

CHAPTER 8

DETONATION EFFECTS ON METAL

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8 DETONATION EFFECTS ON METAL

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8.1 AWARENESS SUMMARY

8.1.1 Fragmentation

If an explosive is detonated inside a metal tube the walls of the tube are subject to intense pressure from the detonation shockwave and high pressure gas products. The strain produced on the tube causes it to plastically deform and expand. Depending on the properties of the metal such as ductility this expansion can increase the tube diameter up to 50 % before the strength is overcome and structural failure occurs. Once fractures occur the high pressure gases will begin to leak through the spaces and relieve the internal pressure. At some point the acceleration of the tube wall will cease and the metal will have a terminal velocity, the casing will separate in to fragments with this initial velocity.

This is often called primary fragmentation producing relatively small high

velocity fragments (



Figure 8-1) that can be lethal many hundreds of metres from the explosion. Initial velocities can be in excess of 2000 m s^{-1} . If a tube is filled with a deflagrating explosive such as black powder and this is initiated the tube will fragment but under these circumstances the fragments will be large and of relatively low velocity (Figure 8-2). Even so at close range these can be lethal. Metal driven by a deflagration will not be considered further.



Figure 8-1 Fragments from the detonation of an artillery shell



Figure 8-2 Metal tube following a deflagration type explosion

8.1.2 Controlling Fragment Mass and Size

Controlling the size of fragments from a warhead is critical to its lethality. To be effective they need to impact the target and so to increase the likelihood it is preferable to have a large number. However, the smaller the fragment the quicker it will decelerate and begin to lose target lethality. Increasing the mass of a fragment that has the same volume can be achieved using denser metals such as tungsten over steel and this will maintain velocity for greater distances although it also will reduce the initial fragment velocity.

8.1.2.1 Natural fragmentation

Natural fragmentation is where the explosive is confined and in contact with a metal casing where there are no features to assist in controlling where case fracture will occur. A typical example is an artillery shell as shown in Figure 8-3. At any point along its length the cross section is cylindrical and the ratio of explosive mass to metal mass together with the material properties of the metal will determine how it fragments including size and velocity. To produce small fragments use a case material of low ductility (low true fracture stress, low fracture strain) and thin wall, filled with an explosive with high detonation pressure. To produce large fragments use a case material of high ductility and thick wall filled with a lower detonation pressure explosive.

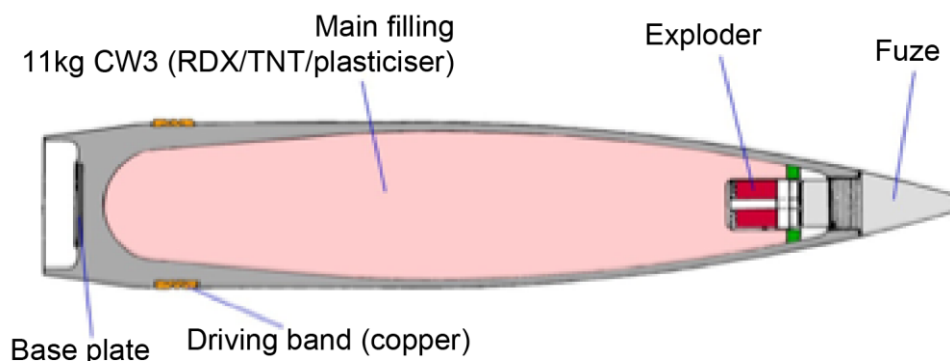


Figure 8-3 Longitudinal section of an L15 155 mm artillery shell

Natural fragmentation is used in ordnance because the munition casing is strong with no induced weaknesses, which is important to withstand the stresses of gun launch g-forces. It is also relatively straightforward to manufacture, which is important for a munition that is made in large numbers.

8.1.2.2 Controlled fragmentation

A means of improving the fragmentation efficiency is to introduce planes of weakness in the case which cause it to break up into fragments of an optimum mass. This is sometimes referred to as "fire-formed" fragmentation.

Consider a hexagonal bar of steel with a circular hole along its axis packed with high explosive. When the explosive is detonated one might expect the gases to burst through the confinement at its thinnest point along the centre of the faces. In reality, an intense shock wave passes through the metal and is reflected as a rarefaction wave from the surface as shown in Figure 8-4. The waves reflected from adjacent surfaces reinforce one another along the planes defined by the axis of the bar and the vertices, and it is at these planes that tensile failure occurs. By using various means to focus the shock waves within the case it is possible to exert useful control over the size and shape of fragment produced.

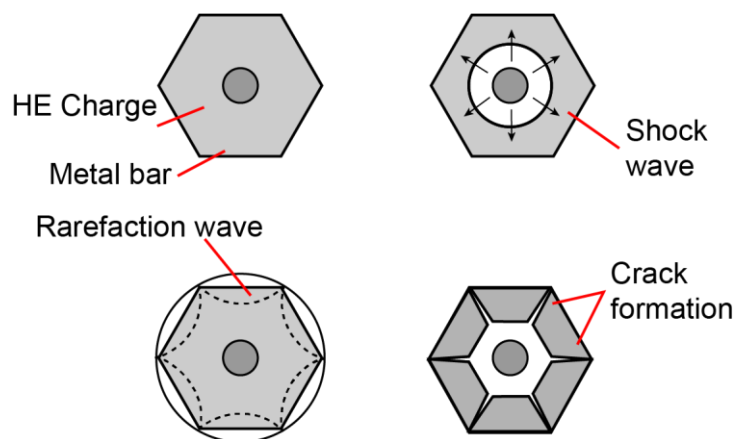


Figure 8-4 Fragmentation of a hexagonal bar (after Held)

There are 3 main ways that controlled fragmentation is achieved:

1. **Scored casing.** The case may be grooved internally or externally (Figure 8-5). It tends to fracture *between* external grooves and *at* internal grooves. Better control is achieved with internal grooves, although in practice they are more difficult and expensive to produce.
2. **Notched wire.** Cases may be constructed by brazing together internally notched metal annuli, or a coil of notched wire (Figure 8-5). The fragment size is defined by the cross-sectional dimensions of the metal and by the distance between notches, which is typically 1-1.5 times the case thickness.
3. **Grooves in the explosive.** It may be more convenient to groove the explosive by inserting a shaped liner between it and the wall of the case, or by using metal inserts (Figure 8-6). These focus the shock wave and

produce high local stresses in the case. The profiled liner is often referred to as a "Buxton liner".

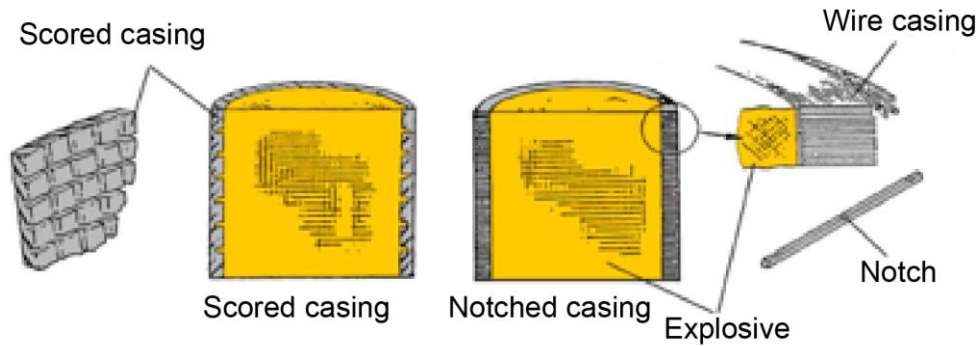


Figure 8-5 "Fire-Formed" fragmentation warheads (scored casing and notched wire)

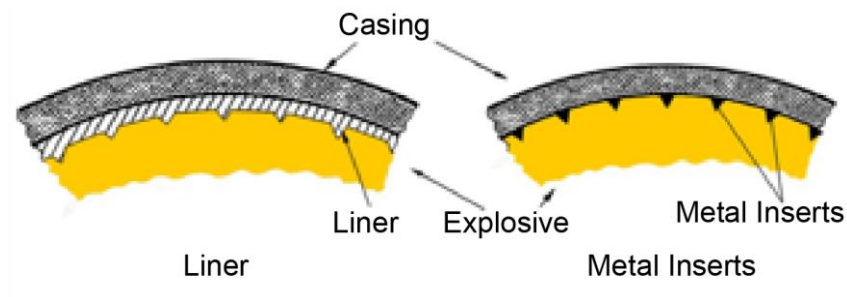


Figure 8-6 "Fire-Formed" fragmentation warhead (grooved liner)

Another technique relies on zone embrittlement of the case by treating it with lasers, electron beams or chemicals. As the shock wave passes cracks form preferentially in the treated regions.

8.1.2.3 Pre-formed fragmentation

Pre-formed fragments of optimum size, shape and mechanical properties for the intended target may be built into the warhead structure. They may be cubes, spheres, flechettes, etc. (Figure 8-7), and they may be pyrophoric as well as penetrating.

