

CHAPTER 7

EXPLOSION PROCESSES

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7 THE EXPLOSION PROCESS

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7.1 AWARENESS SUMMARY

As introduced in Chapter 1 and expanded on in Chapter 2, explosives produce their effects through the liberation of heat and gas products through chemical reactions. There are two processes by which this occurs, the Burning Process and the Detonation Process. This chapter considers the key concepts and underlying physics associated with the reaction of explosives through the processes of burning or detonation. Explosives that detonate in their designed use are called High Explosives and those that burn in their designed use are often called Low Explosives. However, virtually all High Explosives can burn and many Low Explosives are capable of detonation. This latter point is important when considering the safety of munitions, for example those that contain large propellant charges such as are found in missile rocket motors. In its correct use the rocket propellant will burn, however, in certain accident scenarios it may be induced to detonation. Usually the desired outcome in the designed use of explosives will depend on the method of initiation as described in Chapter 5 Initiation of Explosives.

When an explosive material burns explosively it is said to undergo deflagration. There is no specific definition of the term deflagration but it is often considered to be when explosives burn at such a speed as to allow the expanding gas products to perform work such as to accelerate projectiles in guns or create blast. When explosives deflagrate they are undergoing the burning process.

The chemical decomposition of an explosive, releasing gaseous reaction products and subsequent production of heat occurs in both the burning and detonation processes. However, the mechanisms by which these processes occur in the explosive are very different. These two reaction categories are summarised below and described in detail in the subsequent sections.

7.1.1 Burning Explosives

When an explosive burns the explosive chemistry producing heat and gas occurs at any exposed surface. Most of the heat flows away from the burning surface in the gas products; however, some heat is conducted and radiated in to the unburnt explosive below the burning surface. This will reach its ignition temperature and then become the burning surface. Therefore, the burning process will travel in to the bulk of the explosive. This is shown in Figure 7-1 where a stick of explosive is burning along its length.

When the temperature at any explosive's surface reaches the ignition temperature that surface will ignite. For a propellant charge inside a cartridge case, which will have numerous individual grains of propellant, all surfaces of each grain will be ignited in the very early stages of ignition following functioning

of the igniter. This includes internal holes as found in multi-tubular propellant grains.

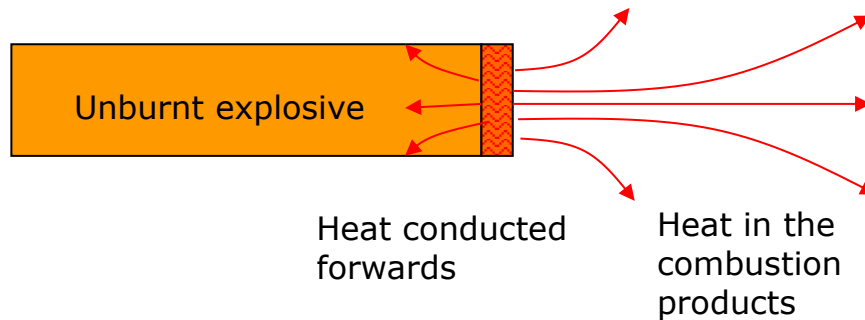


Figure 7-1 Heat transfer during the burning process

A major influence on the speed by which the burning surface progresses in to the bulk of the explosive, called the linear burning rate, is the pressure above the surface and is commonly known as Vieille's Law. As the pressure increase so does the linear burning rate. For example a typical gun propellant will have a linear burning rate of 5 mm s^{-1} at atmospheric pressure but at breech pressures this will approach 400 mm s^{-1} .

As burning is a surface phenomenon how fast a mass of explosive can burn will depend on the available surface area. If a propellant charge consists of spherical propellant grains then for the same mass of propellant if the grain size for charge A has a radius of $x \text{ mm}$ and charge B of $x/2 \text{ mm}$, the charge B will have twice the surface area of charge A.

How quickly bulk explosive, such as a propellant charge, burns is a variable called the mass burning rate, will depend on what initial surface area is available and how it may change during the burning process. When the propellant charge burns in the breech of a gun pressure also will affect the mass burning rate, and these factors together are the basis of internal ballistics. For the duration of the propellant burn the pressure will be changing as will the available propellant surface area. This complex interaction consequently requires challenging calculations to model the process.

Further details of the burning process can be found in section 7.2.

7.1.2 Detonating Explosives

When an explosive detonates the explosive chemistry is initiated by the passage of a shockwave through the explosive charge. A shockwave is an intense pressure wave travelling faster than the speed of sound in that material. As the speed of sound in explosive is around $1,800 \text{ m s}^{-1}$ and for most service explosives detonation velocities are in the range of $6,500 - 8,500 \text{ m s}^{-1}$ it can be seen that detonations occur at 10,000 to 100,000 times faster than the propellant burning in a gun. An explosive charge 1 m in length can completely detonate in a few hundred millionths of a second (micro-seconds) if initiated from one end.

A detonation will often have a curved shockwave travelling away from the point of initiation in to the bulk of the explosive charge. This will occur in 3 dimensions as shown in Figure 7-2 although in small diameter charges this can be almost planar (flat).

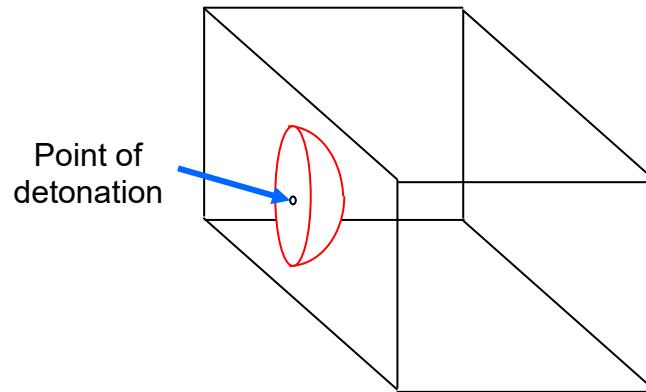


Figure 7-2 Shockwave expanding hemispherically in a block of explosive

Energy to drive the shockwave comes from the explosives chemistry occurring immediately behind it. There is a point behind the shockwave called the Chapman-Jouget (C-J) plane; material to the right of this plane as seen in Figure 7-3 will have particle velocity towards the shockwave and that behind to the left will move in the opposite direction and become the expanding gas products. The energy transferred to the shockwave and its forward velocity will reach a steady state so the shockwave reaches a constant velocity known as the Velocity of Detonation (VoD or D). Only energy released to the shockwave side of the C-J plane can influence the detonation shockwave.

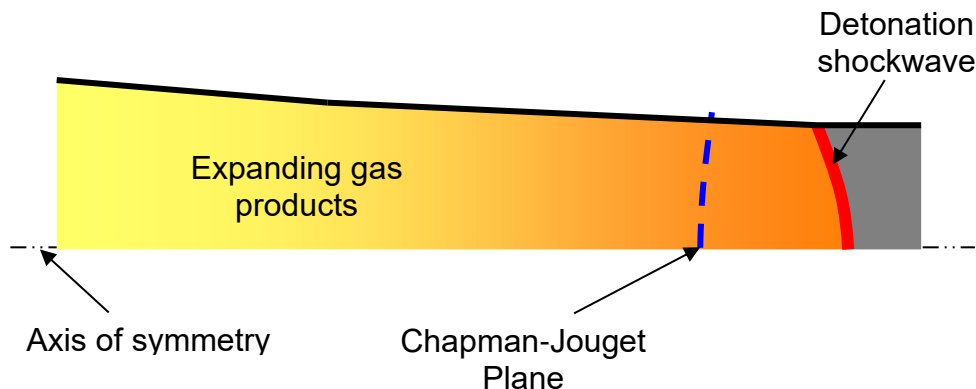


Figure 7-3 A detonating explosive charge showing the Chapman-Jouget plane

The Chapman-Jouget plane is often considered also to define the reaction zone and for explosives formulated from explosive molecules such as TNT, RDX and HMX, etc. this is normally true. However, if the explosive formulation is one containing slow reacting chemical systems such as those containing aluminium powder or those that are fuel oxidiser mixtures such as ANFO, they are considered to be classed as non-ideal explosives and reactions producing explosion products continue outside the zone denoted by the shockwave and the C-J plane.

Figure 7-4 shows how the reaction zone may come behind the C-J plane and explosive chemistry occurring between the C-J plane and the end of the reaction zone cannot influence the shockwave. This will reduce energy available to the shockwave and so the VoD values will be lower for non-ideal explosives than those where the chemistry all occurs before the C-J plane is reached. However, hot dense gas products are still being produced and will add to the power of the expanding gases.

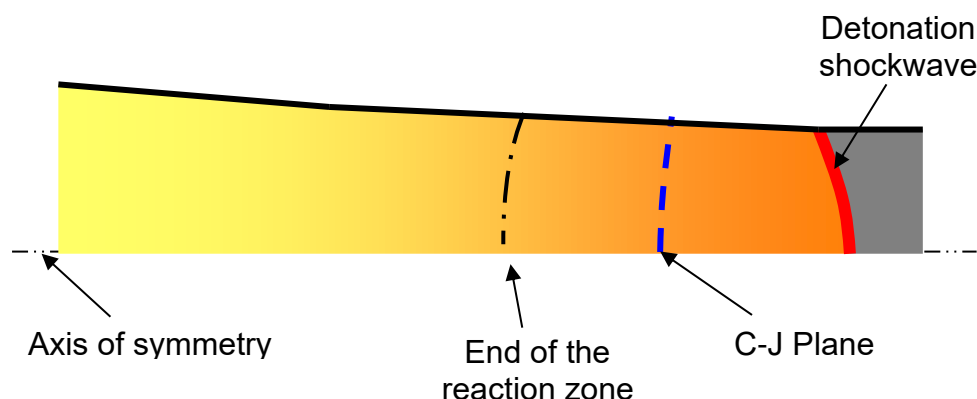


Figure 7-4 The reaction zone for non-ideal explosives

As the diameter of a detonating charge increases so does the distance between the shockwave and the C-J plane giving more time for chemical reaction. However, the converse is true and as the diameter becomes very small the energy released before the C-J plane becomes insufficient to support the shockwave. A point is reached where the charge will not detonate known as the critical diameter (see 7.3.3.3), which is usually quoted for what is essentially a bare uncased charge. Light confinement such as 0.2 mm paper may be used for example if the explosive is a powder. Under these conditions PETN powder has a critical diameter of 0.3 mm whereas the value for cast TNT at a density of 1.61 g cm^{-3} is 7 mm.

Each explosive capable of detonation will have an upper limiting value for its VoD, which is that normally quoted unless other conditions are invoked. Below a certain diameter this will progressively reduce until the critical diameter is reached and for this circumstance confining the charge can increase the VoD from the unconfined charge of the same diameter. Confinement will also reduce the critical diameter. Both the VoD and critical diameter are affected by the density of the explosive.

7.2 THE BURNING PROCESS

7.2.1 Propagation of the Burning Reaction

Once an explosive material has been raised to its ignition temperature it begins to undergo a chemical reaction producing heat and gas. The product gases will flow away from the surface removing most of the heat, however, through

radiation and conduction, heat will transfer in to the explosive below the burning surface as shown in Figure 7-5. This will raise the underlying material to its ignition temperature where it now becomes the burning surface. All available burning surfaces of the explosive will continue this process until it is completely consumed. In this manner, a solid piece of explosive that is burning on all available surfaces will decrease in all dimensions as shown in Figure 7-6 for a cylinder. This is known as Piobert's Law.

