times override the ground commander if the pilot observes something that may lead to unacceptable collateral damage[55].

1.2.6 CDE Methodology

The following covers the Collateral Damage Methodology (CDM) of the United States, the process by which a CDE is conducted. A collateral damage analysis estimates unintended or incidental damage to persons or objects which are not the intended target, and which are not otherwise lawful targets (JCS, 2007). The analysis does not cover weapons malfunction, delivery errors, altered tactics, or transient non-combatants and property. This is an advanced CDE methodology not employed by all militaries, although variations are used by NATO, by most NATO partner countries, and other countries such as Australia and Israel. Other organisations, such as the African Union Mission in Somalia (AMISOM), are also known to employ formal CDE processes to manage risk from explosive weapon use (AMISOM, 2011)[56]. It is instructive as an example of 'good practice'. The CDM is based on the Joint Munitions Effectiveness Manual that "includes damage/kill probabilities for specific weapons and analytical techniques and procedures for assessing munitions effectiveness" (US Army, n.d.).

The methodology must answer five questions:

1. Can the target be positively identified?
2. Are there protected objects, non-combatants, or environmental concerns within the effects range of the weapon?
3. Can collateral concerns be mitigated by employing a different weapon or method of engagement?
4. If not, how many non-combatants are estimated to be killed or injured in the attack?
5. Are the collateral effects excessive in relation to the expected military gain?

The CDM for static targets such as buildings are technical and use software such as FAST-CD to automate the process (Reynolds, 2005; Denny, 2003). They look at the physical composition of the building to determine potential threats to non-combatants from secondary fragmentation, such as glass, cement, and steel. For example, the secondary fragmentation hazard from modern buildings is higher than from adobe residences. Certain types of glass, in particular, can pose a hazard (Smith & Renfroe, 2010). The CDM looks at the soil composition to understand how the blast will propagate through the soil and what the size of the crater will be. It creates a 3D damage model of the target taking all damage mechanisms into consideration and shows expected radii for destruction and damage, and where collateral damage is likely to occur. The damage model takes into consideration the angle of attack and maps the direction of blast and fragmentation, resulting in dynamic model, rather than a static sphere or hemisphere as generated by simple calculations. When population density figures (adjusted for the specific time of day) are also taken into account, planners may determine the predicted number of civilian deaths and injuries. The CDM is an effects-based model. It does not look at weapons in a vacuum, instead looking at each target and determining how the chosen weapon will interact with the target and how those effects may cause collateral damage to persons and objects.

One flaw in the CDM is the lack of civilian casualty analysis feeding back into the system. While ad hoc work has been done, such as ISAF amending its tactical directives in Afghanistan to alter tactics, and employing procedures to deal with high collateral damage issues, most militaries do not conduct dedicated analyses on the after effects of a strike. The United States, for example, will occasionally deploy teams to conduct a weapons-effects analysis; however, there is no requirement under existing

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[54] Ibid.

[55] Briefing from NATO Collateral Damage Analysis Center to UNAMA, Kabul, 2011.

[56] The procedure to assess collateral damage applied by armed forces of other states is not addressed herein.

military policy to determine if the collateral damage estimate was correct[57]. Additionally, the long-term effects of explosive weapons in populated areas, such as how the use of these weapons influence electrical and water supply systems, are not well understood.

1.2.7 Battle Damage Assessment

A battle damage assessment (BDA), often forming part of a broader 'combat assessment'[58], is intended to estimate the damage caused by certain weapon systems against a given target, after the system or systems have been used. BDA is defined by the US military as "the timely and accurate estimate of damage resulting from the application of military force, either lethal or nonlethal, against a predetermined objective. Battle damage assessment can be applied to the employment of all types of weapon systems (air, ground, naval, and Special Forces weapon systems) throughout the range of military operations. Battle damage assessment is primarily an intelligence responsibility with required inputs and coordination from the operators. Battle damage assessment is composed of physical damage assessment, functional damage assessment, and target system assessment" (JCS, 2010). Whilst not all militaries conduct BDA, they are commonplace in most modern military forces[59].

The five steps within the US BDA cycle are: planning, collection, processing and exploitation, production, and dissemination (USJFC, 2004). Reported damage is assessed and validated to include the numbers and types of equipment and personnel, and their level of degradation. This reporting is essentially a physical damage assessment. It can be very difficult to ascertain exactly what damage equipment and personnel have sustained. Often the level of damage incurred must be inferred based upon the observed munitions effects on the environment and knowledge of equipment vulnerabilities, troop densities, and degrees of protection. Multiple reports are collated and deconflicted to prevent redundant reporting.

Whilst some states employ 'lessons learned' procedures to generate data relevant to the protection of non-combatants from the BDA process, this is not true for many countries. There are other measures, often employed in an ad hoc fashion which states use to determine the impact of targeted strikes on non-combatants; few states have formalised such procedures.

57 Interview with former US targeting specialist, name withheld.

58 Combat assessment: "The determination of the overall effectiveness of force employment during military operations. Combat assessment is composed of three major components: (a) battle damage assessment; (b) munitions effectiveness assessment; and (c) reattack recommendation" (JCS, 2010).