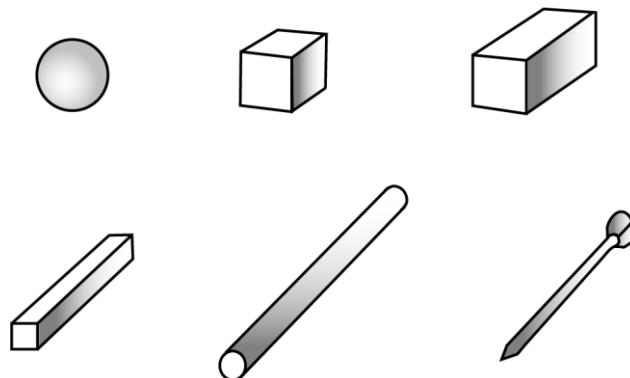


Figure 8-7 Pre-formed fragmentation

The disadvantages are increased manufacturing difficulty, the need for a parasitic structure to support the fragments and reduced fragment velocity, perhaps up to 10 %, resulting from early gas leakage between fragments during acceleration. To counteract this, the fragments usually are assembled around an internal liner sufficiently ductile to accelerate the fragments to near full velocity before rupturing and leaking gas.

8.1.3 Conical shaped charge

A shaped charge is a device that uses the energy of a detonating explosive to collapse a metal cone to its axis at which point a proportion, about 20 %, forms a forward directed jet with the remainder forming a slug of metal moving in the same direction. Figure 8-8 shows a cross section of a shaped charge warhead and Figure 8-9 a flash x-ray showing jet and slug formation.

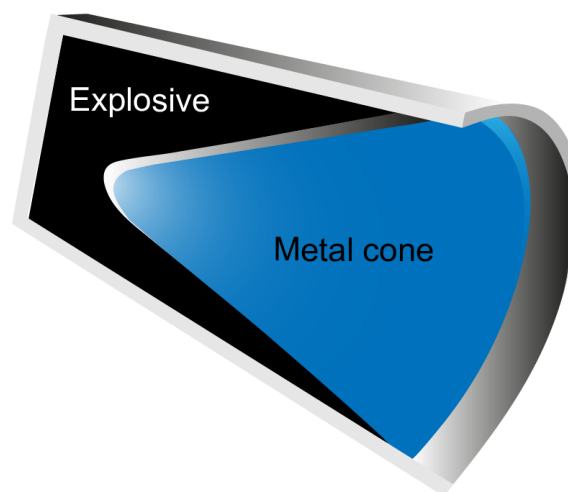


Figure 8-8 Cross section of a shaped charge warhead

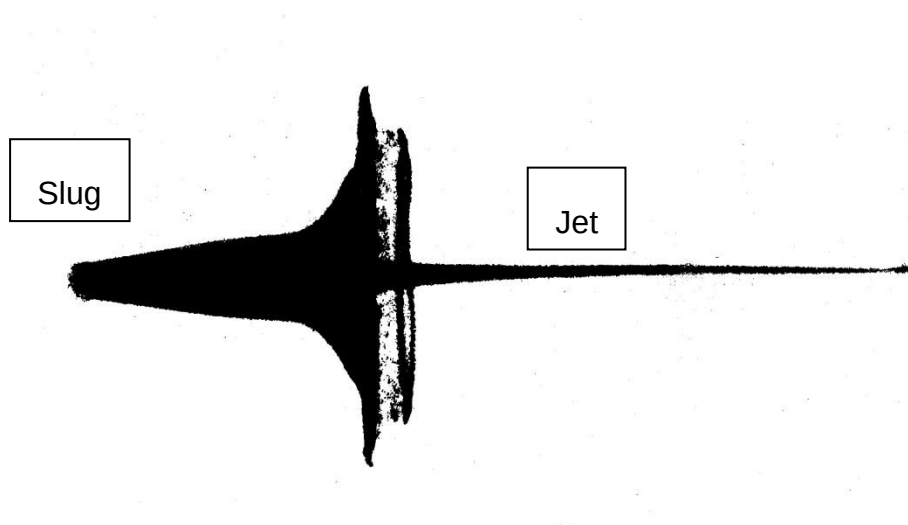


Figure 8-9 Flash x-ray immediately following detonation

The jet has a velocity gradient along its length with the tip travelling at around 8 km s^{-1} and the tail 2 km s^{-1} . This results in the jet stretching in flight to a point where the jet fragments. The jet when it impacts armour overcomes the strength of the target material, which flows allowing the jet to penetrate the target. The metal of the jet coats the cavity wall and so is consumed as the jet penetrates.

For optimum penetration the jet should impact the target before it fragments but has significant length as penetration is directly proportional to jet length. This requires a 'stand-off' distance between the shaped charge and target when it detonates. Typical values will be between 2 and 5 times the diameter of the cone. Also, the metal must have reasonably high density and be able to flow under the intense pressure of the detonation shock wave. Although other metals such as steel have been used the universal choice is copper. A shaped charge warhead with the optimum stand-off, very high detonation pressure explosive and high quality copper cone will penetrate eight times the cone diameter in to armour. Figure 8-10 shows a typical cavity in a steel target created by shaped charge jet penetration.



Figure 8-10 Cross section of a steel target penetrated by a shaped charge jet

8.1.4 Linear shaped charge

A conical shaped charge collapses the metal liner such that it produces a point impact on a target. If a metal liner with the geometry shown in

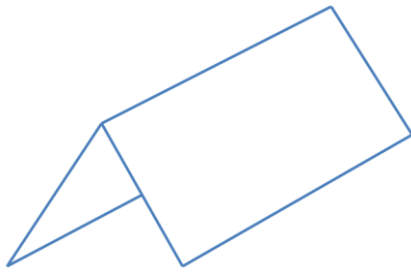


Figure 8-11 is backed by explosive then a planar jet is produced that can cut a line in a target. Early types had a rigid metal liner making the linear shaped charge difficult to employ other than on flat surfaces. However, demolition accessories now include a flexible version using a flexible liner constructed from copper powder and a binder as shown in Figure 8-12. Linear shaped charges usually have a smaller stand-off than conical shaped charges of around 1 × throat width and penetration of no more than 1.5 throat widths in to steel.

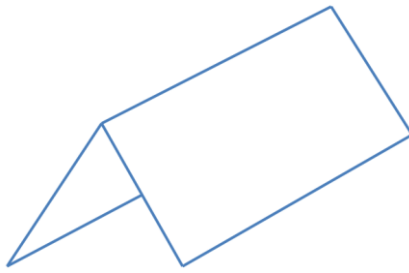


Figure 8-11 Linear shaped charge liner

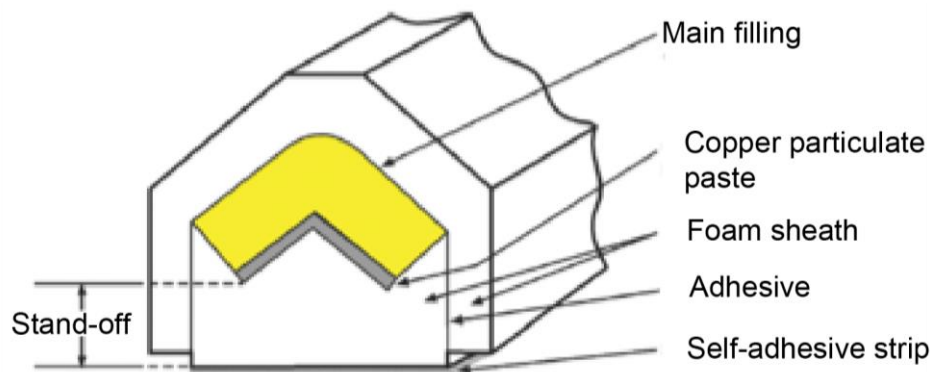


Figure 8-12 Cross section of a flexible linear cutting charge

8.2 FRAGMENTING WARHEADS

8.2.1 Fragment Initial Velocity

8.2.1.1 The Gurney equations

During World War II Gurney considered that the energy available from the explosive is partitioned between the kinetic energy of the detonation products and the kinetic energy of the fragments of the case and derived equations giving the fragment velocity for several simple geometries⁽¹⁾. He assumed that detonation occurs instantaneously, that all the products are gas, and that the geometry is such that only one dimensional flow occurs.

The process may be applied to simple geometries. If the geometry has a centre or plane of symmetry including sphere, cylinder and symmetrical sandwich, then the derivation is particularly simple because only one boundary velocity is unknown and only the conservation of energy equation is required. The gas velocity is zero at the element of symmetry.

If the plates are of unequal mass as for an unsymmetrical sandwich two unknown velocities result, and two equations are therefore required. The second equation is the statement of conservation of momentum. The form of the Gurney equation for various geometries is given in **Table 8-1**.

It must be remembered that the derivation of the Gurney equations assume that the flow is one dimensional. The measured fragment velocity for, say, a very short cylinder is much lower than calculated, because much of the flow is not radial, and Gurney's assumptions are no longer valid. For a cylinder, the length should be at least twice the diameter, and the fragment velocity at the ends is less than that at the centre. For light confinement, when $M/C < \sim 1/3$, Gurney underestimates the fragment velocity due to a greater contribution of shock processes which improve the efficiency of the acceleration.

It must be understood that the Gurney equation takes no account of the mechanical properties of the case material, and makes no judgment on the size, and therefore of size distribution, of the fragments resulting from the detonative dispersal of the case. Gurney predicts the same velocity for a case that flies apart in two pieces, or as a powder. These differing fragments obviously have widely differing lethality. We note also that the Gurney equation gives a single velocity, whereas in reality the velocity varies along the length of the case being reduced at the ends where there is less confinement.