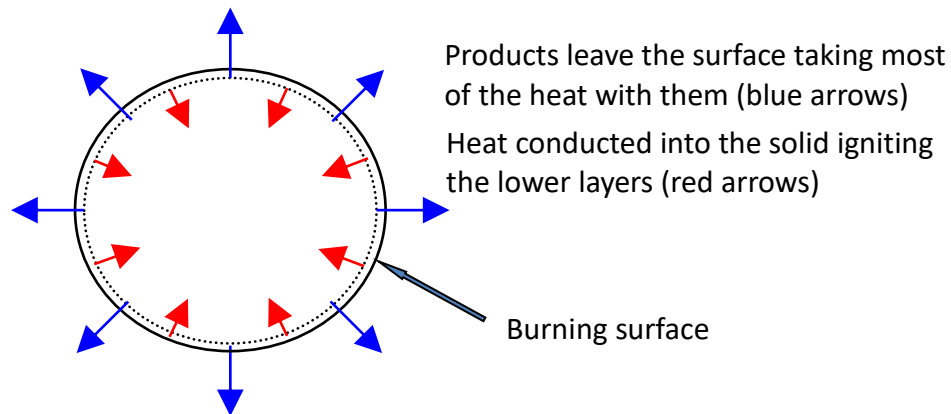


Figure 7-5 Heat transfer for burning explosive

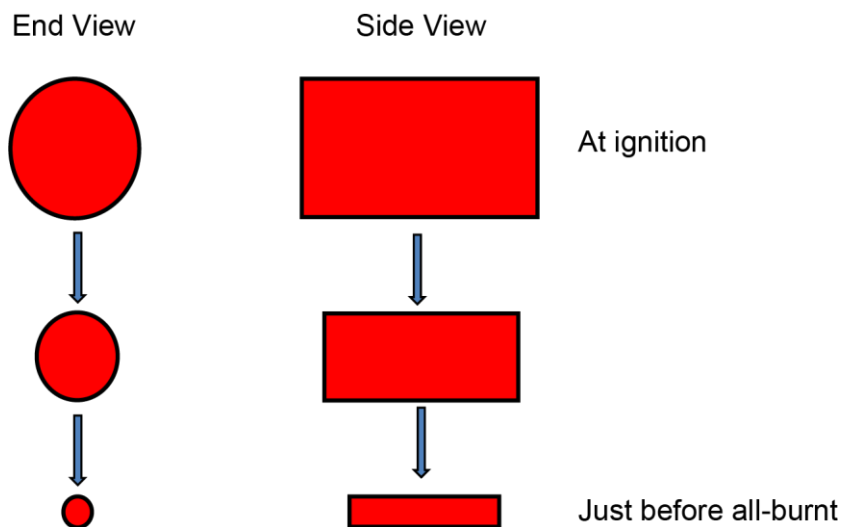


Figure 7-6 Changing dimensions of a burning cylinder

7.2.2 Mass Burning Rate

The most common application of burning explosive is the use of propellants in guns or rockets and to optimise performance it is important to understand how quickly the propellant is converted to heat and gas, that is, the mass burning rate (g s^{-1}). To understand the factors that can affect the mass burning rate consider a cube of explosive burning on only one face as shown in Figure 7-7.

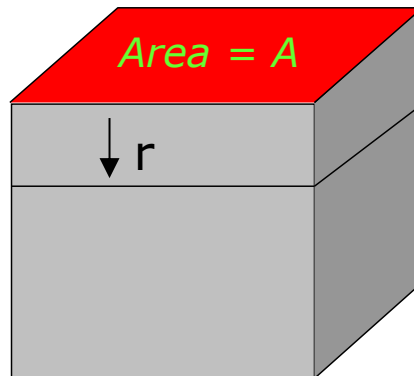


Figure 7-7 Cube of explosive burning on one face (red)

The area of explosive burning is denoted as A (cm^2) and the speed at which the burning surface is moving in to the explosive, called the linear burning rate (also called 'rate of burning'), denoted as r (cm s^{-1}). Therefore, the speed at which a volume of explosive is being consumed is $A \times r$ ($\text{cm}^3 \text{s}^{-1}$). Since mass = volume $\times$ density (ρ) then mass burning rate (g s^{-1}) can be measured using Equation (7-1).

$$\text{Mass burning rate} = A \times r \times \rho \quad (7-1)$$

7.2.3 Factors Affecting Mass Burning Rate

7.2.3.1 Surface area

Using gun propellant as an example, when a propellant charge made up of a large number of small pieces of propellant known as 'grains' is burning each grain will burn on all exposed surfaces. Therefore, if the grains were spheres, as they burned their diameter would reduce and therefore so would their surface area (A). Based only on surface area this would suggest that the mass burning rate for solid propellant grains would decrease from the moment all of the grain surfaces were burning. However, if the propellant grain has internal perforations, for example a cylinder with multiple tubular holes as shown in Figure 7-8, then each hole will increase in surface area as the grain burns. This will create a somewhat complex change in surface area as each hole is increasing in surface area but the outside of the cylinder will be decreasing. In this case the total surface area of the grain would constantly increase throughout the burn.

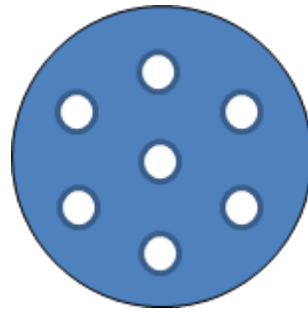


Figure 7-8 Cross section of a multi-perforated propellant grain

The internal ballistics for both guns and rockets depends heavily on the changes to overall surface area of the burning propellant. If the overall surface area reduces it is called regressive burning, whereas if it increases as described above for multi tubular granular propellant grains it is progressive burning. For a grain that is a hollow tube the surface area remains approximately the same and is known as neutral burning. Figure 7-9 shows a number of different shapes found in gun propellant charges. Solid shapes such as cord and flake will have regressive burning, multitubular will have progressive burning with tube and slotted tube having approximately neutral burning. Slotted tube is usually found for stick propellant, where the grains are very long like uncooked spaghetti. Without the slot the internal pressure within the stick would cause it to shatter and produce uncontrolled changes in surface area.

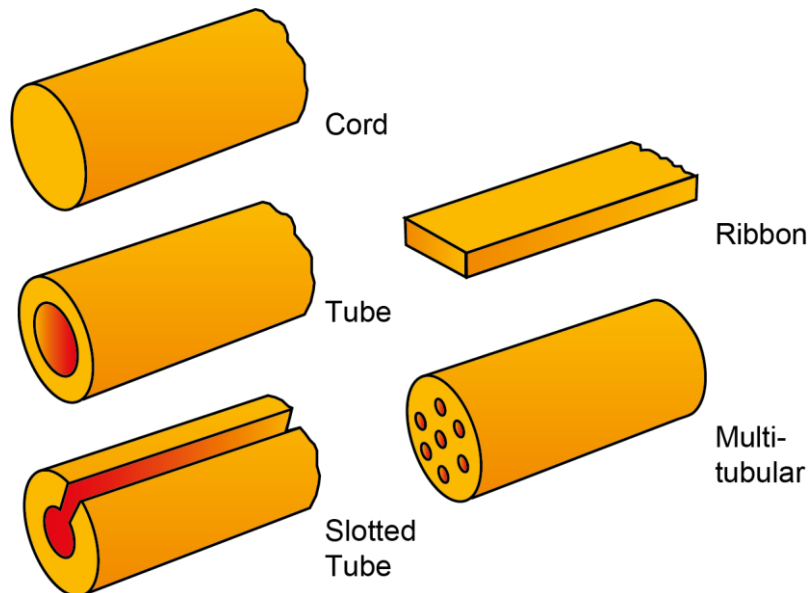


Figure 7-9 Examples of gun propellant grain shapes

Similarly, for rocket propellants the surface area during the burn can be controlled. Figure 7-10 gives some examples of single grain rocket propellants where the outer surface is bonded to the rocket motor casing and so will only burn on the rear face or inside an internal conduit. In these cases the cigarette burn will be neutral with a small surface area whereas the star centre will also

be neutral but with a bigger surface area as the conduit is usually the full length of the grain. A tubular rocket grain will be progressive as the tube increase in diameter during the burn.

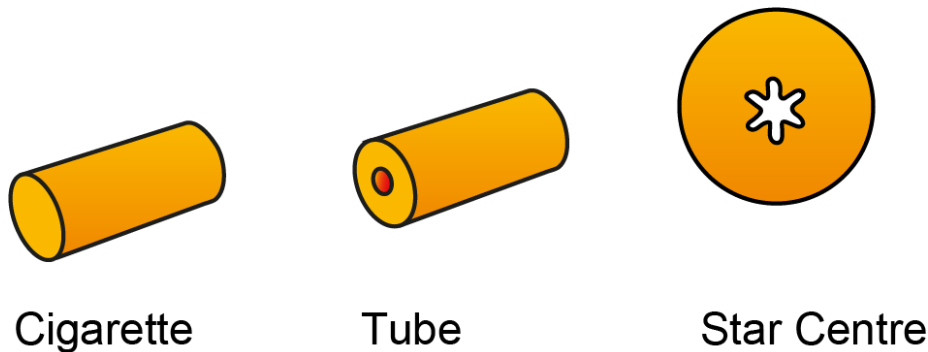


Figure 7-10 Examples of rocket propellant grain shapes

7.2.3.2 Pressure

When propellant charges burn in a gun they are under confinement within the breech and so as soon as the burning begins the pressure (P) will begin to rise, which has a major effect on the linear burning rate (r). The effect of pressure on the linear burning rate was discovered in the 19th Century and is known as Vieille's Law or de Saint Robert's Law. As pressure increases over the burning surface of an explosive the linear burning rate increases. For some applications of burning explosives such as aircraft pyrotechnic decoy flares it is equally important that as pressure decreases the linear burning rate also decreases. This relationship for non-porous homogeneous explosives is given in Equation (7-2) where a is the pressure index, n is the burning rate coefficient also called the pressure exponent. These values are particular to specific explosives.

$$r = a P_c^n \quad (7-2)$$

7.2.4 Processes Occurring at the Burning Surface

7.2.4.1 Homogeneous explosives

The processes that occur adjacent to the burning surface are somewhat complex. For Double Base propellant, an intimate mixture of nitrocellulose and nitroglycerine, the initial release of heat is in a layer above the surface known as the fizz zone. Heat is transferred back from this zone in to the solid explosive raising its temperature and initiating chemical reaction. There is a zone following the fizz zone called the dark zone where little additional heat is released before the final chemistry occurs in the flame zone. This is shown diagrammatically in Figure 7-11 Temperature increase from unreacted explosive to final products. The linear burning rate is controlled by any factor that affects the heat flux from the fizz zone back to the burning surface. These include pressure that decreases the length of the dark zone and increases fizz zone temperature and also energy density of the explosive.

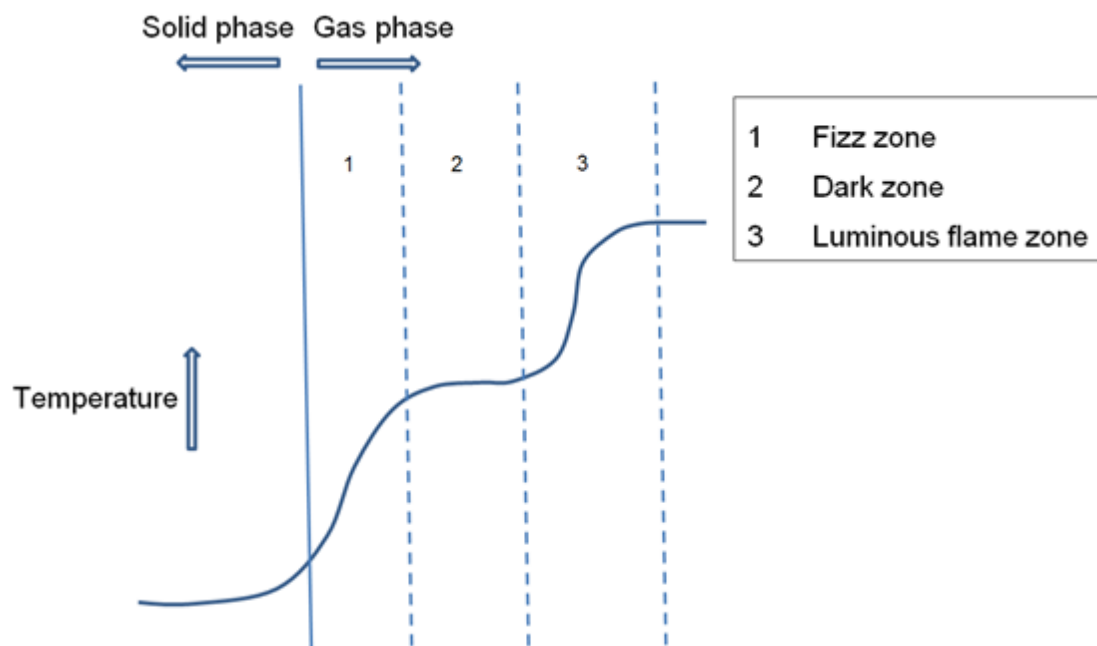


Figure 7-11 Temperature increase from unreacted explosive to final products

7.2.4.2 Heterogeneous explosives

When solid oxidisers such as ammonium perchlorate are present in a burning explosive such as composite rocket propellant the processes that are occurring differ from those that occur for homogeneous explosives. This propellant consists, in its simplest form, of a matrix of ammonium perchlorate (AP) crystals, which may vary in size from 50 – 400 μm , set in to a polymeric fuel binder such as hydroxyterminated polybutadiene (HTPB).