59 At the most basic level, this is a simple yes/no assessment as to whether re-engagement of a target is necessary.

PART 2

Types of Explosive Weapons and their Effects

2.1 Introduction to Types of Explosive Weapons

This section will review broad weapon categories and their archetypal characteristics and expected effects. It is focused on the broad categories of weapon systems which deliver explosive payloads. There are myriad weapons in common use and it is neither possible nor advisable to cover each one individually. The weapon descriptions will review generic types, estimated accuracy, and estimated lethal effects, where available. Specific model examples and references to manufacturers have been avoided where possible, with the focus instead being a description of the technical features relevant to the effects of the weapon. These may include, as relevant and available, estimated blast and fragmentation ranges of examples of munitions types, estimated accuracy or CEP, and other measureable effects.

Note that any figures given here are necessarily estimates and that in real-world use, accuracy and area effects are also affected by the context. Some weapons detailed in this section are designed as area-effect weapons, rather than being intended to engage point targets (see 1.2.1 for a discussion of area and point targets). Additionally, some weapons suffer from inaccuracy or are otherwise incapable of accurate fire due to physical factors such as guidance type, build quality, or requirements for certain operating conditions.

Some weapons may foreseeably cause harm beyond the target when used in areas containing concentrations of civilians even after precautions to limit their effects are taken. As explained in Part 1, weapon effects are the result of a combination of the weapon's design (its technical characteristics and damage mechanism) and the context in which the weapon is used. Which explosive munitions are employed is largely controllable by the parties to a conflict. The technical characteristics described below include many references to concepts introduced and discussed in Part 1, such as accuracy; blast, fragmentation, and thermal damage; and available fuzing options.

Wide area effects are strongly influenced by the accuracy of a weapon and by the warhead's 'lethal area'. Lethal area is a term of military art referring to the area in which a weapon's effects will lead to the probability of target incapacitation (a casualty, in terms of human targets). For the purposes of this report, the interpretation of the lethal area in practical terms is the size of the area that is completely affected by the warhead. Thus, the lethal area quantifies the potential damage a munition can inflict. In quantitative terms, the number of casualties inflicted by a single warhead on a battlefield containing n number targets per unit area is simply n multiplied by the lethal area. Of course, the lethal area depends on the nature of the target; whether the target consists of personnel, vehicles, buildings, etc. In this report, the lethal area will refer to an unprotected adult person. Alternatively, the concept of lethal radius will be used; this is simply the radius of a circle with an area equal to the lethal area.

The fragmentation effects of a particular munition can also be quantified by describing the hazardous fragment distance (HFD), as described in section 1.1.1. This is the distance at which the probability of aperson being struck by a potentially lethal fragment is approximately 1%. This distance is significantly greater than the lethal radius of a munition[60].

Precision affects the lethal area in the sense that a salvo of rounds should have a dispersion that is balanced against the size of the lethal area. The most effective salvo would be one in which the typical distance between each impact is twice the lethal radius. Zero dispersion is quite ineffective as there is no need to incapacitate a target more than once (see section 1.1.5 for a fuller discussion of accuracy). The potential for wide area effects and increased likelihood of collateral damage is significant when warheads with large lethal areas are delivered by inaccurate munitions and/or delivery platforms.

[60] Typically 10 to 20 times greater.

2.2 Air-delivered Munitions

Air-delivered munitions (often referred to as 'air delivered weapons', or ADW) covered in this report may be guided or unguided in nature, and encompass bombs, guided missiles, and rocket[61]. They may be fired or dropped by fixed and/or rotary wing aircraft, including unmanned aerial vehicles. Air-delivered bombs are explosive weapons dropped from aircraft with predictable flight paths. They may be guided or unguided.

Air-delivered bombs are often classified by weight, although this classification does not directly indicate the weight of the complete munition or its payload; rather, these are approximate weight classes. Air-delivered bombs are often listed in pounds (although some militaries use kilos), with the most common bombs being 250, 500, 1000, and 2000 pound-class weapons[62]. The case, fuzing, and guidance system constitute a proportion of the mass. For example, in one particular 2000 lb. penetrating bomb, the explosive fill only accounts for some 28% of the total munition weight; the penetrating casing and other components account for the remainder[63].

There are four basic types of air-delivered explosive bombs (JTS, n.d.):

Penetrating[64]: These weapons are designed to pierce armour with a directional charge and/or kinetic energy. They typically have a 25 to 30% charge-to-weight ratio.

Fragmentation: These weapons are designed to destroy personnel and soft-skinned targets such as vehicles, aircraft, and equipment primarily by fragmentation. They typically feature a thicker hardened metal case, often treated to optimise fragmentation. They typically have a 10 to 20% charge-to-weight ratio.

General Purpose: These are the most common air-delivered bombs and are designed to destroy targets through a combination of blast and fragmentation. There is generally some penetrating effect. General purpose bombs typically charge-to-weight ratio of approximately 50%.