Table 8-1 Gurney Equations for Various Geometries

Cylinder	$\sqrt{2E} \left(\frac{M}{C} + \frac{1}{2} \right)^{-1/2}$	(8-1))
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Sphere	$\sqrt{2E} \left(\frac{M}{C} + \frac{3}{5} \right)^{-1/2}$	(8-2))
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Symmetric sandwich (M is the total mass of the metal)	$\sqrt{2E} \left(\frac{M}{C} + \frac{1}{3} \right)^{-1/2}$	(8-3))
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Open sandwich	$\sqrt{2E} \left[\frac{1}{3} \left(\frac{4M}{C} + 1 \right) \left(\frac{M}{C} + 1 \right) \right]^{-1/2}$	(8-4))
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Unsymmetrical sandwich (plate masses, M_A , M_B and velocities V_A , V_B).	$V_A = \sqrt{2E} \left[\frac{1+Z^3}{3(1+Z)} + \frac{M_B}{C} Z^2 + \frac{M_A}{C} \right]^{-1/2}$	(8-5))
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and

$$V_B = ZV_A$$

$$\text{where } Z = \frac{1 + 2M_A/C}{1 + 2M_B/C} \quad \textbf{(8-6))}$$

8.2.1.2 Properties of explosives

It has been shown by Cooper⁽²⁾ from an analysis of the results for many military explosives that a useful engineering estimate for the Gurney constant is $\sqrt{2E} = D / 2.97$ where D is the velocity of detonation ($\text{mm } \mu\text{s}^{-1}$) of the explosive. It should be noted, however, that values of $D/\sqrt{2E}$ ranged from 2.81 to

3.09 mm μs^{-1} . Table 8-2 gives examples of Gurney constant values^(2,3) for a range of explosives of given density and Velocity of Detonation.

Table 8-2 Examples of Gurney Constants

Explosive	Density (kg m^{-3})	Detonation Velocity ($\text{mm } \mu\text{s}^{-1}$)	Gurney Constant ($\text{mm } \mu\text{s}^{-1}$)
Composition B	1720	7.92	2.71
PETN	1760	8.26	2.93
Composition C-4	1520	8.37	2.18
LX-14	1835	8.83	2.80
Pentolite 50/50 % w/w cast	1640	7.52	2.30
HMX	1890	9.11	2.97
RDX	1590	8.25	2.45
TNT	1630	6.73	2.09
Octol 75/25 % w/w	1810	8.48	2.80
Cyclotol 75/25 % w/w	1.75	8.25	2.79

8.2.2 Fragment Initial Direction

8.2.2.1 Taylor equation

The velocity at which the case is driven outwards depends upon the explosive used and on the ratio of the mass of explosive to the mass of case. The direction of motion tends to be normal to the surface, but modified by the direction of the incident detonation wave as indicated schematically in Figure 8-13.

Final Fragment Profile

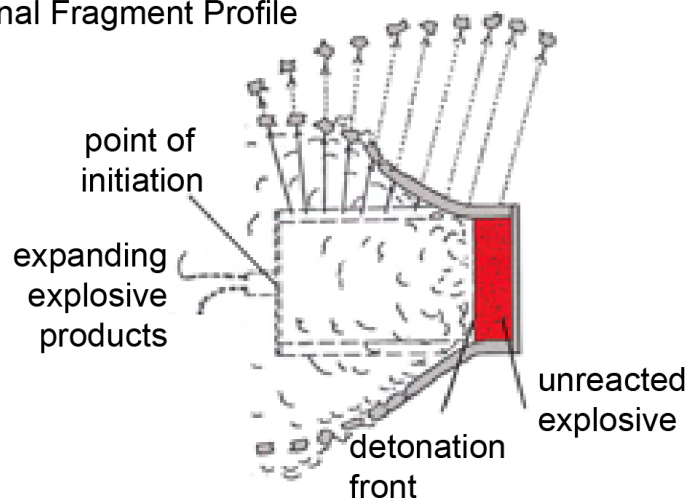
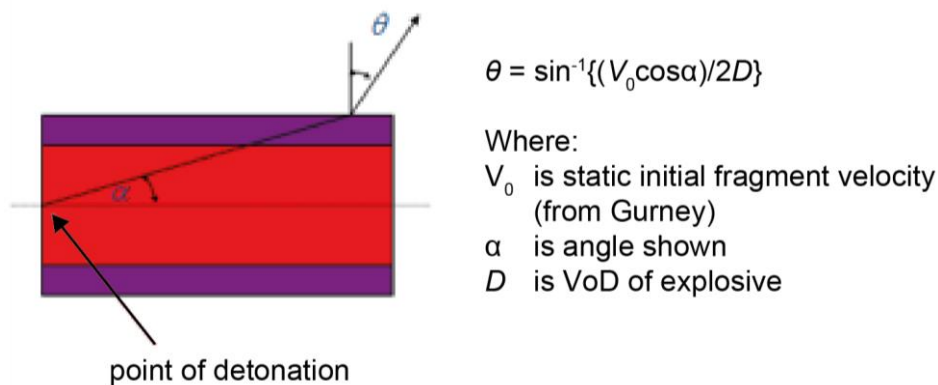


Figure 8-13 Fragment direction from single point, end initiation of a cylindrical charge

Taylor⁽⁴⁾ calculated the ejection angle from the assumption that as the detonation wave passed the case is subject to a pure rotation and the fragment is then accelerated instantaneously. The angle of incidence varies with the relative positions of the point of initiation and the part of the case under consideration and in the simple case of a cylinder the relative positions may be defined as in Figure 8-14. Since $V_0/2D$ does not vary greatly between explosives, at constant geometry changing the explosive has little effect on the ejection angle.

**Figure 8-14 Taylor angles for a centrally end initiated cylindrical charge****8.2.2.2 Beam angle**

The fragments of a warhead tend to travel outwards in a nearly perpendicular direction to the surface of its casing. The total angle which includes all the fragments from the warhead is called the *beam width or beam angle*, and is a useful characteristic for the analysis of the likely effectiveness of the warhead. For a simple cylinder, it is simply the sum of the two extreme Taylor angles.

In the example warhead given above (Figure 8-14), we can calculate the beam angle and observe how it varies as the point of initiation is moved along the axis of the warhead from one end to the centre.

For initiation at one end, and a fragment from the other,

$$\alpha = \tan^{-1} (0.1/0.4) = 14.04^\circ$$

If the VoD of the explosive is 7890 m s^{-1} ,

$$\theta = \sin^{-1} (2407 \times \cos 14.04^\circ) / (2 \times 7890) = 8.5^\circ$$

Since the fragments at the initiation end travel normal to the case ($\theta = 0^\circ$), the beam angle is 8.5° .

For initiation at the centre, and a fragment at either end,

$$\alpha = \tan^{-1} (0.1/0.2) = 26.56^\circ$$

$$\theta = \sin^{-1} (2407 \times \cos 26.56^\circ) / (2 \times 7890) = 7.8^\circ$$

Since fragments at opposite ends depart with the same inclination from the normal, but both away from the initiation point, the beam angle is 15.6° .

Figure 8-15 shows the calculated values along the length of the example warhead assuming initiation at one end. Figure 8-16 shows the effect of initiating at one end, centrally and at both ends of a cylindrical charge.

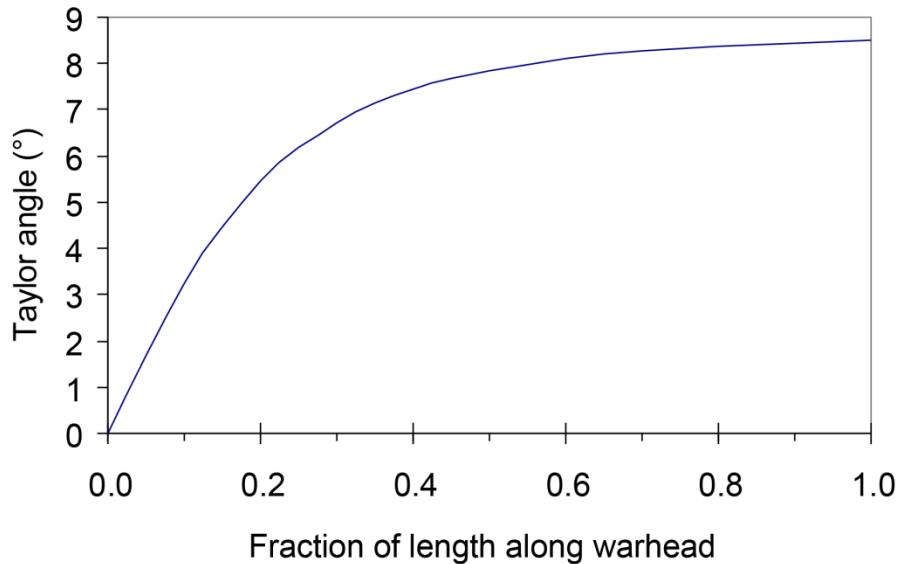


Figure 8-15 Variation of Taylor angle along a warhead

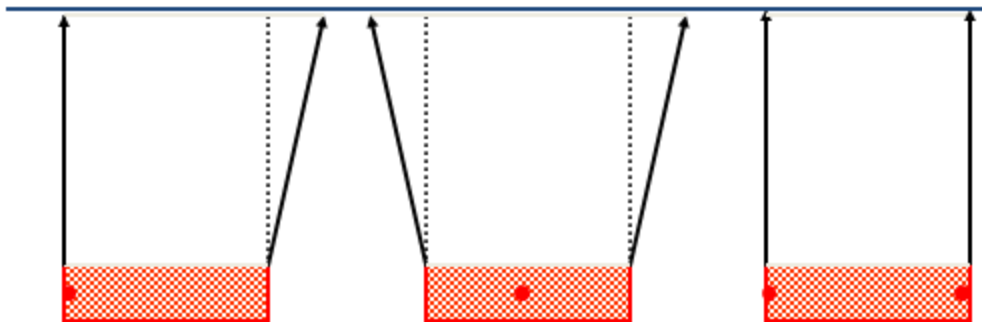


Figure 8-16 Warhead beam width for single end, central and two end initiation

Beam width also is a function of the warhead shape and the position of the point of detonation in the explosive charge. Some case profiles and fragment patterns resulting from central initiation are shown in Figure 8-17.