In this combustion process the AP crystals undergo exothermic decomposition although the products of this still contain oxidising chemical species. This decomposition is driven by the heat evolved in the overall combustion process, which also cause the HTPB to break down in to volatile pyrolysis products. A final diffusion flame is produced where the oxidising chemicals from the AP mix and react with the HTPB pyrolysis products producing the final reaction products of the propellant combustion.

As for homogeneous explosives Vieille's Law can often be applied to heterogeneous explosives but here a major influence on burning rates is the particle size of the AP in the mixture.

7.3 THE DETONATION PROCESS

7.3.1 Introduction

Detonation is defined as a chemically sustained shock wave that is a steady state phenomenon, with an associated characteristic velocity. Unlike

burning/deflagration where heat transfer by radiation and convection dominates the reaction rate, detonation is governing by the energy released from chemical reaction supporting the shockwave. Initially, the products move in the same direction as the shockwave. The rate at which a detonation front propagates through a detonating explosive is known as the detonation velocity, D . As detonation is a shockwave it must be travelling faster than the speed of sound in the material, which for explosives is approximately 1800 m s^{-1} .

7.3.2 Wave Propagation

7.3.2.1 Stress waves

If materials are loaded at a relatively low pressure / deformed at a relatively low rate-of-strain (typically $< 1 \text{ GPa}$ and $10^5 / \text{s}$ respectively), a stress wave will be established. Such waves are dispersive, with the amplitude varying smoothly across the wave profile and reducing with both propagation distance and time as shown in Figure 7-12; e.g. lower pressure portions of the wave propagate at a higher velocity than higher pressure portions.

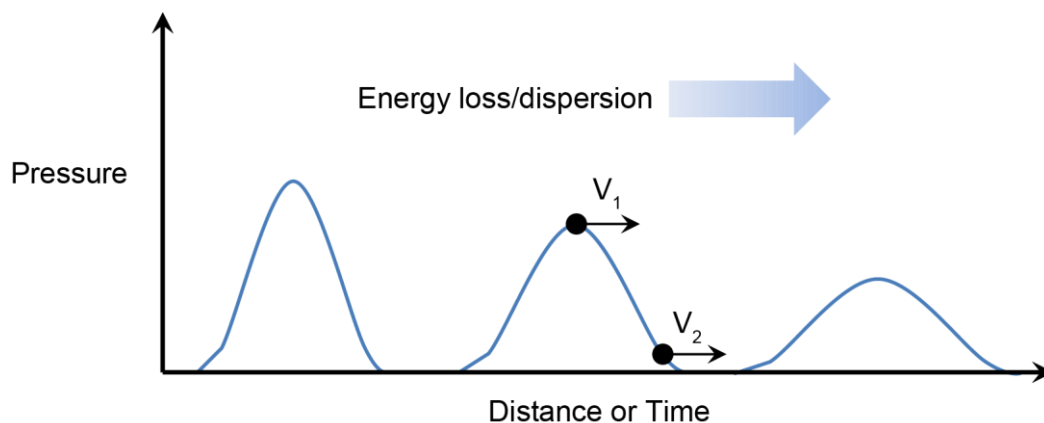


Figure 7-12 Schematic illustration of a stress wave (velocities at higher pressure portions of the wave are less than those at lower pressure portions, e.g. $v_1 < v_2$)

7.3.2.2 Shockwaves

Unlike stress waves, shockwaves are not dispersive. When materials are either loaded at a very high pressure or rapidly loaded (e.g. a high strain-rate) there is insufficient time for momentum to be transmitted away from the point of loading. Consequently, material momentum is entirely confined along the direction of loading with the material said to be 'inertially confined'. Under such circumstances, for example where an explosive is detonated on the surface of a piece of metal, a shockwave will be established, with higher pressure portions of the wave initially moving more rapidly until a discrete front is established as shown in Figure 7-13.

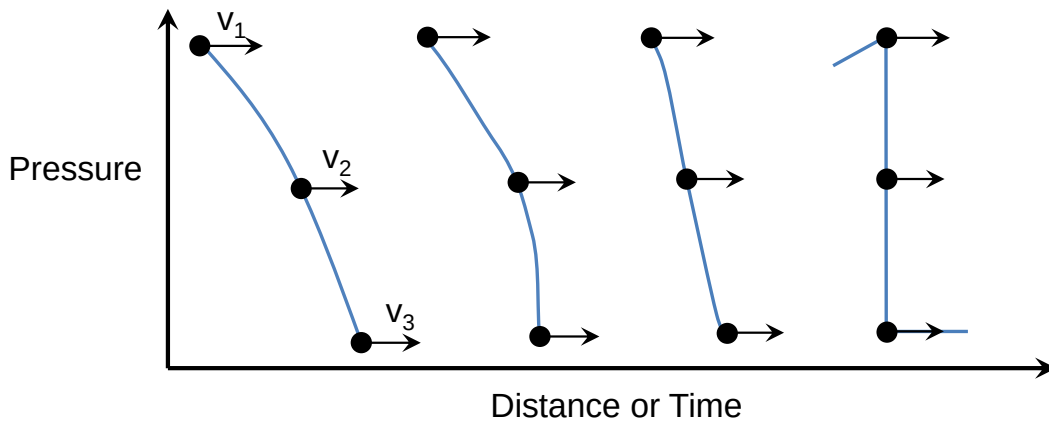


Figure 7-13 Schematic illustration of the formation of a shock wave (velocities at higher pressure portions of the wave are faster than those at lower pressure portions, e.g. $v_1 > v_2 > v_3$)

As a vertical front, a shockwave represents a sudden change from one set of state variables (temperature, pressure, etc.) to another. Such behaviour, while initially slightly counter intuitive, is, in reality, relatively common-place. The reader will be familiar with the concept of a shockwave in air, e.g. as an aircraft breaks the speed of sound at a given altitude. This example provides insight into some key areas associated with shock physics namely:

1. A shock is only formed when the aircraft is moving faster than the speed of sound in the medium (air) through which it is propagating. In this circumstance the system is said to be 'overdriven', and
2. The speed of sound in air changes with altitude. This is primarily due to the change in air density with altitude, a concept which applies more generally for both shock and detonation waves, where velocities are faster in denser systems.

Addressing the points highlighted above, in solid material, longitudinal elastic sound speed (c_L) is a function of density (ρ) and Young's modulus (E) and may be calculated from Equation (7-3).

$$c_L = \sqrt{\frac{E}{\rho}} \quad (7-3)$$

In turn, the bulk sound speed (c_0) in a material is related to c_L and the shear wave speed (c_s), which is always $< c_L$, by Equation (7-4).

$$c_0^2 = c_L^2 - c_s^2 \quad (7-4)$$

Consequently, it is immediately apparent from Equation (7-3) that supported sound speeds will be lower in lower density materials. As well as density, often referred to as specific volume (v) where $v = 1/\rho$, there are four additional

variables which define a shock. These are the velocity of the front itself, U_s , the velocity of the continuum elements (particles) which propagate the shock, u_p (with $u_p < U_s$), the amplitude of the pressure / stress established by the shock (P / s) and the change in material internal energy which results from the passage of the shock, E . Relationships between any of these two variables, when combined with application of the laws of conservation of mass, energy and momentum across the shock front, are sufficient to define the entire set of unknowns. Such relationships are known as Hugoniot equations-of-state.

7.3.2.2.1 Equations-of-state

Typical examples of such equation-of-states are presented in the Pressure-volume plane in Figure 7-14, where data from the literature for a variety of low density materials including the polymeric material Sylgard^{®(1)}.

Figure 7-14 shows both experimental data-points and a best-fit to the data following Equation (7-5) which is based on the conservation of momentum across a shock front, where the subscripts '0' and '1' refer to initial and final material states respectively.

$$P_1 - P_0 = \rho_0 U_s u_p \quad (7-5)$$

From the curves presented in Figure 7-14 it can be seen that as the material is compressed, as expected, pressure increases. However, it should be emphasised that the hydrodynamic (fluid-like/ P) curves fitted to this data do not represent a continuum. In line with the fact that a shock, by definition, represents a sudden and discrete change in state variables, a Hugoniot curve of the type shown in Figure 7-14 simply represents a loci of physically accessible end states from a given initial state (typically for the Hugoniot curve 'ambient' conditions). Consequently, if a change in initial state variables should occur (e.g. a change in initial environmental conditions, a phase change such as the reaction of an explosive during the detonation process or initial mechanical pre-loading, etc.), then use of a new equation-of-state may be required centred on this new initial state. Such a situation is illustrated in Figure 7-15 for the situation where an impacted material is loaded for a second time.

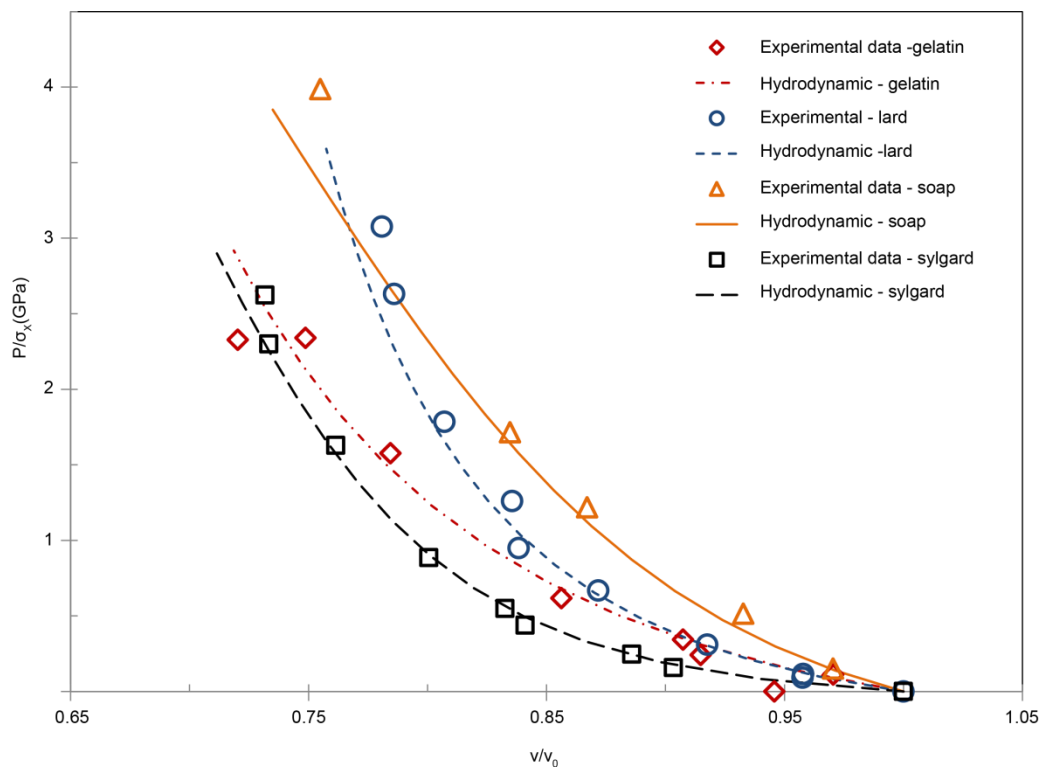


Figure 7-14 Hugoniot equations-of-state in the P-v plane for a selection of low density materials¹

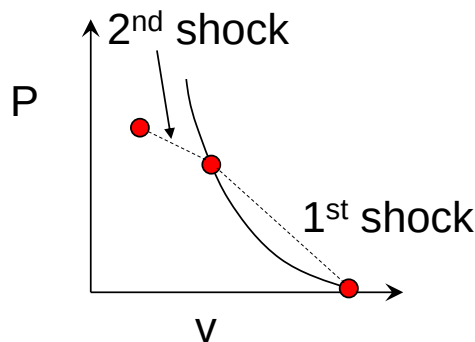


Figure 7-15 Schematic illustration of the effects of a second loading event on a pre-shocked material (Hugoniot centred on the initial ground state shown as a solid black curve)

7.3.2.2.2 Generic equations-of-state

Use of multiple equations-of-state to describe complex loading events would be impractical, primarily due to the cost (both temporally and fiscally) in terms of the resultant requirement to derive new equations-of-state centred on every potential loading scenario which could lead to the final loaded state. To this end, generic forms of the equation-of-state are often employed which allow

prediction of multiple loading paths without explicit knowledge of equation-of-state curves centred on every possible loading eventuality. A useful semi-empirical form for material equations-of-state is the Mie-Grüneisen form as shown in Equation (7-6).

$$P(v, e) = P_0(v) + \frac{\Gamma(v, e)}{v} [e - e_0(v)] \quad (7-6)$$

$P(v, e)$ represents the pressure at a given volume v / internal energy e ; Γ is a value known as Grüneisen gamma which is linked to key thermodynamic properties, and; the system starts at the initial state described by the subscript '0'.