High Capacity[65]**:** These are weapons designed to destroy targets primarily through blast. They tend to be among the largest aerial bombs. They typically have thin cases to maximise blast energy. They typically have a 65 to 80% charge-to-weight ratio.

Table 2.1 – Approximate damage to structures by bomb weight[66,67]

Bomb weight class (pounds)	Damage to brick building (radius in m, from point of impact)			Fragmentation
	Destroyed	Damaged beyond repair	Damaged/inhabitable	range in open
50	6	15	60	890
250	20	40	180	1100
500	30	60	290	1250
1000	40	90	430	1400
2000	90	180	880	1550

Source: King, 2011

A side effect of a bomb blast may be the creation of a crater. Cratering is dependent upon bomb size, warhead type, fuze type and configuration, soil type and composition, building size, and other variables; Table 2.2 provides representative guide to expected cratering effects of unguided and precision-guided aerial bombs (for additional information on cratering, see 1.1.1).

Table 2.2 – Approximations of crater size by bomb weight[69]

Bomb weight class (pounds)	Surface attack (width x depth in m)		Subsurface (width x depth in m)	
	Heavy soil	Light soil	Heavy soil	Light soil
50	2.75 x .9	1.65 x .55	6 x 1.8	3.6 x 1.1
100	3.25 x 1.2	2 x .75	7.5 x 2.4	4.5 x 1.45
250	4.5 x 1.5	2.7 x .9	10 x 3	6 x 1.8
500	5.5 x 1.8	3.3 x 1.1	13.7 x 3.7	8 x 2.2
1,000	8 x 2.4	4.8 x 1.5	17 x 4.9	10 x 3
2,000	9 x 2.7	5.5 x 1.6	19.5 x 5.5	11.7 x 3.3

61 Note that air-delivered missiles are covered in the section on guided missiles.

62 The term "class" refers to the fact not all bombs adhere strictly to the weights listed and may be slightly over or under the listed class size.

63 Hence, the total weight or weight class of an air-delivered bomb may not always be strictly indicative of its wide-area effects.

64 Sometimes referred to as 'armour piercing'.

65 Sometimes referred to as 'demolition bombs'.

66 Note: Specifications and figures given in Part 2 have been taken from specific models that have been genericized for this report, and should be taken as representative. Actual figures, depending on the specific munition, may differ.

67 Chart refers to a general purpose air-delivered bomb with an impact fuze. Please note that actual field results will vary depending on the context in which the munition is used.

2.2.1 Unguided Aerial Bombs

Unguided air-delivered bombs, often called 'iron bombs', 'dumb bombs', or 'gravity bombs' due to their unpowered nature and absence of a guidance system, are the most widely used air-delivered munitions in history. These munitions consist primarily of a case containing an explosive fill and fuze, and rely upon the skill of the pilot and conditions at the time of their use for their accuracy. Even though they are unguided, their flight path is still predictable, though the predicted area in which they will fall is almost always larger than that of precision-guided equivalents. Table 2.1 provides a general guide to typical blast and fragmentation effects of aerial bombs.

There are three modes of delivery typically available for unguided aerial bombs: unretarded, retarded, and in-flight selection. Retarded or in-flight selection delivery modes may not always be available depending on the munition type and delivery platform (aircraft). Unretarded munitions are released from the aircraft and the weapon free-falls to its target. When a munition is delivered in a retarded mode, a device is actuated to increase drag and slow the delivery of the munition. Such devices are most commonly employed during low-level bombing operations where the aircraft could be damaged by the blast. Different mechanisms such as spring loaded fins, parachutes, and air inflatable retarders ('ballutes') are employed to retard a munition (USNA, 2000).

2.2.2 Precision-guided Aerial Bombs

Precision-guided aerial bombs are a type of PGM which uses a guidance system to steer the bomb to the target. The guidance system can use, for example, GPS-guidance, laser-guidance, electro-optical (camera) guidance, or a combination of these options (see section 1.1.6 for a discussion of PGMs). Some precision-guided bombs may also incorporate an inertial navigation system (INS) either as a backup in case the primary guidance loses lock on the target and/or to improve the accuracy of the primary guidance system.

[68] Note: Specifications and figures given in Part 2 have been taken from specific models that have been genericized for this report, and should be taken as representative. Actual figures, depending on the specific munition, may differ.
[69] Chart refers to a general purpose air-delivered bomb with an impact fuze. Please note that actual field results will vary depending on the context in which the munition is used.

Several ‘bolt on’ type conversion kits are now available, which convert unguided aerial bombs into PGMs. Kits have now been produced to fit a number of different unguided bombs, ranging from 500 to 2,000 lbs. The key components of these systems consist of a tail section with control surfaces, a strake kit (which fits around the body of the munition), and a combined inertial guidance system and GPS control unit. CEP for early models was 10 m but is now less than 5 m (Jenzen-Jones, 2015a). The damage to structures and cratering potential of these PGMs built around existing munitions are reflected in Tables 2.1 and 2.2, above.