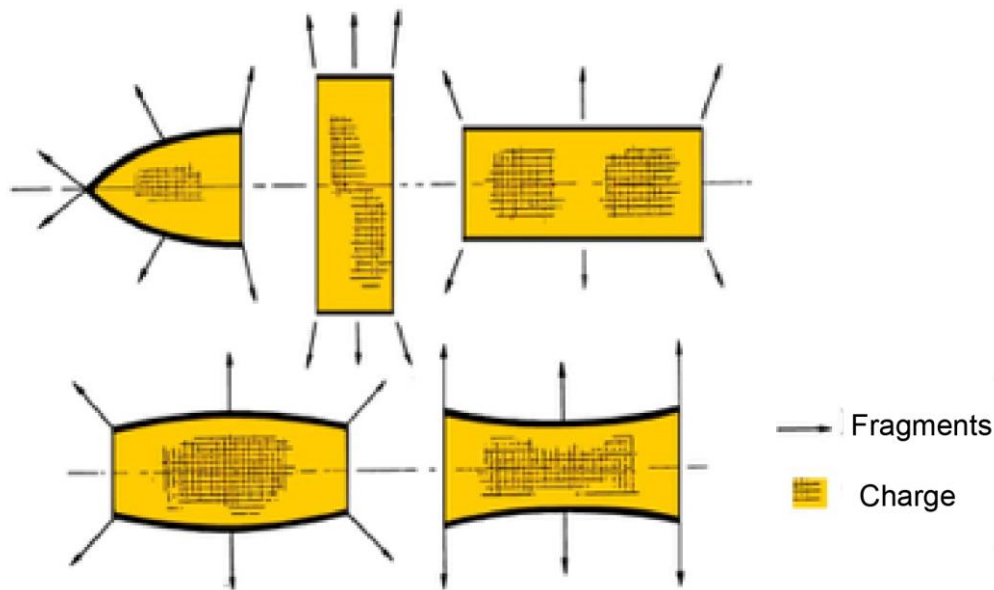


Figure 8-17 Effect of warhead shape on fragmentation patterns

8.2.3 Fragment Dynamic Velocity – the Effect of Warhead Velocity

Many warheads when they detonate such as missiles or air burst artillery shells have forward velocity, which will contribute to the overall velocity of the fragments. The static velocity of a fragment as can be calculated applying the Gurney equation, V_0 , combines vectorially with the forward motion of the warhead, V_m at the moment of detonation to produce the dynamic velocity V_d . This is shown in Figure 8-18 for the front and rear fragments of a cylindrical warhead initiated at the rear.

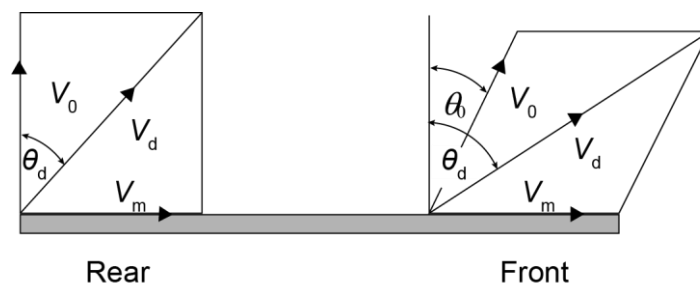


Figure 8-18 Vectorial combination of initial fragment velocities and warhead velocity

The Gurney velocity of each fragment is V_0 and for rear initiation the Taylor angles are 0° (rear) and θ_0 (front). The *dynamic fragment velocity*, V_d and the *dynamic ejection angle*, θ_d may be calculated by simple vectorial addition of the velocities.

$$V_d = \sqrt{V_0^2 + V_m^2} \quad (8-7)$$

Rear fragment

$$\theta_d = \tan^{-1} \left(\frac{V_m}{V_0} \right) \quad (8-8)$$

$$V_d = \sqrt{V_0^2 + V_m^2 - 2V_0V_m \cos \alpha} \quad (8-9)$$

Front fragment

$$\theta_d = \sin^{-1} \left(\frac{V_m}{V_d} \sin \alpha \right) + \theta_0 \quad (8-10)$$

Where $\alpha = (90 + \theta_0)^\circ$

8.2.4 Fragment Slow-down

Once a fragment has ceased to be accelerated by the explosive, it slows down as it travels through air (or any other medium) according to drag as given in the following equation:

$$V_s = V_d \exp \left[\frac{-C_d r_a A s}{2m} \right] \quad (8-11)$$

Where V_d = initial dynamic velocity of the fragment relative to the medium ; V_s = velocity (m s^{-1}) after travel of s (m) distance in air ; C_d = drag coefficient of the fragment in the medium ; m = fragment mass (kg) ; A = cross-sectional area of the fragment (m^2) ; r_a = density of air (kg m^{-3}) through which the fragment moves.

8.2.4.1 Fragment density

Conventional fragments have a constant mass (m) and size (A) as defined in the section on controlling fragment mass. These depend upon their shape but also upon the material. If a fragment is made of a denser material (e.g. tungsten rather than steel), it will have a smaller ratio of A/m and so will maintain its velocity and hence its kinetic energy to a greater distance.

Figure 8-19 shows the drop in velocity and kinetic energy density for 5 mm steel and tungsten cubes travelling with an initial velocity of $2,400 \text{ m s}^{-1}$ in air. Note how the velocity drop is greater for steel than tungsten and how the tungsten fragment always has greater kinetic energy density (KED) at any given range due to the smaller ratio of A/m . KED is a measure of how penetrative a fragment may be when impacting a target and depends on fragment velocity and cross sectional area: $\text{KED} = mV^2/2A$

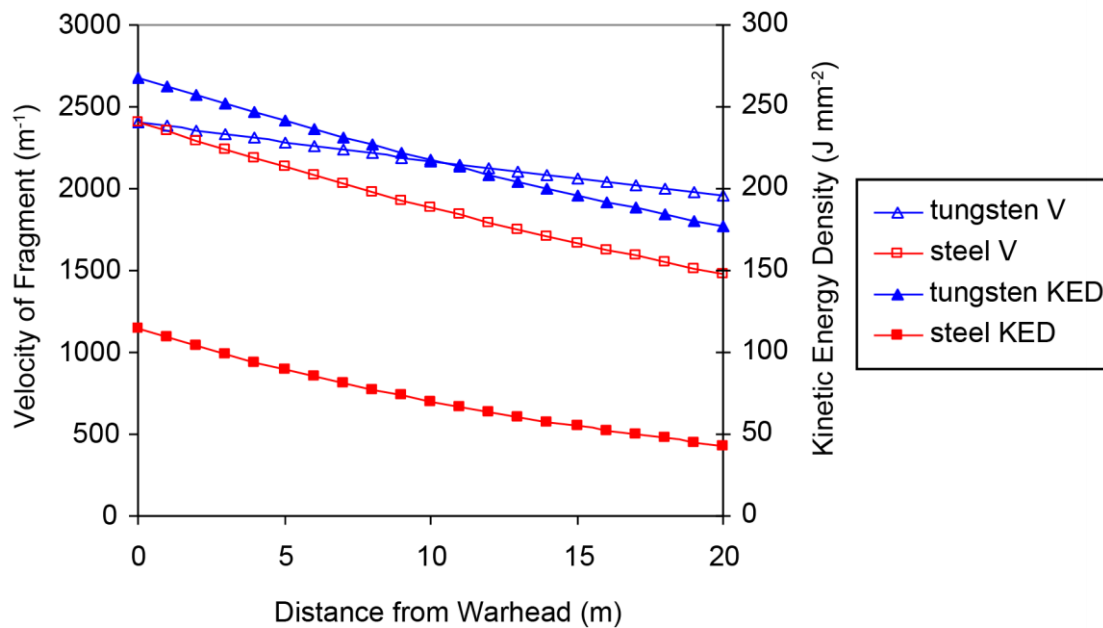


Figure 8-19 Effect of drag on velocity and kinetic energy density

8.2.4.2 Drag coefficient and fragment shape

Most fragments of interest to warhead designers have velocities which are comfortably supersonic, which is very convenient for the application of the drag equation because in this region the drag coefficient is essentially constant, and the values in Table 8-3 may be used. If more accurate calculations are required, variations in drag coefficient with respect to velocity as represented by Mach number, the velocity divided by the speed of sound in the medium, are available⁽⁵⁾. Examples are shown in **Figure 8-20**.