Equation (7-6) essentially describes an equation-of-state surface in the Pressure-Volume-Energy plane, with Γ controlling the curvature of the resultant surface. As an example, an equation-of-state surface calculated using Equation (7-6) for the epoxy resin RTM6 is shown in Figure 7-16. As illustrated in this figure, the Hugoniot equation-of-state describes one allowed curve across this permissible (shock phase-space) surface. Such a generic equation-of-state would therefore allow the calculation of material end-state following multiple loading events, subject to the caveat that no change in state (phase change or similar) occurs.

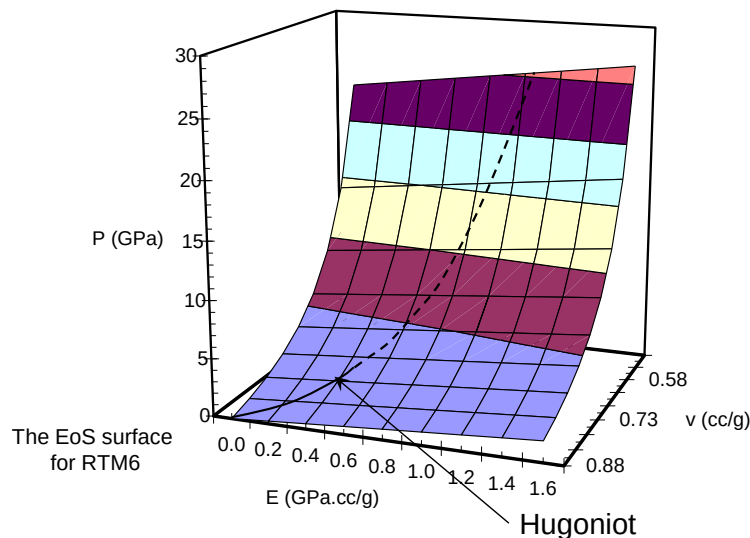


Figure 7-16 Generic equation-of-state surface for RTM6⁽²⁾ (Γ assumed equal to unity)

7.3.2.3 Impedance and shock wave reflection (scabbing / spall)

When a stress of shock wave encounters an interface, the nature of the subsequent transmitted and reflected waves is a function of the properties of the materials either side of the interface. Wave interaction is governed by a property known as impedance (Z), defined in Equation (7-7). Where ρ_0 is the initial material density and U_s the shock speed under given loading conditions.

$$Z = \rho_0 U_s \quad (7-7)$$

However, in the event that the material is in the elastic regime, Z is termed acoustic impedance and $U_s \rightarrow c_L$ as defined in Section 7.3.2.2. In general, the use of acoustic impedance is sufficient to predict the nature of wave interaction across an interface. This allows for the following modification to be made to Equation (7-7).

$$Z = \rho_0 c_L = \rho_0 \sqrt{\frac{E}{\rho_0}} = \sqrt{\rho_0 E} \quad (7-8)$$

Knowledge of the impedance of different materials can subsequently be used to predict wave propagation across an interface from material A to material B via conservation of force (equilibrium) and particle velocity (continuity) across the interface (Equations (7-9) and (7-10) respectively).

$$\sigma_A + \sigma_B = \sigma_C \quad (7-9)$$

$$u_A - u_B = u_C \quad (7-10)$$

For a two-layer system as shown in Figure 7-17, such an approach leads to Equation (7-11) which, combined with the equilibrium and continuity equations, allows calculation of the transmitted stress across the interface.

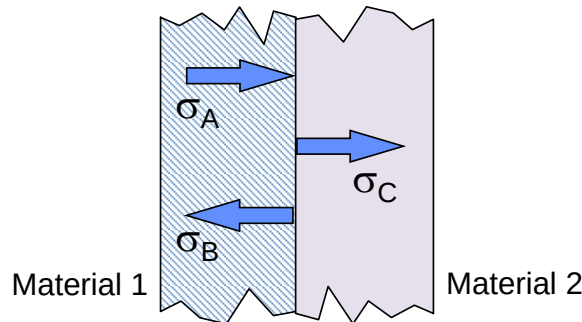


Figure 7-17 Schematic illustration of wave transmission/reflection at the boundary of two materials of differing impedance

$$\sigma_C = 2 \left[\frac{Z_2}{Z_2 + Z_1} \right] \sigma_A = 2 \left[\frac{\sqrt{\rho_2 E_2}}{\sqrt{\rho_2 E_2} + \sqrt{\rho_1 E_1}} \right] \sigma_A \quad (7-11)$$

From Equations (7-9) and (7-11), the effect of removing the rear-most material in Figure 7-17 (leading to an air or 'free' rear surface) is apparent. Essentially, E_2 and ρ_2 will $\rightarrow 0$, leading to a reflected stress wave, σ_B , with the opposite sign

and same magnitude as the originally incident wave. Assuming an initially compressive loading, such a reflection will therefore be tensile in nature. This phenomenon is exploited in the High Explosive Squashed Head (HESH) round. As illustrated schematically in Figure 7-18. This munition deposits and subsequently detonates an explosive charge on the surface of a target (e.g. armour plating on a vehicle); the resultant compressive wave reflects at the rear surface of the target as a tensile wave, moving back into the target. Eventually, the material will enter a state of net tension. At this point, as materials are, in general, very-much stronger in compression than tension, the target will fail under dynamic tensile loading and a plate of material (a 'scab') will spall / separate, moving away in the direction of the initial compressive loading.

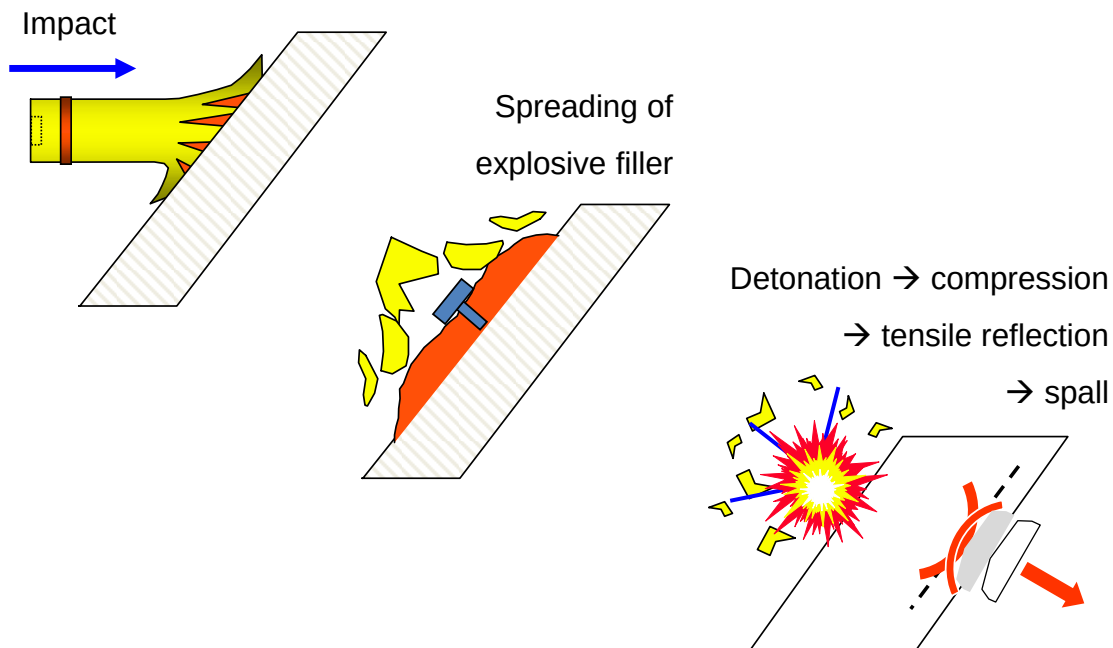


Figure 7-18 Schematic illustration of the operational stages of attack by a HESH round on armour

7.3.3 Detonation Physics

7.3.3.1 Detonation waves

Detonation consists of the passage of a shock wave through an explosive supported by the energy released by chemical reactions. As the detonation wave passes through an explosive there exist three core zones, with these highlighted for a one-dimensional case in Figure 7-19, namely: (1) un-reacted material ahead of the detonation wave; (2) a reaction zone where chemical reaction occurs, releasing the energy which supports the detonation, and; (3) a zone behind the reaction zone containing the resultant gaseous products at elevated pressure and temperature which provides useful work. This expanded region of gas is known as the Taylor release wave. The detonation / shock front

itself exists at the border of the reaction zone and the un-reacted material; however this is infinitesimally small and consequently neglected here.

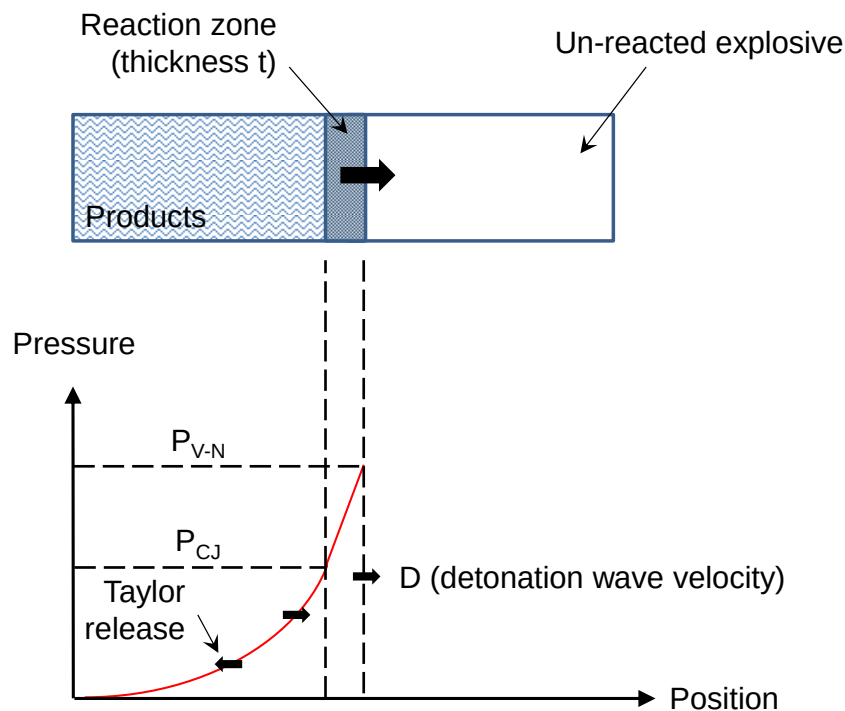


Figure 7-19 Detonation wave propagating into un-reacted explosive (scale of reaction zone exaggerated for clarity)

Figure 7-19 also highlights the waveform which results from the detonation process, generally known as a Taylor wave (although strictly, this term refers to the release portion of the wave behind the detonation front only). It comprises several key features, namely:

- A spike to a peak, known as the von-Neumann pressure P_{V-N} , at the interface between the reaction zone and the un-reacted explosive (e.g. at the shock / detonation front). This peak rapidly decays behind the front (the scale of the reaction zone is exaggerated in Figure 7-19 for clarity).
- A lower pressure, known as the Chapman-Jouguet (CJ) pressure – P_{CJ} , representing the pressure at the interface between the reacted and un-reacted explosive.
- An exponential-like drop-off in pressure behind the reaction zone caused by the change in chemistry of the detonation products. Essentially, as the detonation wave is now un-supported it is released back down the isentrope along a Taylor wave from the CJ pressure back to the ambient conditions for the detonation products.