As discussed in section 1.1.5, accuracy depends on various factors, including conditions at the time of attack and the technical capabilities of the weapon. Precision-guided bombs are generally accurate to less than 20 m, though some militaries have munitions typically capable of accuracy to 10 m or better. PGMs can be difficult to describe using the normal CEP metric, as a normal distribution of impacts is necessary to calculate CEP. Precision-guided bombs almost always have smaller miss distances than unguided weapons. If a precision-guided bomb falls outside the CEP for the weapon it will fall closer to the intended point of impact than an unguided bomb, making CEP a less useful concept for describing the likely distribution of munitions which miss their target. For example, the average miss distance of a particular air-delivered PGM with an 5 m CEP is approximately 3 meters (see Section 1.1.5 for a discussion for CEP) (Hewin, 2012; USAF, 2003). When examining larger weight class aerial bombs, in particular, the lethal area of the munitions is often wider than the CEP or maximum miss distance. Some militaries have invested in GPS-jamming or other guidance system jamming equipment, which can return the PGM to a ‘dumb bomb’ state during its descent. If this occurs, the bomb will follow a ballistic trajectory from the point at which it is jammed – i.e. out of the control of either the launch platform or the jamming party. The consequence of this is that the bomb is likely to impact an unpredictable distance away from the intended target.

2.2.3 Air-to-Surface Missiles

Air-to-surface missiles (ASMs) are guided missiles that are fired from airplanes, helicopters and UAVs. In current conflicts, the most common types are anti-tank guided missiles (ATGMs[70]) or derivatives of these, but anti-radiation[71] and anti-ship models are in the stockpiles of most modern militaries. This category does not include cruise and standoff weapons that are covered in section 2.4.
Air-launched ATGMs often feature a tandem HEAT warhead to defeat armour. The warhead operates as described in section 1.1.3, however a smaller precursor charge, located forward of the main charge, is intended to breach explosive reactive armour (ERA), common on many modern main battle tanks (MBTs) (PEO MS, 2012). HEAT warheads are significantly less effective against structures and soft targets. They typically have minimal fragmentation and collateral effects; “substantially” less than 15 m, according to one targeting professional[72].

Some ASMs can employ a fragmentation sleeve when enhanced anti-personnel effects are required. A representative fragmentation sleeve could be an approximately 1.9 kg, two-piece hinged metal ring that clips around the outside of the body of the missile along the warhead. The use of such a sleeve degrades blast effects, whilst enhancing fragmentation effects out to 20 m.

[70] Often referred to as ‘anti-tank guided weapons’ (ATGWs), a term which more properly refers to the complete weapon system.
[71] Missiles designed to home in on radiation sources, most often radar.
[72] Interview with USAF targeting professional, name withheld.

Table 2.3 – Generic Technical Specifications for Air-to-Surface Missiles

	Small/Medium	Large
Weight	34 kg - 49 kg	300 kg
Warhead	3 - 12.5 kg blast and fragmentation	136 kg
Range	4 – 8 km	25 km
Accuracy[73]	5 m CEP or less	1 m CEP
Lethal Area	Fragmentation: 500 m^2	Blast: 11 m[74] Fragmentation: 1800 m^2
Fragments	Varies greatly	Varies greatly

Source: (Hewson, 2012)

Guided bombs, having no propulsion, can only be guided within a relatively small footprint. Air-to-surface missiles can be used against a wider cross-section of target types, including relatively fast-moving land and maritime vehicles, and consequently tend to employ various types of guidance. There is an external guidance subset that is focused primarily on anti-armour applications, but the majority of ASMs currently employ some form of homing guidance, such as:

- Laser-based
- Electro-optical/IR-based
- Active radar-based (generally used to engage large targets, armoured fighting vehicles, and ships)
- Passive radar-based (most commonly employed in the suppression of air defense targets)

2.2.4 Air-to-Surface Rockets

A rocket is a munition that uses rocket propulsion; namely, the ejection of hot gases from a self-contained fuel and oxidizer[75]. For the purposes of this report air-to-surface rockets are free-flight, unguided direct-fire weapons fired from aerial platforms.

Recent developments have added guidance capabilities to some air-delivered rockets, but these are not in widespread use. Although unguided, rockets still have controlled flight through aerofoils (wings) and/or fins, spin stabilization (where the spin of the rocket stabilizes flight), direction of exhaust gases, and other methods. Air-launched rockets are typically unguided direct-fire area-effect munitions fired in salvos at targets. The use of salvo fire is to make up for the weapons' inaccuracy, being unguided direct-fire weapons, meaning they fire in a straight line or arc towards their target. Rockets are sometimes 'ripple-fired' (typically 10 or more) from a rocket pod, with an entire pod emptied in seconds for maximum area coverage.

In several conflicts these weapons have been pressed into service as makeshift surface-to-surface rocket artillery even though they are designed to be air-delivered from purpose-built and mounted rocket pods. The methods used to mount these weapons and the way they are employed in this role make them very inaccurate and mean they can pose a significant collateral concern, mitigated only by their limited blast and fragmentation effects (Jenzen-Jones & Lyamin, 2014).