Table 8-3 Typical Drag Coefficients for Simple Shapes

Shape	Drag Coefficient (C_d)
Sphere	0.9
Cube (edge-on, tumbling)	1.1
Cube (face-on, tumbling)	1.6
Cylinder (end-on)	1.7
Cylinder (side-on)	1.2

The drag coefficient values given demonstrate that some shapes are more aerodynamic than others and will maintain velocity and kinetic energy to a greater distance. For example, spheres will travel further than cubes.

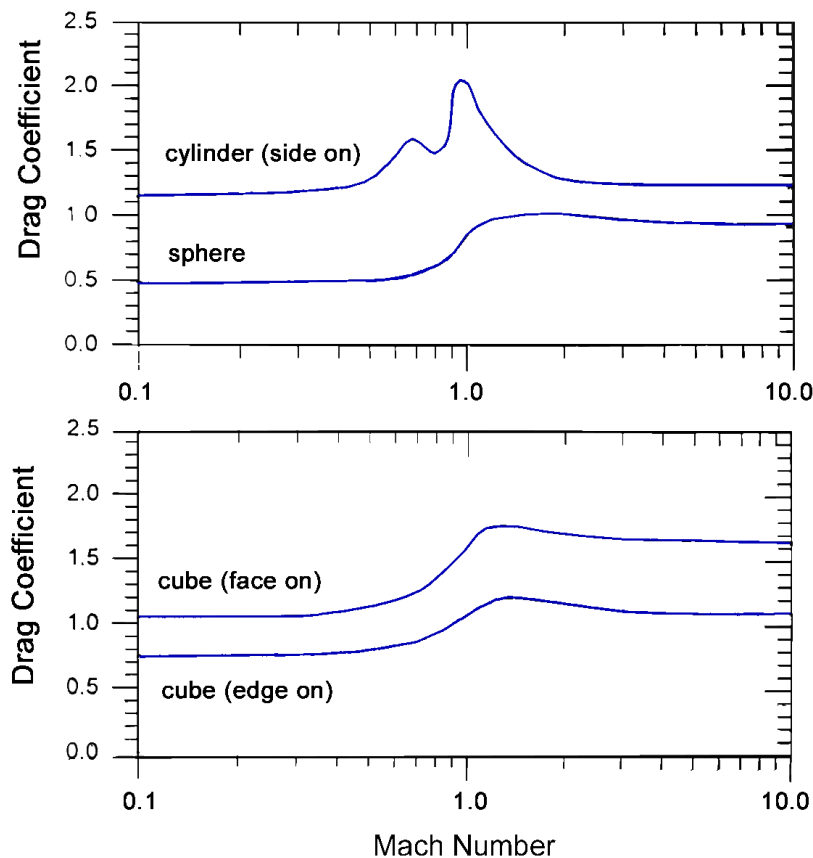


Figure 8-20 Aerodynamic drag coefficient versus Mach number

8.2.4.3 Air density and altitude

Air density varies with altitude and also is dependent on temperature and humidity at a given altitude. Example figures for air density at different altitudes are given in Table 8-4. It is clear from the equation for fragment slowdown that fragments lose velocity much more slowly at low density and therefore high altitude. This is of particular value to the lethality of missiles that attack air targets.

Table 8-4 Variation of Air Density with Altitude

Altitude / m	Example Air Density / kg m ⁻³
0	1.206
1,000	1.098
5,000	0.746
10,000	0.425
20,000	0.092
30,000	0.019

8.2.4.4 Lethal range

An initially lethal fragment slows down until it becomes sub-lethal at a sufficient distance. That distance is the *lethal range* and can be assessed. There will be a minimum critical velocity at which a given fragment will just defeat a target. This critical value is inserted into the fragment slow down equation and the resultant critical distance is the lethal range.

The lethal range is increased if:

- The fragment initial dynamic velocity is increased (increased initial static velocity or increased engagement velocity for a forward-projected fragment).
- The fragment mass is increased (via natural, controlled or pre-formed fragments) although this will also increase drag.
- The fragment density is increased (e.g. tungsten rather than steel).
- The fragment drag coefficient is reduced (e.g. spheres rather than cubes).
- The air density is reduced (e.g. at higher altitude).
- The target is weaker (e.g. due to a lack of ballistic protection).

8.3 THE DAMAGE VOLUME

Damage volume is the volume surrounding a fragmenting device which, for a given target and engagement scenario, is lethal. Looking at a cross-section of the damage volume for a rear-initiated, cylindrical warhead attacking a stationary target (Figure 8-21), the effects of forward velocity of the warhead is clear. As the warhead gets faster, the beam angle narrows and the lethal range increases. If the target is approaching, the beam angle stays the same but the lethal range increases with velocity of the target (Figure 8-22). These effects alter the likelihood of hitting a target and of defeating it.

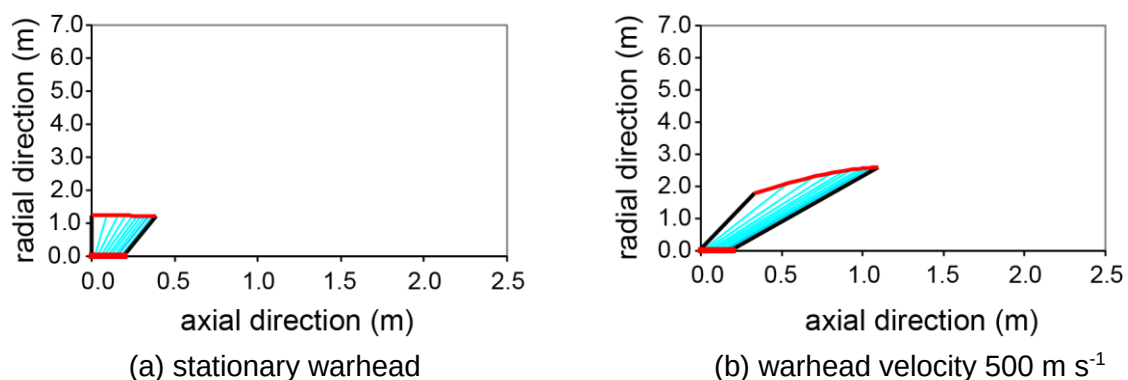


Figure 8-21 Damage volume of a warhead (Stationary Target)

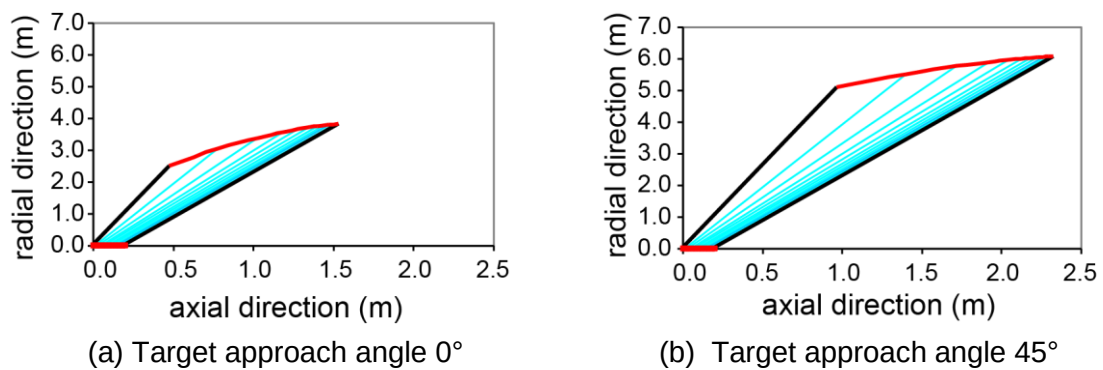


Figure 8-22 Damage volume of warhead with velocity of 500 m s⁻¹ (target approaching at 300 m s⁻¹)

8.4 DIRECTED EXPLOSIVE ENERGY

8.4.1 Introduction

In 1885 Charles Edward Munroe, an American explosives chemist, noted an important effect during tests involving guncotton (nitrocellulose). Letters indented on the explosives surface were replicated on the target post-detonation, with corresponding raised marks occurring if embossed letters existed. This crucial observation with the phenomena subsequently termed the 'Munroe effect' provided the first tangible evidence of ability to focus detonation waves.

Figure 8-23 schematically illustrates this effect:

- An explosive detonated against metal with a planar interface produces a shallow crater.
- If the explosive has an indentation in the face contacting the target a deeper crater is formed.
- If the explosive has a protrusion on the face contacting the target a raised structure is formed.

In all cases the explosive would be in intimate contact with the target.

The phenomena demonstrated in Figure 8-23 involves focusing of the detonation front thus producing '*directed explosive energy*'. A hollow at the output end of an explosive concentrates the detonation wave, focusing it in a manner akin to a convex lens, leading to a greater resultant crater depth; in corollary, a raised structure at this explosive / target interface will lead to detonation wave divergence (analogous to a concave lens). This concept is illustrated schematically for the hollow interface case in **Figure 8-24**.