As detailed in Figure 7-19, the detonation reaction is finished at a point corresponding to the CJ pressure. This interface between the reaction zone and the detonation products, known as the Chapman-Jouguet interface, must be moving at the same rate as the main detonation front if the process is to be

considered stead-state, thereby maintaining a constant reaction zone thickness. In practice, as shown in Equation (7-12), the velocity of the reaction zone relative to the un-reacted explosive (e.g. the detonation velocity, D), is simply the sum of the sound (shock) speed (C) within the compressed gas found at the CJ interface and the particle velocity across the CJ interface (u_{p-CJ}).

$$D = C + u_{p-CJ} \quad (7-12)$$

Usefully, the structures highlighted in the wave-form presented in Figure 7-19 can be related back to the Hugoniot equations-of-state for the explosive. Unlike inert materials, because a change in phase occurs as detonation breaks out two separate equations-of-state are required to fully describe an explosive. These separate equations-of-state are those for the un-reacted explosive and the detonation products respectively. Usefully, the various features present on the detonation wave in Figure 7-19, such as the von-Neumann pressure, can be resolved from these two characteristic equation-of-state curves. This is illustrated in Figure 7-20.

Particular features apparent in Figure 7-20 are as follows:

- The Hugoniot curve for the detonation products lies above that of the unreacted material, e.g. the detonation products have a lower density than the unreacted material (it is this expansion which allows for useful work).
- The gradient of a Hugoniot curve is a function of wave velocity; in order for the detonation wave detailed in Figure 7-19 to move at a constant velocity, the rate of propagation of the reaction zone behind the front must be equal to that of the detonation front itself. Consequently, the Rayleigh line followed by the reacting explosive must lie on a tangent to the detonation production Hugoniot curve through the initial volume (v_0); a steeper curve would cause the detonation wave to be caught via the reaction zone, whereas a less-steep tangent would lead to dispersion of the detonation front, both non-physical options for steady-state detonation.
- Such a tangent to the detonation products Hugoniot curve through the initial volume (v_0) intercepts the detonation products Hugoniot at the Chapman-Jouguet pressure and the unreacted explosive Hugoniot at the von-Neumann pressure.
- The gradient of the aforementioned tangent is $(\rho_0 D)^2$; consequently, knowledge of the initial volume and Hugoniot curves for both reacted and unreacted explosive allows calculation of the detonation velocity e.g. in Figure 7-20, taking $\rho_0 = 1.6 \text{ g cm}^{-3}$, $D = 7.6 \times 10^3 \text{ m s}^{-1}$.

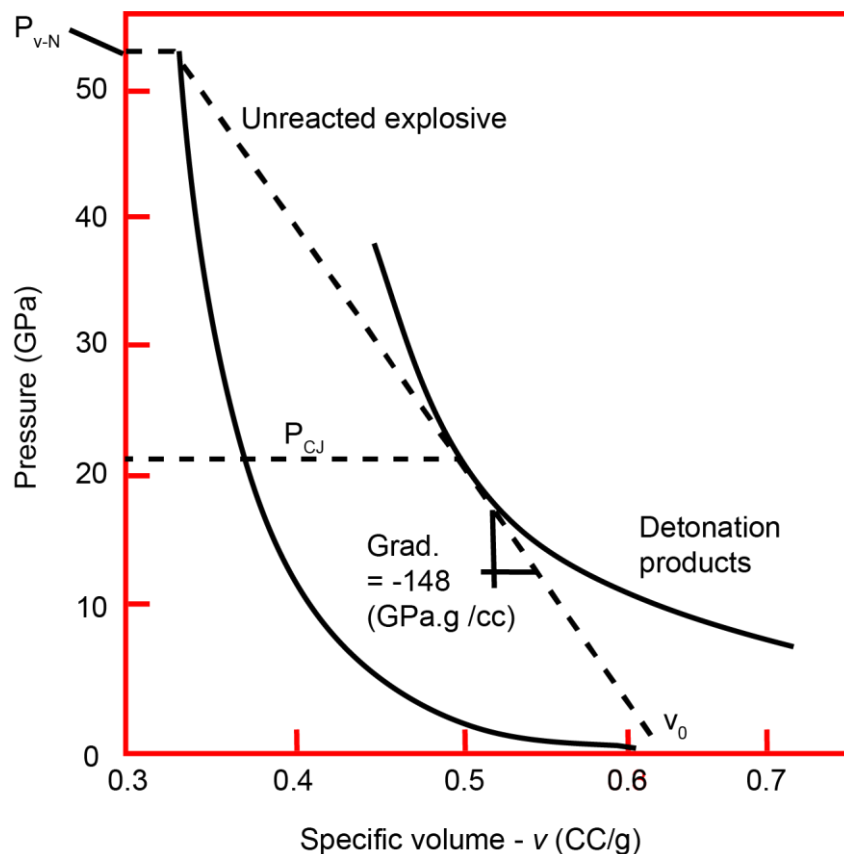


Figure 7-20 Illustration of the relationship in the P-v plane for equations-of-state of un-reacted explosive and resultant detonation products⁽³⁾

7.3.3.2 Equations-of-state – energetic materials

As discussed in Section 7.3.2.2, conservation of mass, energy and momentum across the shock front allow description of a shocked system. The same continuity equations apply for an explosive, however, additional account needs to be made of key thermodynamic factors. Further, as the system is reacting, in line with the description set out in Figure 7-20, to form an equation-of-state which allows prediction of key state variables, Hugoniot relationships are required for both the un-reacted explosive and the resultant detonation products. Several different approaches exist with regards to prediction of the detonation behaviour of an explosive. If the chemistry of the products is treated explicitly, the final-state equation-of-state may be calculated from a weighted combination of the individual product / component equations-of-state (e.g. application of a 'rule-of-mixtures' approach). Such chemical equilibrium based approaches are implemented in a number of thermochemical / hydrodynamic computational codes, in particular the Fortran BKW implementation utilised, for example, in the CHEETAH code⁽⁴⁾.

Alternatively, an explicit equation-of-state will be required. Semi- and fully-empirical forms of the equation-of-state for explosive systems / products are relatively commonly employed. The disadvantage of such approaches is that

they require the use of experimentally measured constants for specific explosive compositions, for example, constants derived for a given composition with a given initial pressed density, rather than necessarily being based upon underlying physical principles, something which would allow scaling to different compositions. Forms of the equation-of-state employed for energetic materials range from versions based on the Ideal gas law through to purely empirical forms for detonation products where constants have typically been experimentally measured for given common explosives. Typical equations-of-state adopted by the shock / explosives community include the thermal relation-based Kuznetsov-Shedov equation focused on RDX and the more general semi-empirical Brinkley-Kistiakowsky-Wilson (BKW) relation, which accounts for the molecular weight of detonation products. A further example of such an approach is widely employed the Jones-Wilkins-Lee (JWL) formulation.^(5, 6) This equation, which takes the general form shown in Equation (7-13), with typical values for experimentally measured constants for a variety of different explosives presented in Table 7-1, allows prediction of behaviour (in particular the expansion isentrope) from CJ state parameters.

$$P = Ae^{-R_1 \frac{v}{v_0}} + Be^{-R_2 \frac{v}{v_0}} + C \left[\frac{v}{v_0} \right]^{-[1+\omega]} \quad (7-13)$$

Table 7-1 Typical JWL equation-of-state constants for selected explosive compositions (Table / data from Ref.⁽⁶⁾)

Explosive composition	CJ parameters			JWL parameters					
	ρ_0 (g/cc)	P_{CJ} (GPa)	D (mm/ μ s)	A (GPa)	B (GPa)	C (GPa)	R_1	R_2	ω
Composition B	1.717	29.5	7.98	524.2	7.678	1.082	4.20	1.10	0.34
HMX	1.891	42.0	9.11	778.3	7.071	0.643	4.20	1.00	0.30
PETN	0.880	6.2	5.17	348.6	11.29	0.941	7.00	2.00	0.24
TNT	1.630	21.0	6.93	371.2	3.231	1.045	4.15	0.95	0.30

Essentially, Equation (7-13) acts as the reference pressure, $P_0(v)$, in a Mie-Grüneisen description of both un-reacted and detonation products, in line with Equation (7-6). With such a formulation, Γ is typically assumed to be constant in value for simplicity⁽⁵⁾.

7.3.3.3 Effects of charge diameter

Detonation in a given explosive has been shown to only be supported once the diameter of a charge exceeds a given critical size. Further, detonation velocity is found to vary with charge diameters for lower diameter values, with a constant velocity only obtained once the charge becomes sufficiently wide that it

may be considered semi-infinite in scale (e.g. the outer edges of the charge have no influence on the central detonation region). This phenomenon has been linked to the thickness of the reaction zone (Figure 7-19), with the behaviour of explosives with thinner reaction zones showing less dependence on charge diameter. The general form for the relationship between charge diameter and detonation velocity is shown in Figure 7-21.

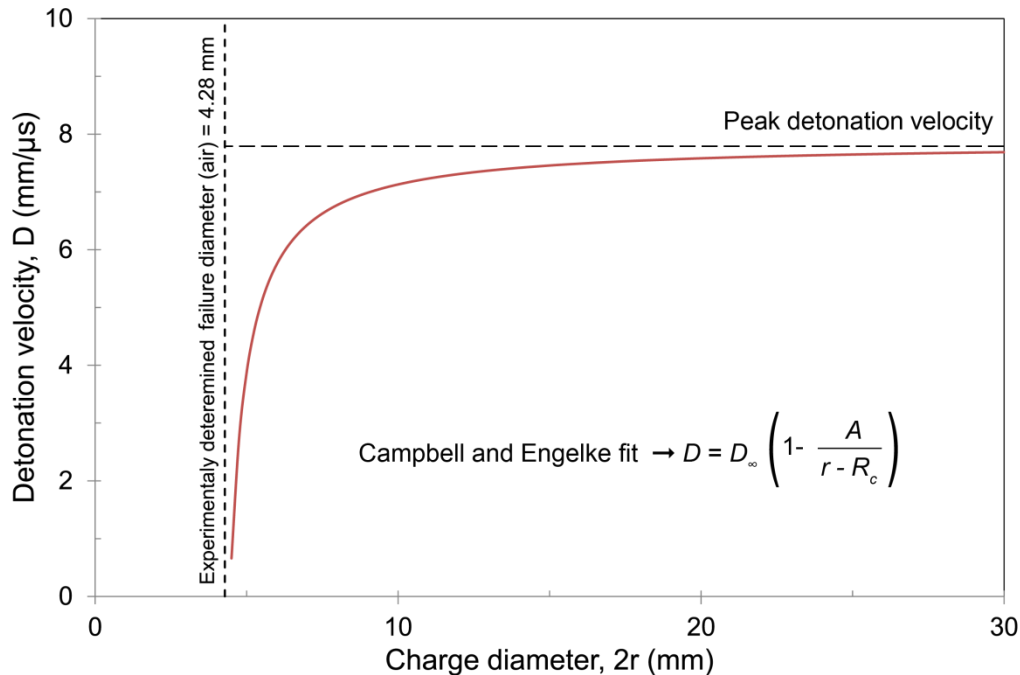


Figure 7-21 Variation of explosive detonation velocity with charge diameter (2r) for Composition B, based on Campbell and Engelke fit data⁽⁶⁾

Several features are apparent in Figure 7-21 including:

- At higher charge diameters the detonation velocity can be observed to asymptote towards a constant / peak value.
- At lower charge diameters an exponential drop-off in detonation velocity is observed, with a critical diameter below which detonation cannot be sustained.