Air-to-surface rockets are typically outfitted with high explosive, armour piercing, or high explosive fragmentation warheads. Two of the most commonly encountered calibres of air-to-surface rockets are 57 mm and 80 mm. Interviews with former pilots indicate many unguided air-to-surface rockets have poor accuracy and are considered area-effect weapons incapable of accurately engaging a point target[76].

[73] Accuracy and size are often related in legacy weapons. With advances in miniaturisation smaller weapons are increasingly accurate.
[74] (Kingery & Bulmash, 1984)
[75] An oxidizer is a chemical that provides the oxygen that a fuel needs in order to burn in during combustion
[76] Interviews with former pilots, names withheld.

Table 2.4 - General Technical Specifications: Air-to-Surface Rockets

	57 mm	80 mm
Warhead weight	4 kg	11 – 17 kg
Explosive content	1.1 kg	3.6 - 9.5 kg
Range	4 km	4 – 6 km
Accuracy	20+ m CEP (estimate)	20 m CEP (estimate)
Lethal Area	130 m^2	200 m^2
Fragments	75-360 depending on model	Hundreds to thousands, depending on model

Source: (Hewson, 2012)

2.2.5 Improvised Air-delivered Munitions

Improvised air-delivered munitions have been observed in several armed conflicts. In various cases, these improvised air-delivered munitions take the form of so-called 'barrel bombs', which can be as large as a 50-gallon oil drums, and filled with something like 300 kg of almost any type of explosive compound available. Evidence indicates these munitions are simply underslung from helicopters or rolled out of the doors of cargo aircraft (Brown Moses, 2013). This combination of unknown explosive fill, inconsistent manufacture and unreliable sighting and delivery system means that the damage radius for any of the main damage mechanisms is highly unpredictable. These munitions have proven very unreliable, and pose a significant risk of collateral damage whether or not they function as intended (ARES, 2015).

2.3 Land Service Ammunition

Land service ammunition (LSA) is comprised of any munition containing explosive or pyrotechnic compounds employed so as to cause damage to people, structures, or equipment during land warfare. LSA is divided into five main categories: artillery gun projectiles, mortar projectiles, rockets, grenades, and land mines (CAT-UXO, n.d.).The latter two will not be assessed in the context of this report. Systems firing artillery gun projectiles, mortar projectiles, and rockets, in the context of the wide area effects assessed in this report, are most often indirect-fire artillery weapons.

Artillery weapons are designed to provide fire support for armour and infantry by launching or firing munitions at greater distances than small arms. These types of weapons 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, artillery may be employed in a direct fire role, most typically naval artillery or field artillery in mountainous regions. Assessed under the heading of LSA are field artillery and naval artillery projectiles[77], mortar projectiles, rocket artillery, and improvised artillery.

[77] Naval artillery projectiles will be assessed under this heading due to their similar characteristics.

2.3.1 Field Artillery

Field artillery is classified in this report as indirect-fire gun artillery. It is used to provide fire support to armour and infantry and falls in the middle range for artillery weapons, between mortars and rocket artillery. It is often used in salvo fire with multiple weapons firing simultaneously. Common projectiles have a blast radius of approximately 10 m with a lethal fragmentation radius between 50-150 m and a fragmentation-wounding radius of approximately 100-300 m (Ness & Williams, 2011). Field artillery reviewed in this report is divided into medium (105 mm and 122 mm) and heavy (152 mm and 155 mm). NATO nations, as well as other western nations and countries purchasing from them typically employ the 105 mm and 155 mm calibres. The former Warsaw Pact and countries purchasing from them typically employ 122 mm and 152 mm calibres as standard (Ness & Williams, 2011).

The accuracy of all field artillery is range dependent and degrades the farther it is fired. For example, the accuracy for the standard 105 mm and 155 mm artillery projectiles are listed below. Even at short range the potential error is significant. Some new projectiles have an optional 'Course Correcting Fuze', a GPS-based guidance system that improves the accuracy to 50 m CEP at all ranges (Ness & Williams, 2011).

Table 2.5 – Accuracy of 105 mm and 155 mm Artillery

105 mm Artillery Accuracy	
Range	**CEP**
5 km	60 m
10 km	97 m
15 km	120m
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

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

Table 2.6 – Generic Technical Specifications for Field Artillery Projectiles

	105 mm	122 mm	152 mm	155 mm
Weight	18 kg	27 kg	40 kg	40 kg
Warhead	2 kg	3.6 kg	6.25 kg	11 kg
Maximum Range	12 km	12 km	17 km	23 km
Accuracy (see Table 2.5)	Range dependent	Range dependent	Range dependent	Range dependent
Lethal area	Not available	500 m^2	Not available	800 m^2
Fragments	Not available	1,000	3,000	>2,000

Source: Dullum, 2010; Ness & Williams, 2011

2.3.2 Naval Artillery

Naval artillery refers to gun artillery mounted on warships. Depending on the gun, it may be used in a variety of different firing modes to engage missiles and aircraft; attack other surface vessels; and as a fire-support weapon targeting land-based threats. 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, the system uses a complex fire-control system to provide fires accurate enough to destroy high-velocity anti-ship missiles. Ammunition is selected based on the target from an internal carriage holding numerous types of projectiles with various warhead options (DA, 1989).