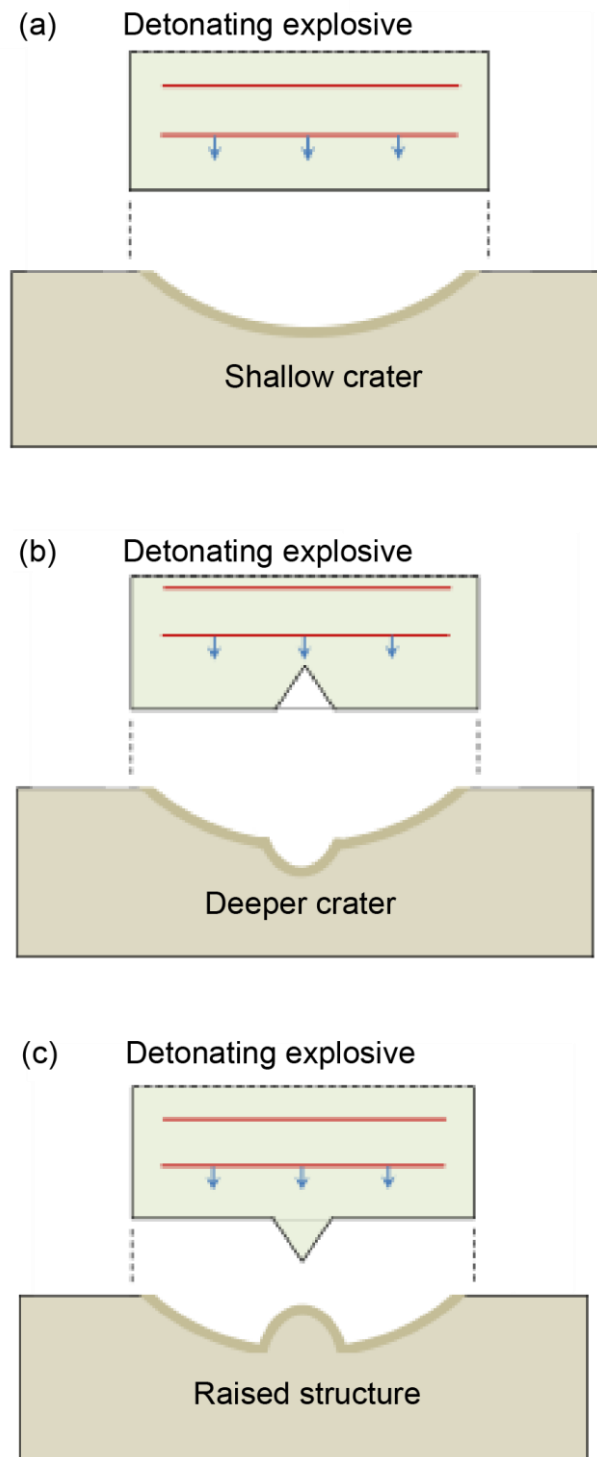


Figure 8-23 Schematic illustration of the Munroe Effect

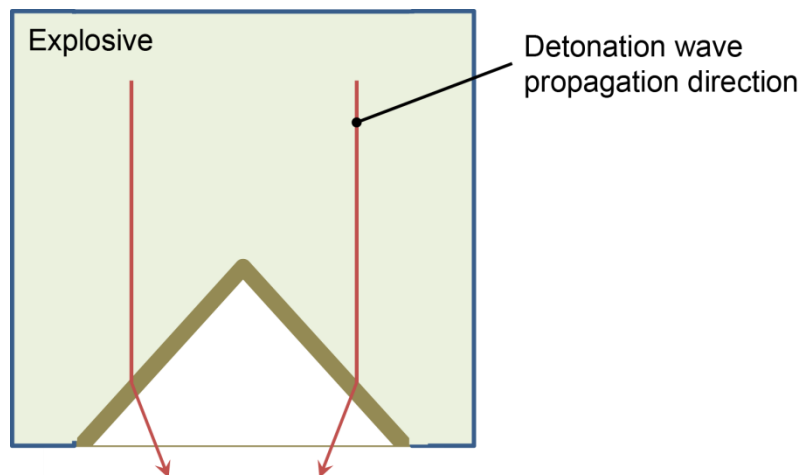


Figure 8-24 Illustration of the production of a converging detonation shockwave via the hollow charge effect

This effect, exploited in the hollow charge warhead can be tailored via control of the cavity shape and through the introduction of a metal liner, which enhances the penetration. Broadly speaking, the effect follows the shape of the cavity in the explosive. Consequently, a wider, shallower cavity at the explosive / target interface will lead to a corresponding wide, shallow crater, whereas, narrower, deeper cavities lead to deeper, but narrower, penetrations and eventually perforation of the target. This is universally known as the shaped charge effect and the term 'shaped charge warhead' used for weapons that exploit it. The complex physics and details of the shaped charge phenomenon can be found in Walters and Zukas⁽⁶⁾.

8.4.2 Shaped Charge Warheads

8.4.2.1 Mechanism

The shaped charge warhead, as shown schematically in **Figure 8-24**, comprises a hollowed-out explosive head with a metallic liner. This hollow, and the corresponding liner, normally have a conical section. Initiation of the explosive head leads to a detonation front which propagates through the device until it reaches the apex of the conical liner. The pressure exerted by the detonation front is so great that it exceeds the shear strength of the liner material. This consequently flows in a hydrodynamic manner, that is, in a fluid-like state, despite the fact that the material remains in the solid phase, something confirmed via X-ray diffraction experiments⁽⁷⁾. Collapse of the liner subsequently proceeds with material accelerated inwards towards the central axis of the cone. The resultant structure consists of two elements. Typically around 20 % of the liner material will be deflected forwards to form a jet with the rest forming a slug which travels behind. In general, the proportion of material in the slug will increase with the presented angle of the shaped charge liner. The jet tip possesses a substantial velocity of the order of 8-12 km s⁻¹

whereas the slug is ballistic in nature typically moving at less than 1.5 km s^{-1} . The process of jet collapse is illustrated in the flash X-ray radiograph presented in **Figure 8-25**⁽⁶⁾ showing two exposures on a single film and illustrating the progressive collapse of a copper liner. The lower image shows the early stage of cone collapse and the upper image the jet stretching to the right with the slug forming behind. As illustrated by this figure, a shaped charge jet takes a finite amount of both time and space to form. Consequently, a space or 'stand-off' from the target is required in order to allow for full jet formation. In addition, a white dashed ring include on the later time (upper) of the two exposures highlights a perturbation in the jet, likely a function of microstructural imperfections in the liner or alternatively a slightly asymmetric collapse.

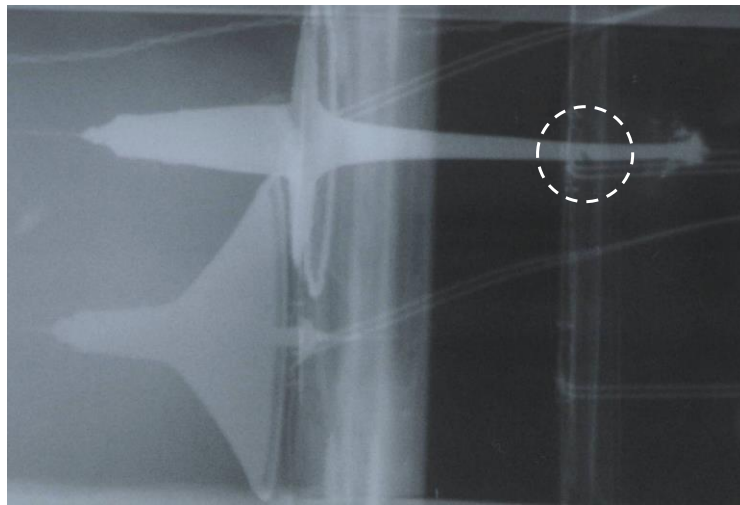


Figure 8-25 Flash X-ray radiographs illustrating collapse of a shaped charge liner

As shaped charge jets have very high on-axis momentum, such perturbations act to disrupt the jet as it develops, limiting the stand-off at which shape charge warheads can act. Further, as shown below, to a first-order, subsequent penetration (P) by the jet is velocity independent and a function only of target (ρ_T) and liner (ρ_P) densities and jet length (L):

$$P = L \sqrt{\frac{\rho_P}{\rho_T}} \quad (8-12)$$

A shaped charge jet will typically form in $\sim 40 \mu\text{s}$ and given a resultant tip velocity of around $8\text{-}12 \text{ km s}^{-1}$, which implies accelerations in the order of $25 \times 10^6 \text{ g}$ or 25 Mega-g. As the jet forms it stretches due to a velocity gradient along its length caused by the increase in metal mass being driven by decreasing explosive mass as the cone collapses. The jet tail will have a velocity of $\sim 1\text{-}2 \text{ km s}^{-1}$ with the slug at $0.5\text{-}1.5 \text{ km s}^{-1}$. Ultimately, if left to stretch in free space the jet will fragment and not provide optimum target penetration.

When the jet tip impacts a metal target the pressure exerted is so great it overcomes the strength of the material such that it undergoes hydrodynamic flow. The jet still behaving hydrodynamically flows and lines the surface of the resulting hole. A typical shape charge penetration path is illustrated in **Figure 8-26** showing a series of sectioned 20 mm deep blocks penetrated by a copper shaped charge. Although the depth of penetration is independent of jet velocity the diameter of the hole does decrease as slower elements of the jet penetrate as the hole depth increases.