7.3.3.4 Hot spots

In solid polycrystalline explosives, detonation has been strongly linked to the presence of regions within the material where shock loading can lead to significantly elevated local heating. These hot-spot (see 5.3) regions are thus considered the likely source for initiation of the detonation process, with hot-spot density therefore of key import in terms of explosive sensitivity (see Section 7.3.4). Six key mechanisms which can lead to such localised heating under shock loading / compression have been identified and are detailed below^(3, 7):

1. Jetting of explosive material between the explosive's grains

2. Collapse of pores (with high temperatures reached when the collapsing inner walls of the voids collide)
3. Viscous heating, e.g. due to plastic material flow around pores
4. Localised shock ring-up due to the presence of higher-impedance particles / inclusions
5. Frictional heating due to differential particle flow
6. Formation of adiabatic shear bands (a plastic failure mechanism which leads to significant localised heating).

7.3.4 Effects of Pressure – POP (Popolato) Plots

For a heterogeneous explosive where hot-spot formation is crucial to detonation, pressure has been observed to play a key role in sensitivity to initiation. This is illustrated in Figure 7-22 which shows the variation with pressure of the distance required before detonation breaks out for three different varieties of PETN. Several key points may be drawn from this POP plot:

- In general, run-to-detonation distance, assuming that the charge diameter is greater than the critical diameter, decreases as pressure increases. Factors influencing this behaviour include the associated higher temperatures achieved at higher pressures, which would inevitably lead to faster (shorter distance) reaction times.
- Higher density explosives are observed to require a greater pressure to obtain a given run-to-detonation distance. This is due to two effects: (1) higher density materials (e.g. those that have been pressed / compacted) will likely exhibit a lower number of pores or similar regions where hot-spot formation could potentially lead to initiation, and (2) lower pore sizes / volume fractions (due to pre-compression) will lead to lower peak temperatures on material collapse, thereby further reducing the probability of initiation / increasing the distance of sustained shock loading required for detonation to break-out.

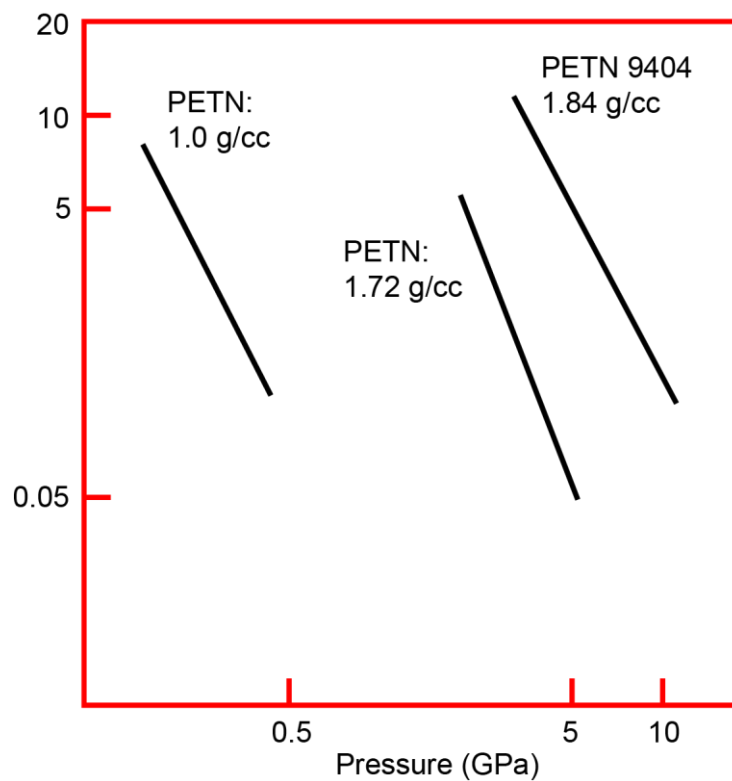


Figure 7-22 Pressure vs Distance to Initiation (POP) plot for three forms of PETN⁽³⁾

An additional observation from is that, in general, a loading pulse should have a long enough duration to subsequently span a spatial extent equal to or greater than the run-to-detonation distance if initiation is to be ensured.

7.3.5 Effect of Detonator Strength

Choice of detonator is of key importance in terms of an explosive train. In line with the observation at the end of Section 7.3.4, the loading pulse generated by a detonator needs to have sufficient temporal / spatial duration, as well as pressure, to allow detonation to break out. This is illustrated more clearly in Figure 7-23, which illustrates the result of the impact of a 10-mm thick SintoxTM flyer plate on to an explosive target containing a series of wire-element gauges measuring particle velocity (u_p) (see 7.3.2.2) in a plate-impact configuration⁽³⁾. The input pulse (in blue) is observed to have a square shape whose duration corresponds to a combination of the flyer plate thickness and impact velocity. The measured particle velocities are seen to rapidly ramp-up as the shock propagates through the explosive, indicative of a change in chemistry as detonation begins to break-out.

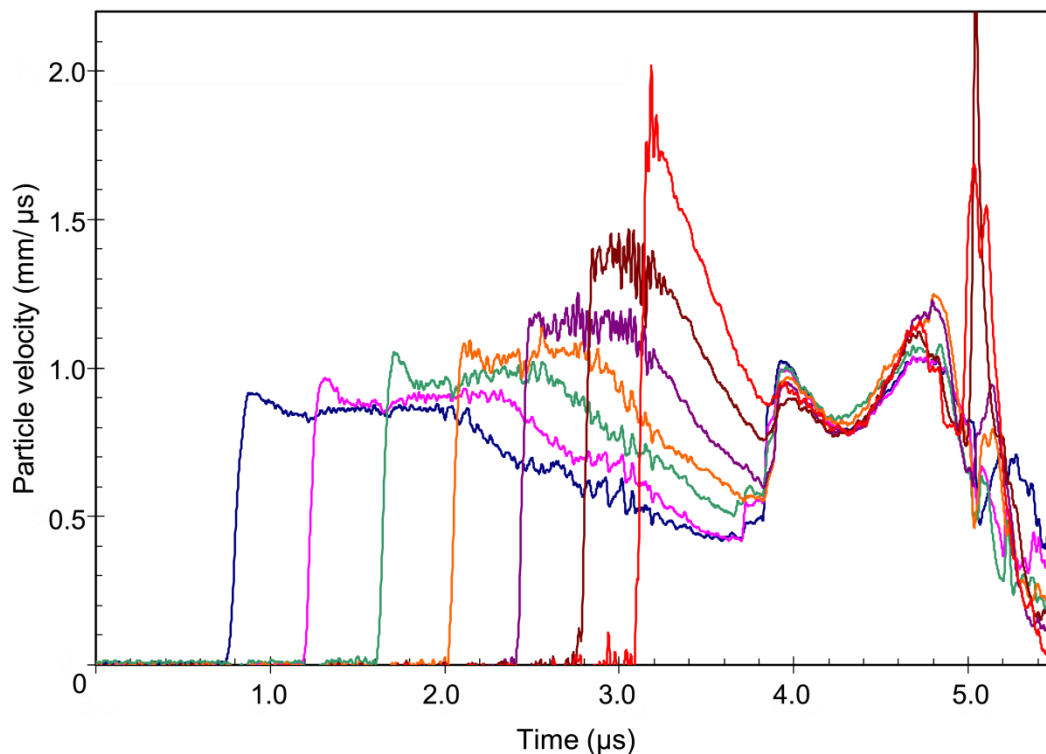


Figure 7-23 Particle-velocity traces at various depths showing the results of the impact of a 10-mm thick Sintox™ flyer plate generating an initial 5.1 ± 0.25 GPa stress in an explosive target⁽⁸⁾

In addition to pulse duration, the amplitude of the loading pulse also needs to be appropriate to the explosive in question. As an example of the importance of this issue, while precise details of the underlying physical causes are beyond the scope of this book, it is interesting to note that the detonation velocity of nitroglycerine is highly dependent on the method of initiation, ranging from $\sim 1,500$ to $7,700 \text{ m s}^{-1}$ ⁽⁹⁾.

7.4 WAVE SHAPING

Detonation fronts typically propagate hemispherically away from the point of initiation. However, in order to use an explosive to achieve useful work it is often desirable to modify the nature of the detonating front. Techniques to achieve this aim can either involve modification of the detonation front within the explosive charge (internal wave shaping), or once the front has left the charge (external wave shaping).

7.4.1 Internal Wave Shaping

A number of techniques exist to allow modification of the detonation front within the explosive charge itself. These range from exploitation of the different wave velocities inherent to different types of explosive to mechanical means.

7.4.2 Explosive Lenses

At the most basic level as a detonation wave crosses the interface between two explosives with different detonation velocities the wave-front will distort. This is illustrated in Figure 7-24 which illustrates a centrally-initiated hemispherically-fronted detonation wave propagating from an explosive (no. 1) with a slower inherent wave velocity to one (no. 2) with a faster inherent wave velocity. The wave-front is observed to accelerate as it crosses the boundary, leading to a greater degree of curvature once the wave has fully entered explosive no. 2.

For comparison, in Figure 7-25 an initially hemispherical wave-front propagates from an explosive with a high detonation velocity to one with a slower velocity. The net effect is a constriction of the wave with the resultant formation of a nominally planar front. The system acts as a plane-wave generator.

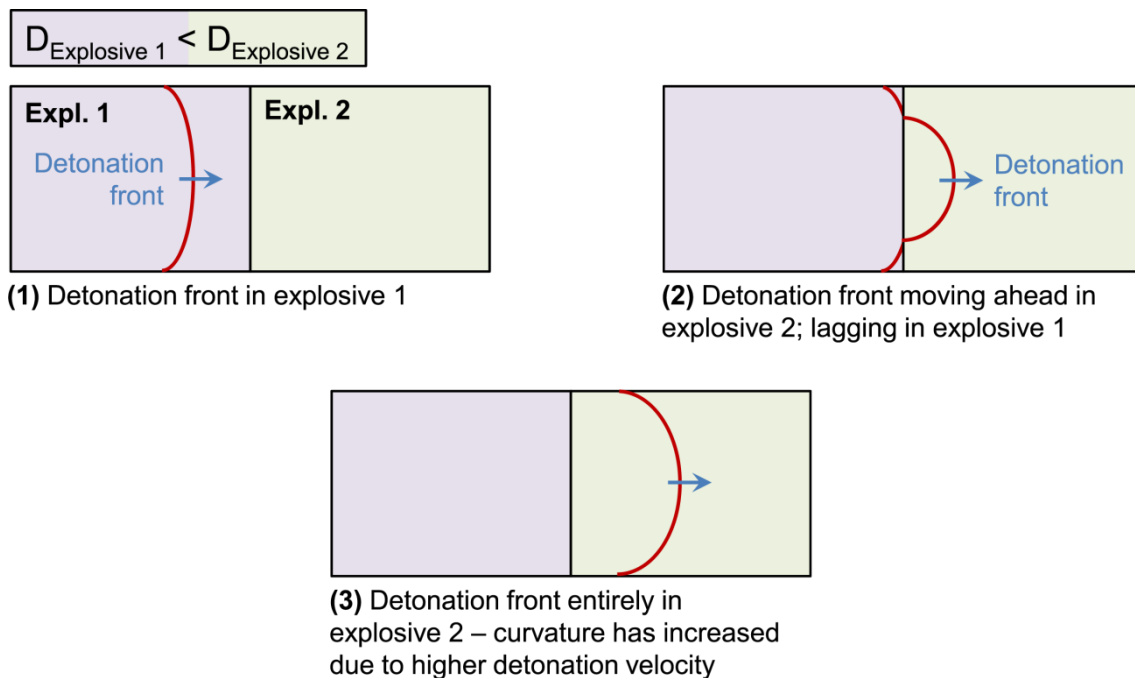


Figure 7-24 Schematic illustration of the propagation of a detonation wave across a planar interface from an explosive with a lower detonation velocity ($D_{\text{Explosive1}}$) into an explosive with a higher detonation velocity ($D_{\text{Explosive2}}$)