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. 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). 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 (see Section 1.1.5) (DA, 1989).

Table 2.7 – Generic Technical Specifications for Naval Artillery

	76 mm	127 mm
Warhead weight	12.4 kg	30 kg
Warhead Explosive content	1.5 – 2kg	4 - 5kg
Range	16 km standard round 40 km GPS guided	24 km 100 km with extended range projectiles
Accuracy[78]	Varies	Varies
Lethal Area	300m^2	650m^2
Fragments	Not available	Not available

Source: King, 2011; authors

2.3.3 Mortars

Mortar projectiles are tube-launched indirect-fire, typically unguided artillery projectiles. Mortars are often relatively portable and use smoothbore tubes to launch projectiles at targets, though some systems use rifled barrels. The primary distinction between guns and mortars is that most mortars are restricted in elevation, only capable of firing at high-angle trajectories (above 45°). Other points of difference are the lack of a recoil mechanism, the fact that they are muzzle loaded, although there are exceptions to these (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” (DA, 2011). Mortar accuracy is limited and they are therefore usually fired in a salvo at a target with a forward observer used to correct the impact location (Calloway, 2011). The lethal area from fragmentation is variable, typically between 150 and 650 m^2 depending on the size of the projectiles (see Table 2.8).. The largest mortar presently in service is 240 mm in calibre and has potentially considerable wide area effects. A high explosive-to-weight ratio and relatively low accuracy combine in practice to the point that some militaries do not allow the use of 120 mm mortars in some areas due to collateral concerns (Calloway, 2011). The 240mm mortar is of particular concern due to its large warhead combined with the poor accuracy of an indirect-fire weapon.

[78] Can vary significantly with range, system, and platform.

Table 2.8 – 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 – 900g HE	2.5 kg HE	32 kg HE
Range	3,500 m	5,500m	To 7,500m	9,500 m
Accuracy	Not available	Not available	~136 m CEP	Not available
Lethal Area[79]	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

Source: Jones & Ness, 2013; Ness & Williams, 2011

Most mortars are restricted in elevation and are only capable of firing at trajectories above 45°, meaning that they cannot be used in the direct-fire support role (Ryan, 1982)[80]. Guided mortar systems allow for precision targeting and increased first-round hit probability, which reduces the potential for collateral damage. Current PGMs for mortars have a CEP of less than 10 m – meaning they are more than seven times as accurate as common unguided mortar projectiles. These are not yet common in military arsenals (Jenzen-Jones, 2015b).

2.3.4 Rocket Artillery[81]

Rocket artillery is generally accepted to include conventional ground-launched rocket systems with a range of less than 500 km. Rocket artillery are usually purpose-built systems that are towed or vehicle mounted, although the use of aerial rockets in indirect fire mode as rocket artillery has become more common by non-state armed groups[82]. Rocket artillery is an economical method to maximize area effect fires, typically delivered in salvos (barrage fire[83]), at ranges longer than traditional projectile artillery can accomplish. Projectile artillery systems typically fire a projectile from 12 – 22 km while artillery rockets can reach out to 70 km, depending on size and variant (Dullum, 2010). It allows for a large payload to be delivered at significant distances and over a wide area. Rocket artillery is highly effective against massed enemy formations, as counter-battery fire[84], and against rear area targets such as communications arrays and lightly armoured targets. However, rocket artillery is an indirect fire weapon with a potentially substantial lethal area and potentially considerable collateral effects over much wider areas than traditional gun artillery.

As the size of an artillery rocket increases, the payload size and range also increase. The most common artillery rockets are of 107 mm, 122 mm, 240 mm, and 300 mm in calibre, and typically deliver between 1,000 to 3,000 fragments. Artillery rockets generally fire salvos of rockets rapidly, relocate for safety, reload, and fire again. Note that salvos may also mean multiple launchers firing simultaneously (Dullum, 2010). See section 1.1.5 for a detailed discussion of the accuracy of rocket artillery. Table 2.9 shows some generic accuracy information for common rocket calibres. Table 2.10 shows some estimated lethal area figures for common rocket calibres.

79 Given for single munitions.
80 There are a handful of exceptions to this rule.
81 For a comprehensive analysis of rocket artillery see Dullum, 2010.
82 See section 2.2.4 for more information on air-delivered rockets used as artillery rockets.
83 Barrage fire is a way to describe massed fire from multiple weapons firing simultaneously.
84 Counter-battery fire is a method of engaging an adversary's indirect fire weapons, often using radar to determine the point of origin. It may allow a military to destroy these weapons rapidly and before they relocate.