Figure 8-26 Photograph showing sectioned mild steel blocks penetrated by a small-scale shaped charge.

8.4.3 Factors Effecting Shaped Charge Jet Penetration

While the basis of a shaped charge warhead is intrinsically simple being a metal cone backed by a detonating explosive there are a wide range of variables that contribute to the performance of a shaped charge warhead. These are illustrated in **Figure 8-27** with detail below. Dimensions of a shaped charge warhead scale such that it is usual to consider stand-off, charge length and target penetration as multiples of charge diameter (CD).

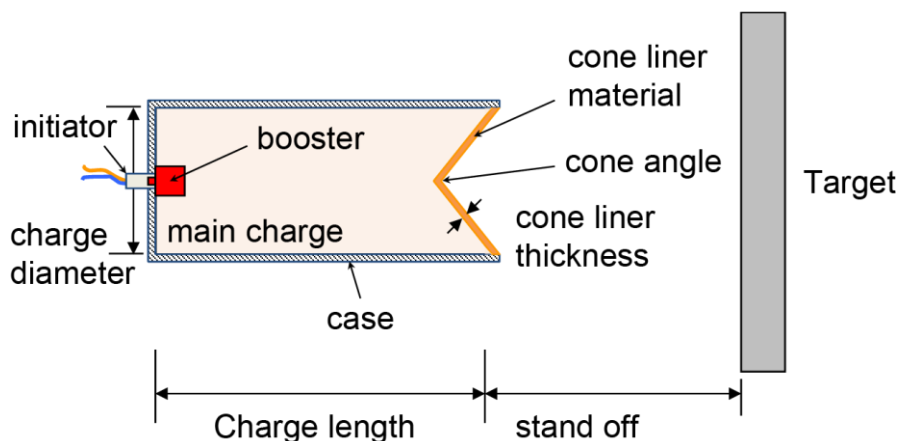


Figure 8-27 Schematic illustration of a simplified shaped charge warhead/target system, highlighting key variables.

8.4.3.1 Stand-off

This is a critical factor for a shaped charge warhead. Insufficient stand-off will not allow the jet to fully form as maximum target penetration requires a fully stretched jet that has not begun to fragment. Consequently, an appropriate triggering mechanism is required to ensure optimal stand-off. Too short and the jet has insufficient time to form; too long and inevitable perturbations will lead to

jet instability. Figure 8-28 shows this effect showing penetration in to steel for a particular design of shaped charge at varied stand-offs.

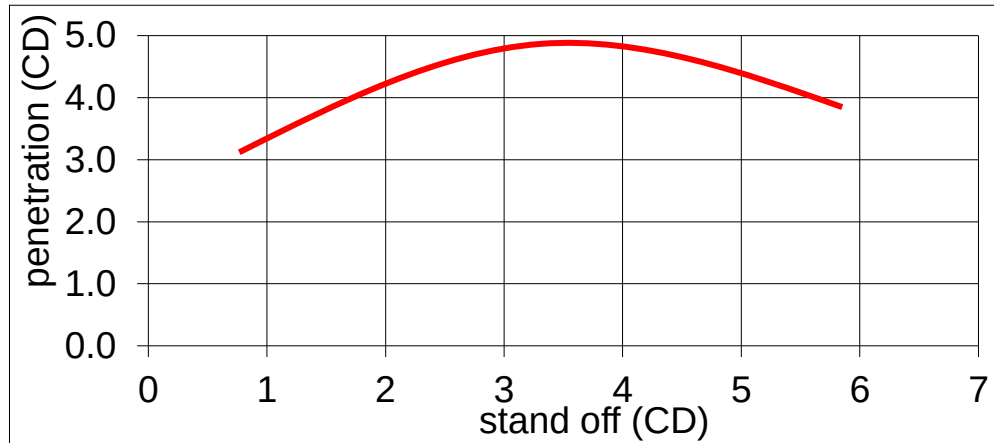


Figure 8-28 The effect of stand-off on penetration of a shaped charge warhead

A stand-off of between 2-5 CD is usually appropriate depending on other design factors. This is a challenge for weapon designers as impact fuzes will require a probe on the front of the warhead as found in infantry anti-tank weapons. For larger warheads sensors can be employed, however, these would be in the nose of the warhead and can affect the jet formation.

8.4.3.2 Charge length

The detonation wave from a centrally initiated warhead as shown in **Figure 8-27** needs to be fully formed and axially symmetrical once the apex of the cone is reached. Only minimal performance gains are found for charge lengths greater than one CD. It is now common practice in shaped charge design to utilise wave shapers to manipulate the detonation shockwave such that shorter warheads can be produced with improved penetration. Figure 8-29 shows how a waveshaping element set in to the explosive forces a centrally initiated shockwave to travel to the periphery of the charge and then converge on to the apex of the metal liner.

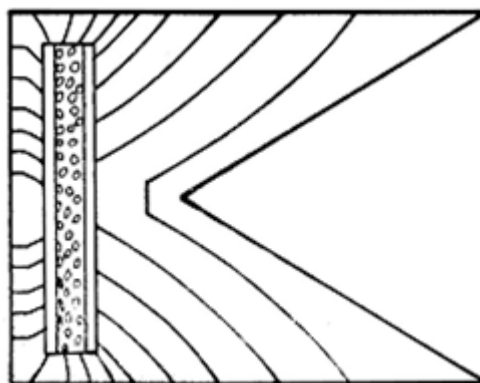


Figure 8-29 Shaped charge warhead with waveshaper**8.4.3.3 Explosive**

Explosives with very high detonation pressures optimise metal driving and so it is usual to find shaped charge warheads with explosive fills with high HMX content.

8.4.3.4 Cone liner material

In line with equation (8-12), use of a higher density liner material will lead to a corresponding increase in subsequent penetrative ability of the warhead provided the selected material is able to demonstrate sufficient high strain-rate ductility to flow in an appropriate manner.

As a comparison, Table 8-5 illustrates the relative potential effects of varying liner material density for a selection of common materials compared to copper. The figures are theoretical as the material must have the ability to flow and form a jet. Tungsten would appear to be a suitable material, potentially 47 % more penetrative than copper but due to its material properties it does not form jets. Some unlikely materials, however, do form jets such as glass. Improvised shaped charges have been constructed from wine bottles that have a deep, almost conical, indentation in the base as found in champagne and red wine bottles.

In practice the material commonly used worldwide is copper for anti-armour warheads due to its relatively high density and high strain-rate ductility linked to an ability to recrystallize under high strain-rates. It is not expensive, easy to fabricate and by careful control of the microstructure will provide penetration of up to eight times the diameter of the cone. However, there is evidence that aluminium performs better than copper against concrete.

Table 8-5 Relative Resultant Penetration Calculated Based on Equation [Error! Reference source not found.](#)2) for a Nominal Shaped Charge Warhead as a Function of Cone Liner Material

Cone liner material	Relative penetration (CDs, normalised to copper)
Depleted Uranium	1.45
Tungsten	1.47
Copper	1.00
Steel	0.94
Aluminium	0.56
Glass	0.53

8.4.3.5 Cone angle and cone geometry

The angle of the metal cone at its apex has a major impact on penetrative performance of a shaped charge as shown in Figure 8-30. Most shaped charge warheads will have a cone angle between 45° and 60° . A narrower cone angle will produce a faster, but narrower, resultant jet and vice-versa.

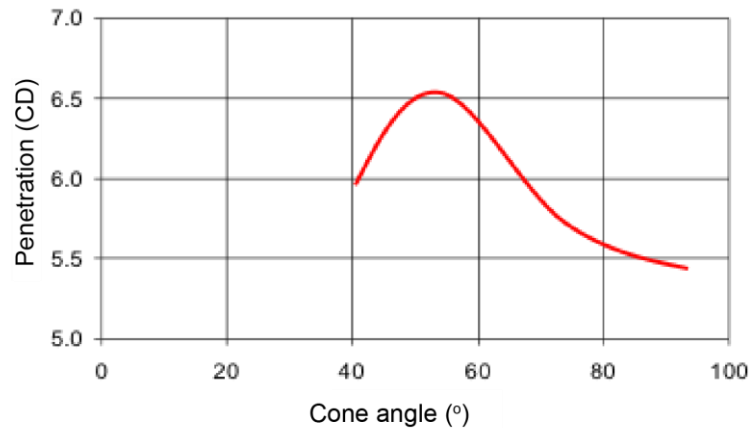


Figure 8-30 the effect of cone angle on penetration of a shaped charge warhead

Other cone geometries do exist for example, trumpet-shaped liners that have a continually changing cone angle from apex to base. However, these are more difficult to manufacture and are not commonly found.

8.4.3.6 Cone/charge diameter (CD)

If the diameter of a shaped charge is doubled this will double its penetration in to steel or armour. As shaped charges and their effects scale by dimension this will require the stand-off also to be doubled.

8.4.4 Explosively Formed Projectiles (EFPs)

Explosively formed projectiles in essence represent a limiting case of a shaped charge in which the presented angle of the liner is such that all of the material in the liner forms the slug. In general, this occurs once the presented angle of the cone is around $120^\circ - 140^\circ$. However, for an EFP the liner often made of high-purity iron is more typically replaced with one with the form of a hemispherically divergent dish rather than a conical section. Figure 8-31 shows how the dish liner collapses to form a single slug, which is fully formed in to its aerodynamic shape in around $40 \mu\text{s}$.