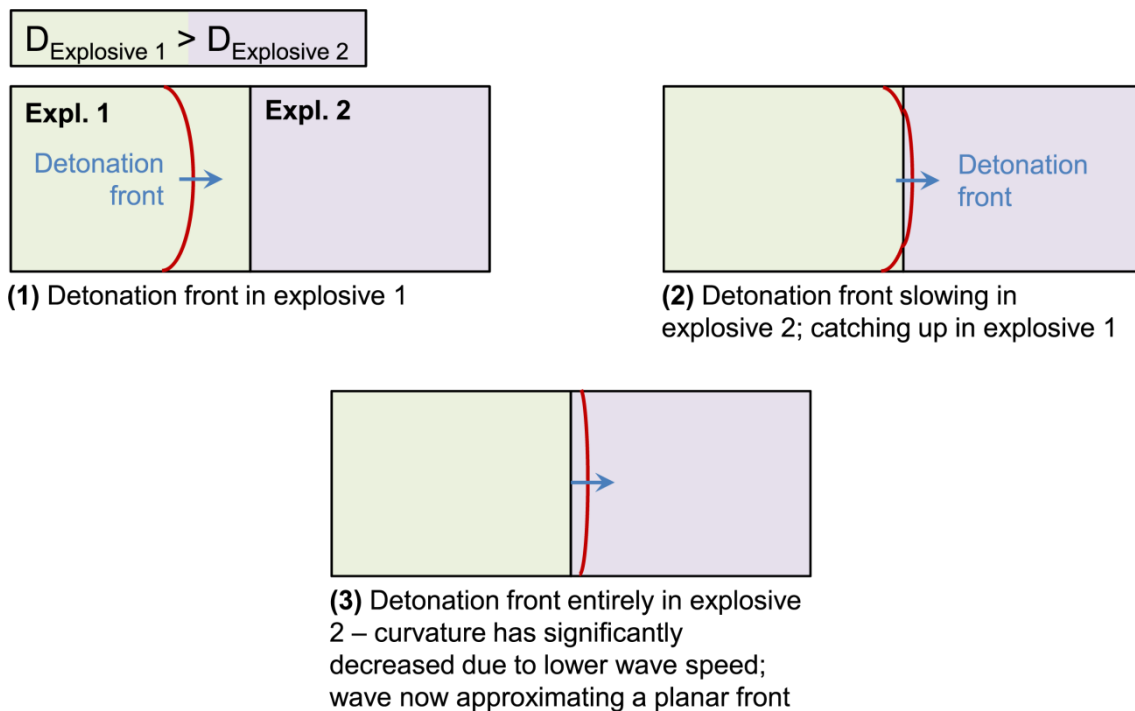


Figure 7-25 Schematic illustration of a ‘plane wave generator’ involving the propagation of a detonation wave across a planar interface from an explosive with a higher detonation velocity ($D_{\text{Explosive1}}$) into an explosive with a lower detonation velocity ($D_{\text{Explosive2}}$)

In addition to the influence of explosive detonation velocity, if the explosive interface has a non-planar form then additional effects can be obtained, potentially allowing for further refinement of the resultant wave shape. This is illustrated in Figure 7-26 for the case in which a hemispherical wave-front moves from an explosive supporting a high detonation velocity to one supporting a lower velocity consistent with Figure 7-25, although in this case with a curved rather than planar interface. In this case, the initially curved wave-front is modified both by a reduction in velocity and by the geometry of the interface, leading to the inversion of the curvature of the wave.

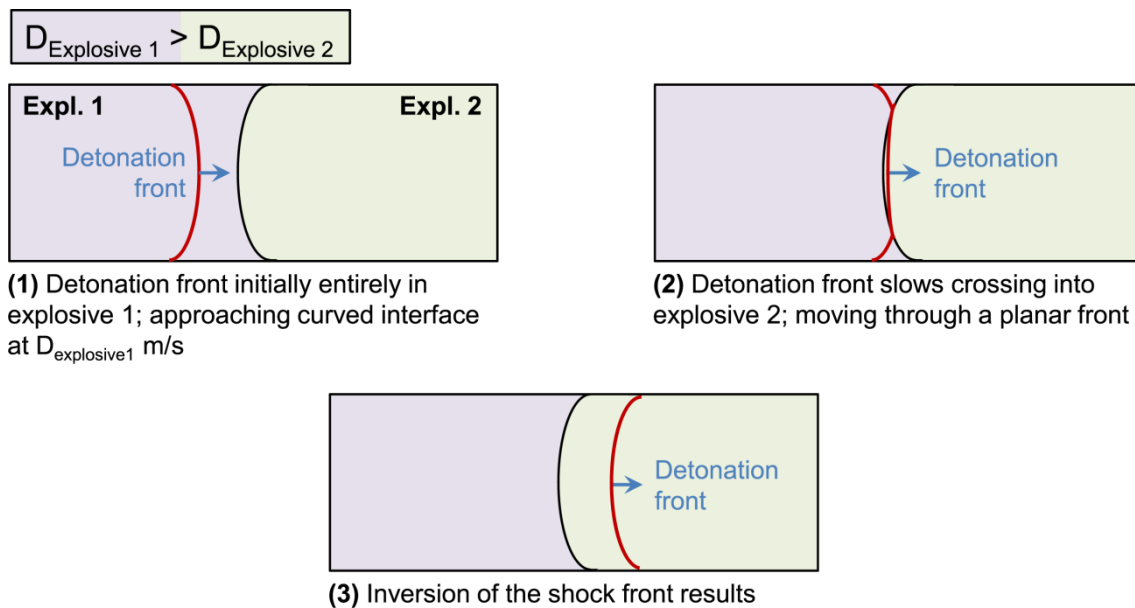


Figure 7-26 Schematic illustration of the propagation of a detonation wave across a curved interface from an explosive with a higher detonation velocity ($D_{\text{Explosive1}}$) into an explosive with a lower detonation velocity ($D_{\text{Explosive2}}$)

From the cases presented in Figure 7-24 to Figure 7-26, it can be seen that differing combinations of explosive (e.g. wave velocities) and interface geometries would therefore allow for the formation of complex, refined, wave front structures.

A classic example of such a construct is the implosion device as used in early nuclear weapons, in which a series of hemispherical detonation waves are created via an array of explosive structures, an arrangement known as an explosive lens, to allow simultaneous arrival at, and subsequent symmetric collapse of, a central spherical structure comprising fissile material. Such an arrangement is illustrated schematically in Figure 7-27.

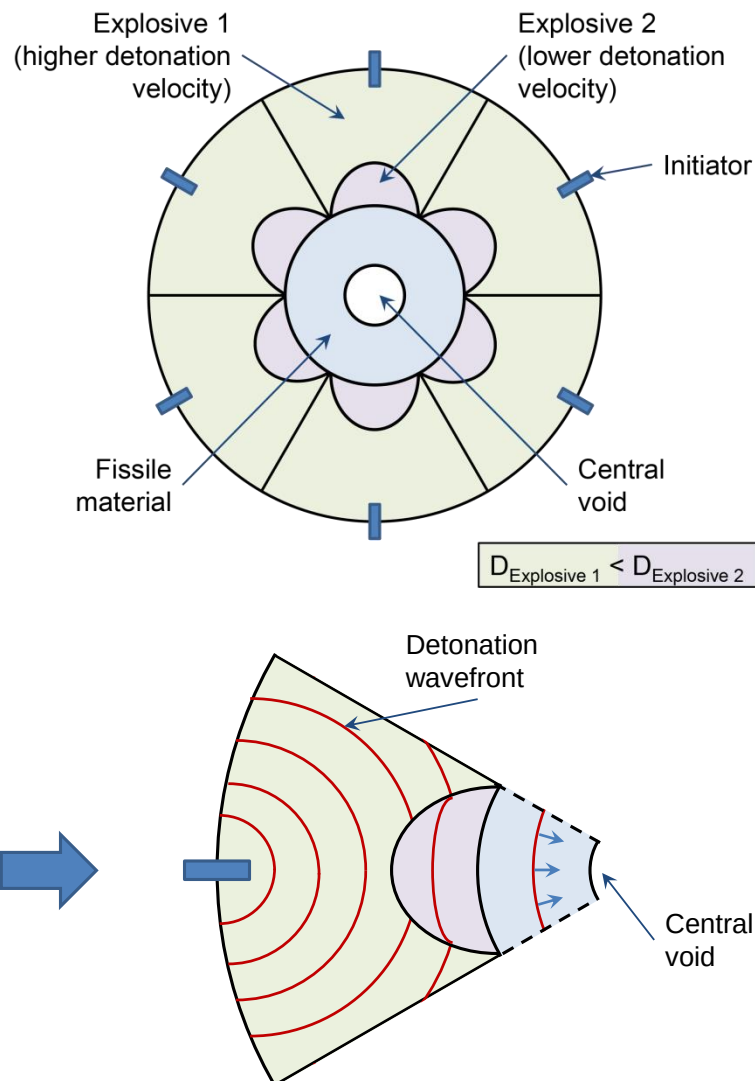


Figure 7-27 Schematic illustration of an implosion device

7.4.3 Wave Shapers

In addition to the use of differing explosives to control wave propagation, the form of a detonation front can also be modified via mechanical modification of the system. In particular, inclusion of a barrier of some description within an explosive construct will modify wave propagation. One application of such an approach lies with shaped charge warhead design (see 8.4.1). A typical shaped charge arrangement is shown in Figure 7-28. Essentially, at its most basic level, the device comprises a case containing an explosive head situated above a conical liner. On initiation from the rear of the explosive head the device is constructed such that the resultant detonation wave symmetrically loads the

liner leading to a symmetric collapse and formation of a shaped charge jet and accompanying slug of material.

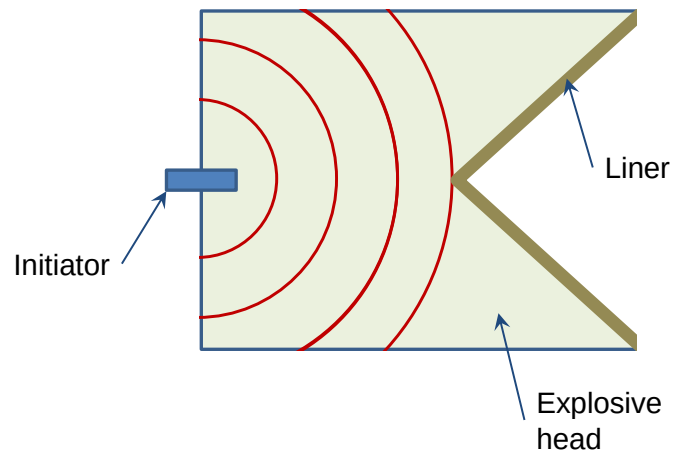


Figure 7-28 Diagram illustrating a cross-section through a typical shaped charge warhead arrangement (detonation waves emanating from the initiator indicated in red)

This arrangement can be further optimised by the inclusion of a device known as a 'wave shaper' within the explosive. The effect of such a device is illustrated in Figure 7-29, which allows for a more compact warhead. Hemispherical detonation waves are diffracted by the wave shaping insert while still ensuring simultaneous convergence of the front at radially opposite elements of the shaped charge liner.

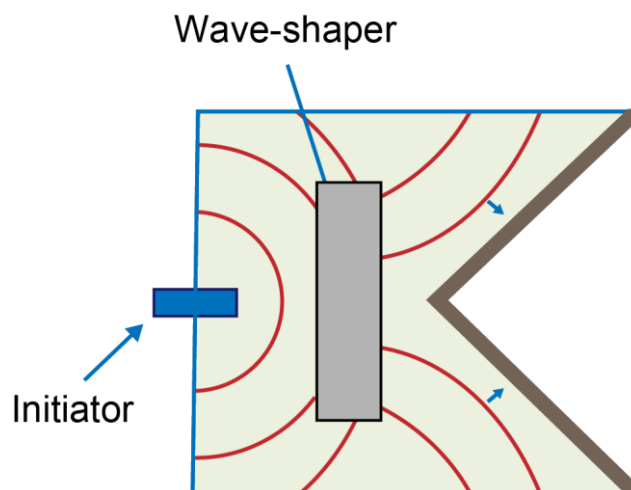


Figure 7-29 Diagram illustrating a cross-section through a shaped charge warhead arrangement containing a wave shaper / insert (detonation waves emanating from the initiator indicated in red)

Another example of a wave shaper is that of the explosive-metal 'air-lens'. This is essence a shaped charge-like device. However, it employs a dish rather than conical liner and, rather than generating a jet to attack a target, is instead designed to exploit the reduction in wave velocity which will occur as the detonation wave meets the metallic liner. Essentially, the detonation wave will collapse the liner across the air gap leading to a reduction in wave velocity at the far side. Suitable linear geometric / material combinations can thus be used to modify the initial pulse into a more useful form, e.g. in the case of Figure 7-30 a plane-wave.