Table 2.9 – Accuracy of Common Artillery Rockets

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

Source: Dullum, 2010

Table 2.10 – 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

Source: Dullum, 2010

2.3.5 Improvised Artillery

In some recent conflicts non-state armed groups have extensively employed improvised artillery. These have included both improvised rockets (often referred to as improvised rocket-assisted munitions, or IRAMs) and improvised mortars. Improvised rockets feature a notable variety of designs, most fitted around standard artillery rockets[85]. The models employed have ranged in size from 107 mm to 450 mm in diameter and are primarily documented on social media. Improvised mortars have been observed to overwhelmingly be fin stabilized. All models of improvised artillery rocket used have thus far been spin-stabilized, with designs using additional fins to impart spin and terminal trajectory. The action of spinning increases the accuracy of these otherwise aerodynamically inefficient weapons, though little effort has been observed in precision targeting; these remain inaccurate yet very potent weapons. These weapons are, by their nature, very inaccurate and deliver significant amounts of explosive into the target area, either individually or in salvo. If they also employ improvised fuzing, there is likely to be a high incidence of failure to detonate as designed, creating a persistent risk of unexploded ordnance and and increasing the duration of the explosive hazard in the targeted area.

2.4 Guided Missiles

Many militaries and some non-state actors, own and use guided missile systems as tactical and strategic weapons. This section will consider tactical surface to surface guided missiles and strategic guided missiles. Missiles are any self-propelled projectiles. Guided missiles are self-propelled weapons with four elements; an engine, flight system, guidance system, and warhead.

One of the key elements of guided missiles is the ability to course-correct during flight in order to strike the target. Course correction is due to guidance such as electro-optical (or television), laser, and satellite (GPS). Below are some of the most common forms of guidance in use:

[85] Some examples of very large IRAMs using homemade rocket motors have been observed but use has not been widespread.

Electro-optical guidance/Infrared: these missiles have a camera in their nose that allows the operator to remotely steer the missile into the target using a television screen broadcasting the feed from the missile's camera. At night it uses an infrared camera. The operator simply uses a joystick to point crosshairs to the desired point of impact. These are considered precision weapons capable of hitting point targets. This is a common guidance system for various anti-tank guided missiles (ATGMs). Such weapons are commonly fired from planes, helicopters, UAVs, vehicles, and from tripods.

Laser guidance: these missiles have a seeker head that follows a targeting laser that is aimed at the desired point of impact. These are among the most accurate guided weapons available though they are limited by smoke and cloud cover that may make it difficult for the seeker to pick up the laser or else diffracts the laser light, interfering with guidance. The targeting laser may be used by ground troops, by the firing aircraft, or by support aircraft.

Radar guidance: these missiles use the radar on the targeting aircraft to direct them.

Satellite guidance: these missiles provide an all-weather capability. The missile has one or multiple satellite receivers that use one of various global satellite systems to direct the weapon to the target using coordinates entered into the missile before launch. There has recently been growing concern over jamming of the satellite signal and missiles are now designed with anti-jamming capabilities.

Multi-mode seeker: these are precision-strike weapons that combine multiple seekers such as GPS and laser[88]. This provides an all-weather, precision-strike capability resistant to jamming. This is a fairly recent development and relatively few such weapons are in service.

2.4.1 Surface-to-surface Missiles

Surface-to-surface missiles are tactical missiles fired from dedicated launchers, typically vehicles. The missiles reviewed for this report all carry unitary high explosive warheads. Their accuracy is highly variable with guided versions accurate to less than 9 m while unguided versions may have their accuracy measured in kilometres. Due to warheads ranging up to 500-900 kg the lethal area from blast and fragmentation can potentially be considerable. Many common surface-to-surface missiles are legacy[86] weapons still in service with their militaries. Their accuracy is often considered poor and would generally not be considered adequate for use in populated areas.

Table 2.11 – Generic Technical Specifications for Surface-to-Surface Missiles

	Unguided	Guided
Warhead weight	6,000 kg	1300 kg
Warhead Explosive content	500 – 900 kg HE	250 kg HE
Range	300 - 700 km	300 km
Accuracy	450 m - 3,000 m CEP	9 m CEP
Lethal Area	Potentially considerable	Potentially considerable
Fragments	Not available	Not available

Source: Source: Lennox, 2005; Ness & Williams, 2011; authors

[86] Weapons no longer in first-line service with major military powers.

2.4.2 Cruise Missiles

Cruise missiles are guided missiles that deliver large warheads over great distances and fly at a constant speed, or cruise, over a large portion of their flight, much like a small airplane. They can be launched from air, land and sea-based platforms. And instead of range, cruise missiles are categorized by function such as land attack or anti-ship (NASIC, 2013).

Cruise missiles have three phases of flight: launch, mid-course and terminal. In the launch phase, the primary objective to get to the cruise speed, altitude and direction. When launching from land or sea platforms, this requires the use of a disposable rocket motor. Once in the mid-course phase, the missile can use a number of different guidance techniques to correct its trajectory to the target. An inertial guidance system is typically aided by one of more of the following systems: satellite-based navigation, terrain contour matching and/or scene matching (where images of the ground from cameras or radar are compared to stored images). In the terminal phase, the missile may continue to use its mid-course guidance techniques, but with increased accuracy, or use a homing guidance technique to improve CEP. At various times during the flight, the missile may alter altitude and direction to counter air defences as well as properly orient itself for impact.