Figure 8-31 Computer model of an EFP dish forming a slug

Via careful design, the resultant projectiles with a ballistic velocity in excess of 1 km s^{-1} are aerodynamically stable and able to penetrate targets over a hundred cone (dish) diameters from the detonating warhead. This makes such EFPs suitable for stand-off weapons such as off-route mines or top attack area mines. A recovered EFP is shown in **Figure 8-32**. It is placed in a cross section of the hole it would produce in an aluminium target.



Figure 8-32 Recovered EFP projectile placed in a penetrated aluminium target

8.5 LINEAR CUTTING CHARGES

The physics underlying shaped charge formation can be exploited to produce a planar jet, useful for cutting through hard targets for demolition purposes. As shown schematically in **Figure 8-33**, this comprises of a box whose upper half is filled with an appropriate explosive composition, while the lower half consists of a metal liner and a built-in spacer to provide a stand-off.

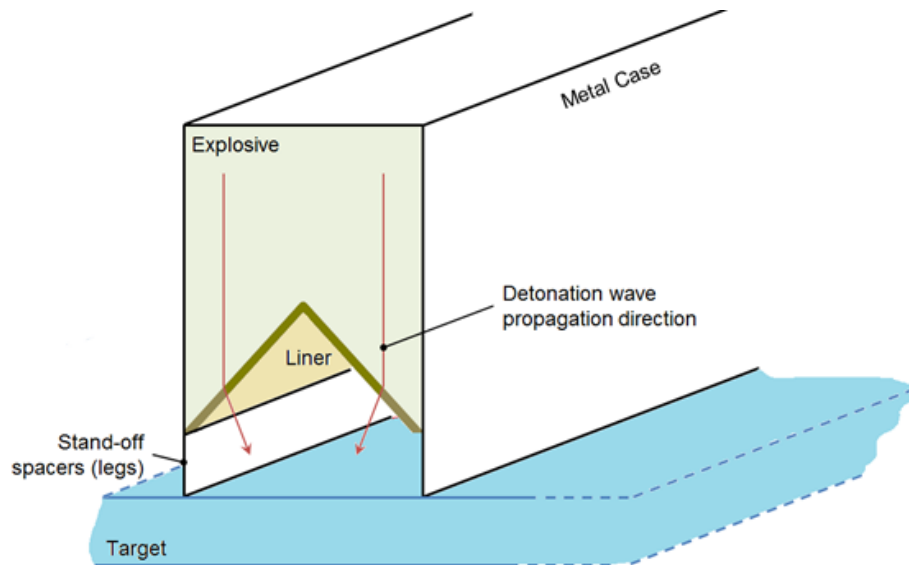


Figure 8-33 A linear cutting charge

Large charges of the type shown in **Figure 8-33** are used for rapid bridge demolition. These have rigid metal liners; however, for smaller applications a more flexible design uses a lead liner made by filling a lead tube with explosive and then pulling through dies to give the necessary size with a 'v-shaped' groove along one side providing the focusing element for the charge. Fillings typically comprise a powdered high explosive such as RDX or PETN, with the systems flexibility making it ideal for demolition tasks involving cutting through metal plates, girders, etc. More recently this lead type of linear cutting charge is being replaced by foam sheathed extruded explosive with a flexible liner manufactured from copper powder and polymer as shown in Figure 8-12.

In addition to the linear cutting charges detailed above, it is possible to exploit the influence of material impedance on shock propagation to fracture or cut a target. Essentially, if a diamond shaped charge is placed on a target and detonated at opposing corners the interaction of the resultant shock waves in the target, in particular, their reflection as tensile release waves from the unconfined rear-surface, will lead to fracture along the diamonds plane of symmetry. This process exploiting the phenomena of material spallation is illustrated schematically in **Figure 8-34**. It has been successfully employed in both 'Fracture Tape', which comprises a series of nominally diamond shaped individual charges which are initiated at their extremities, and in 'Shock

Refraction Tape' – which instead uses wave shapers to achieve a comparable effect from a continuous strip of explosive material.

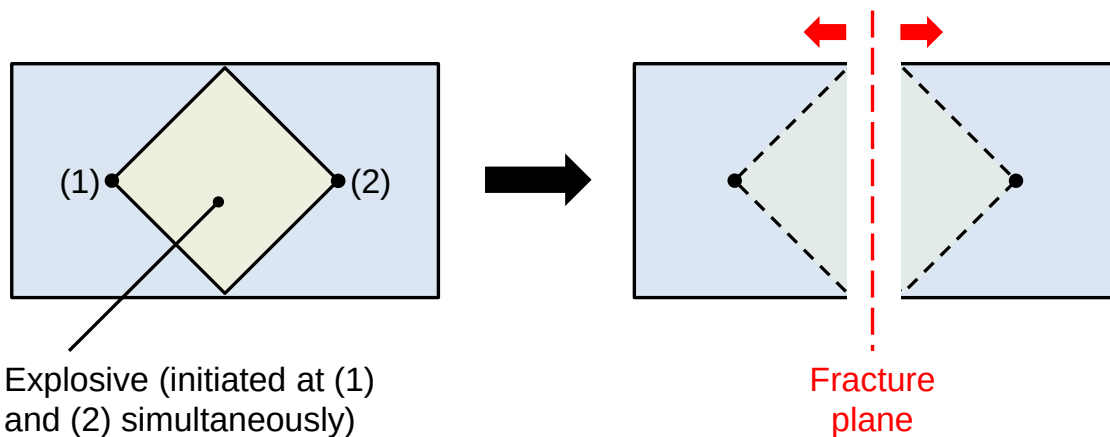


Figure 8-34 Schematic illustration of the effect of metal cutting using a diamond shaped charge (top-view)

8.6 EXPLOSIVE WELDING

Explosive welding essentially involves the use of an explosive to accelerate one metallic material into a dissimilar metallic material, creating a region of extremely high pressure. This high pressure acts for a sufficient time for material bonding and subsequent cooling to occur leading to a welded interface. In the process of accelerating one material into the other, a jet is formed ahead of the welding front analogous to the formation of a jet from a collapsing shaped charge liner. This jet acts to clean the interface between the materials, resulting in a very strong bond. The major advantage of the approach is the ability to bond materials which would otherwise not conventionally weld for example, titanium to steel, copper to aluminium and aluminium to steel. This process, described in more detail elsewhere⁽²⁾, is illustrated schematically for a planar geometry in **Figure 8-35**.

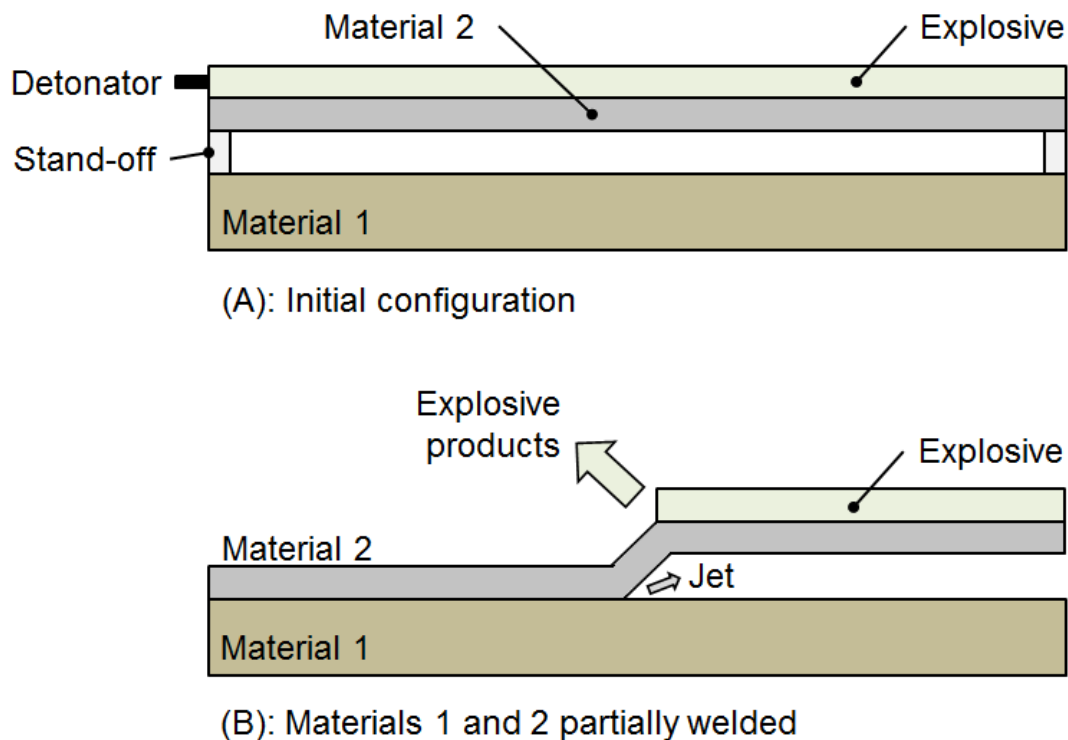


Figure 8-35 Schematic illustration of the explosive welding process

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