Table 2.12 – Generic Technical Specifications for Cruise Missiles

Warhead weight	700 – 1600 kg
Warhead Explosive content	222 kg – 450 kg HE-FRAG
Range	280 – 2,500 km
Accuracy	3 m CEP
Lethal Area	3000 – 5000 m^2
Fragments	Variable

Source: Hewson, 2011; authors

2.4.3 Ballistic Missiles

For the purposes of this report, we will consider a ballistic missile to be any guided missile that is used as a weapon delivery vehicle and which is guided for only a portion of its flight, following a ballistic trajectory under the influence of gravity and air resistance (except for any exo-atmospheric portion) for most of it[87]. Technically, almost any missile or rocket that follows such a trajectory could be called a ballistic missile, however, it is generally understood that the term refers to large, guided missiles which deliver an offensive payload to a target. There are unguided rockets that can carry similar payloads and of course they have a completely ballistic trajectory once the rocket motor ceases to function, however, they would not generally be classed as ballistic missiles.

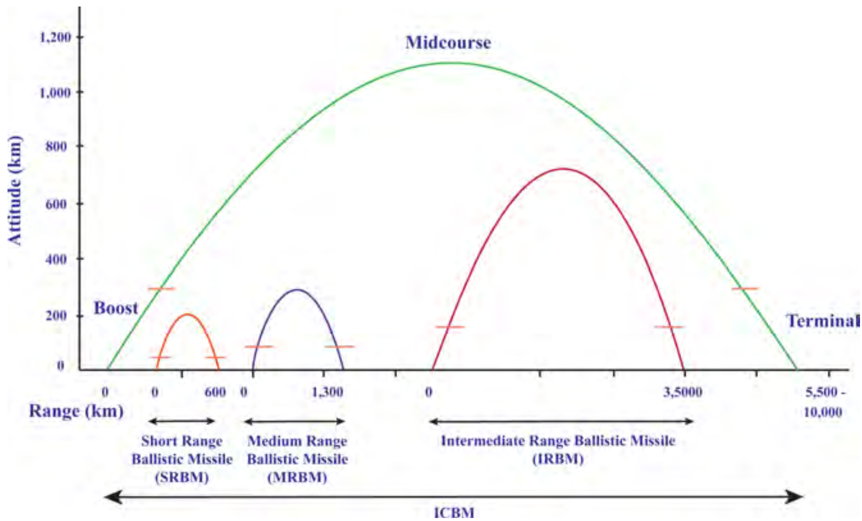
Ballistic missiles are categorized according to their maximum range, or the maximum distance measured along the surface of the round earth from the point of launch to the point of impact. There are four general categories: short-range, medium-range, intermediate-range and intercontinental (NASIC, 2013). Exact maximum range values for each category can vary from organization to organization, but broadly speaking, they are:

- Short-range - less than 1000 kilometres.
- Medium-range - 1000 to 3000 kilometres
- Intermediate range - 3000 to 5500 kilometres
- Intercontinental – more than 5500 kilometres.
-

A special category, however, exists for one particular type of missile. Any missile, regardless of range, launched from a submarine is categorized as a submarine-launched ballistic missile. Figure L shows some sample ranges and altitudes for various types of ballistic missile.

[87] Adapted from (FAS, n.d.)

Figure L – Sample ranges and altitudes for various types of ballistic missile



Source: Centre for Strategic & International Studies (CSIS)

A ballistic missile flight consists of three parts: the boost phase, the free-flight phase which constitutes most of the flight time, and the re-entry phase (Hale, 1994). The boost phase, or powered flight phase, can last from a few seconds to several minutes and can consist of multiple rocket stages. Many ballistic missiles are only able to correct their trajectories during this phase because they utilize rocket motor-based steering instead of aerodynamic controls. The free-flight phase is usually conducted in space or the highest extremes of Earth's atmosphere after the missile has achieved the desired speed and direction. The longer the range, the higher the maximum altitude. Thus, intercontinental ballistic missiles are known to achieve altitudes of 1200 kilometres or more during their 30 minute flights (Kucherov & Marisov, 1964). Very short-range missiles, on the other hand, barely make it to the edge of the atmosphere or about 100 kilometres. The re-entry phase begins at an altitude where atmospheric density begins to have an effect on the missile, and lasts until missile impact. Ballistic missiles may re-enter as a whole unit, which includes the spent rocket stage(s), or only as a re-entry vehicle (RV), which only includes the warhead[88]. Modern ballistic missiles may also employ decoys as well as RV maneuvering which is intended to counter missile defense systems (Fisher, 2003). While most of the guidance is performed during the boost phase, guidance can be employed during re-entry for some ballistic missiles. Some missiles even use precision guidance techniques such as scene matching to greatly improve CEP. Typical high explosive warheads range in size from 50-500kg. In order to deliver such payloads to the ranges quoted, it is typical for a ballistic missile to incorporate a very large liquid- or solid-fuel rocket motor, consisting of tens or hundreds of kilograms of fuel and oxidiser, which can pose an explosive or toxic materials hazard in its own right (Fargo, 2012).

88 The spent rocket stages may also present a danger to persons on the ground.

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