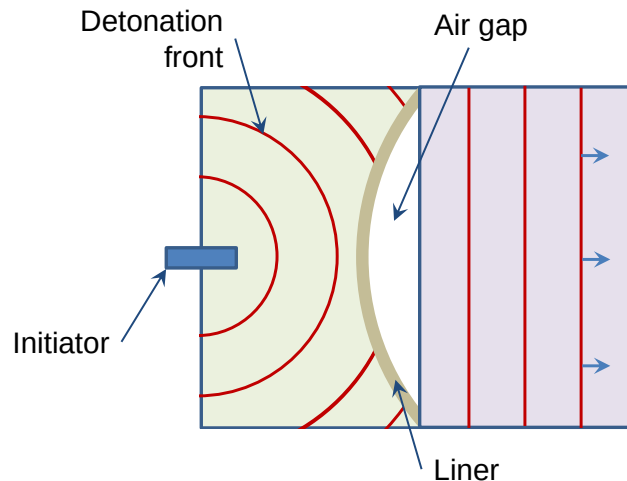


Figure 7-30 Illustration of an air-lens explosive metal wave shaper

7.4.4 Cored Charges

Approaches to modify detonation front shapes such as explosive lenses and wave shapers have a significant limitation in that in order to produce a desired output wave their construction is often complex and, consequently, expensive. One solution which allows formation of a quasi-planar wave is the cored charge. This construct, illustrated schematically in cross-section in Figure 7-31, comprises of a cylinder of explosive with a relatively low detonation velocity fitted into a surrounding bored-out larger diameter cylinder of higher detonation velocity explosive. Essentially, with such a device a hemispherically-fronted detonation wave will slow on entering the central lower wave velocity core, with outer elements of the wave then being able to catch-up / over-run the central elements. Consequently, careful design can allow the output at the far end of the device to correspond to a nominally planar front.

7.4.5 Surface (External) Wave Shaping

In an analogous manner to the way in which the internal wave shaping approaches discussed in Section 7.4.1 exploits differences in detonation velocity to modify propagating wave front geometries, it is possible to utilise the lower resultant velocity of a shock at an explosive / air boundary to create tailored wave front structures. The practical application of this effect, which

exploits the development of phenomena known as 'Mach disturbances', is illustrated schematically in

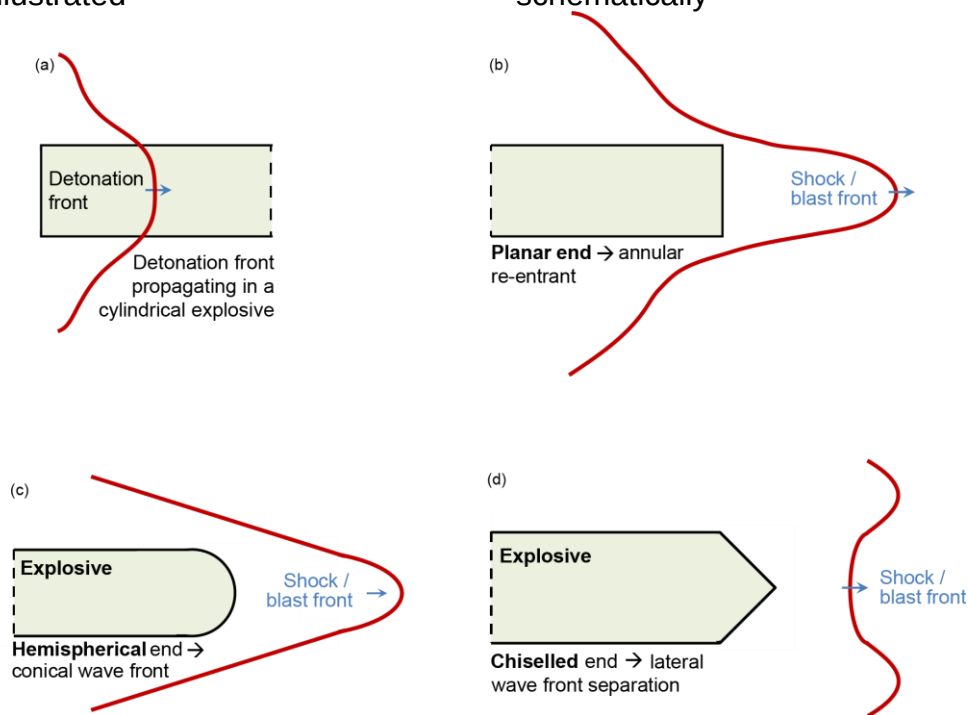


Figure 7-32. The hemispherical detonation front apparent in

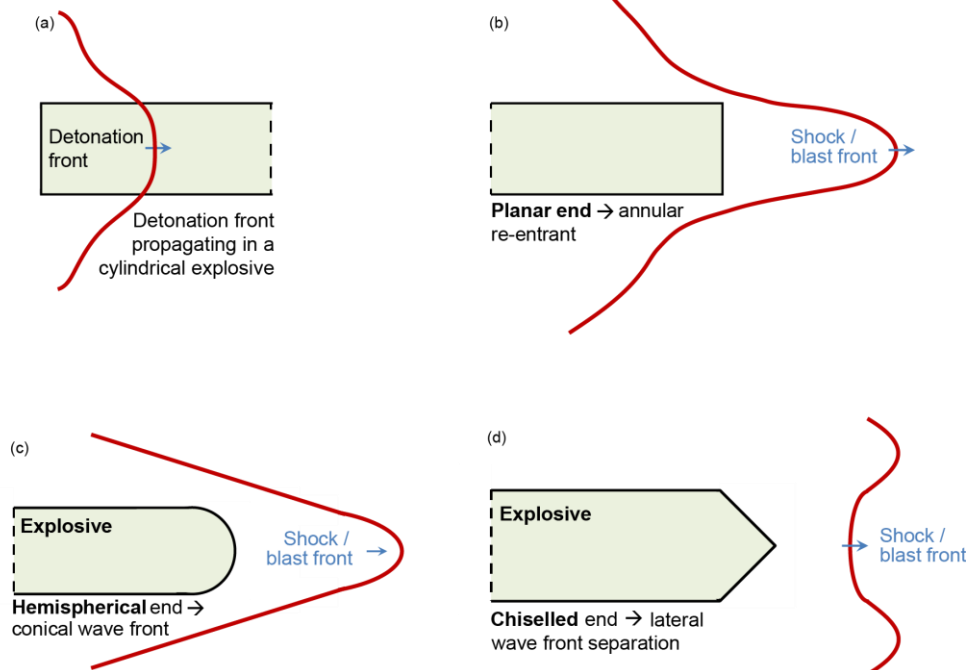
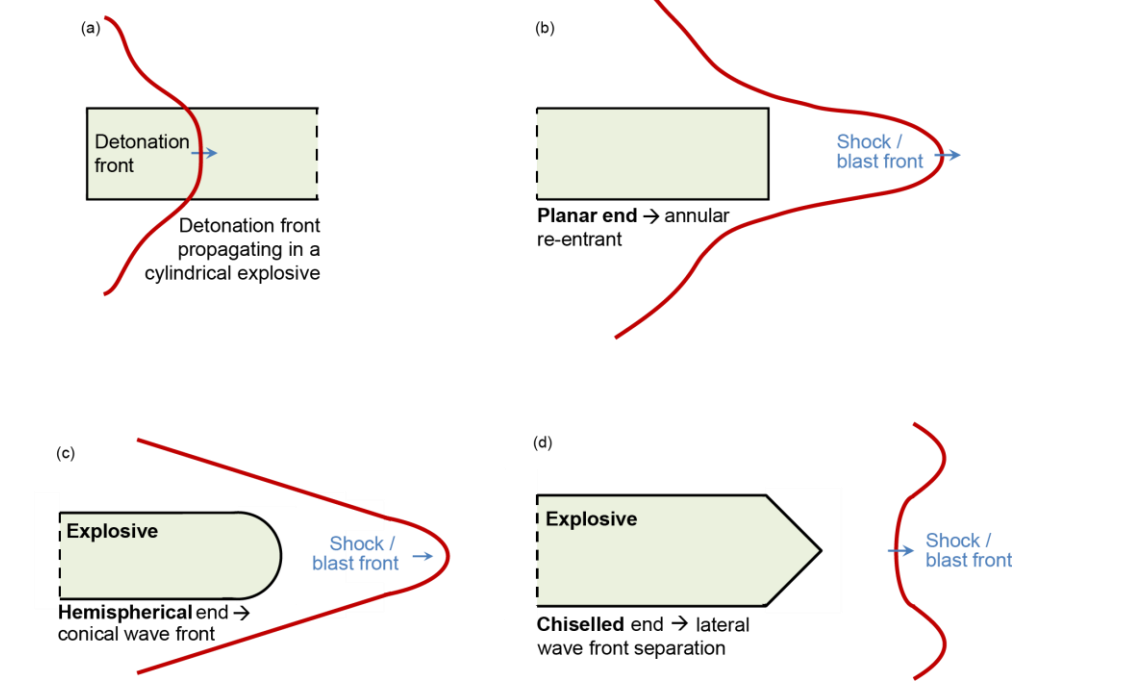


Figure 7-32(a) is modified to an annular form at the tip by a planar end section



in
Figure 7-32(b); whereas in

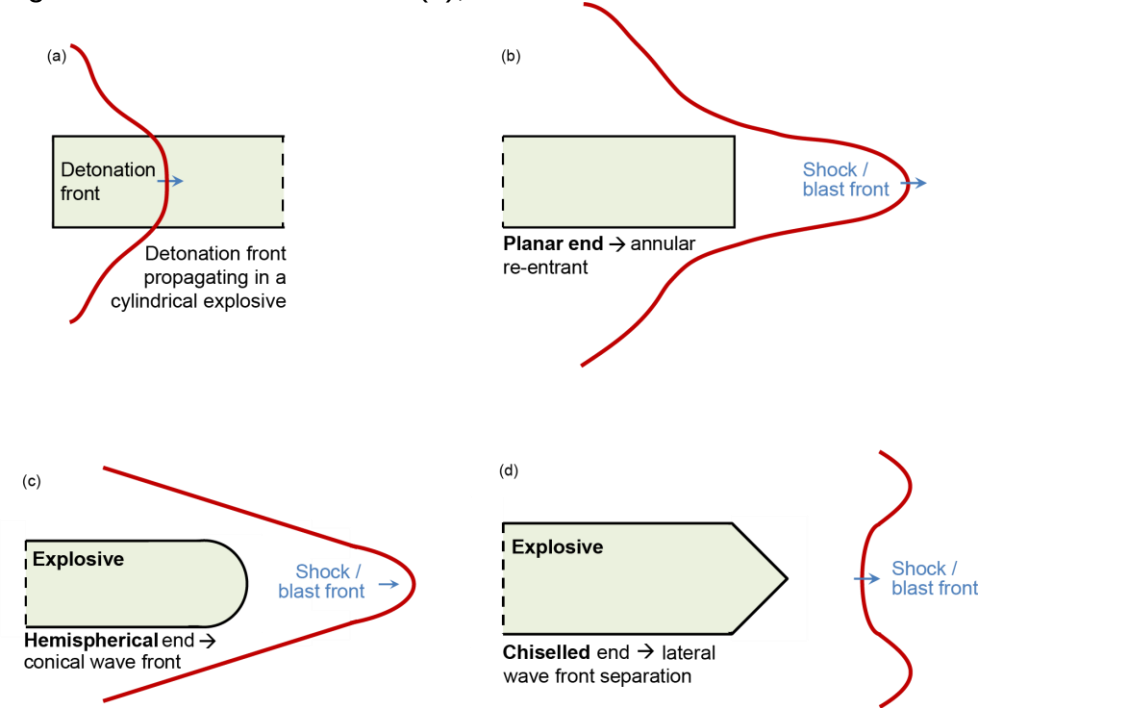


Figure 7-32(c) a hemispherical tip to the explosive leads to a conical shock / blast front, while in

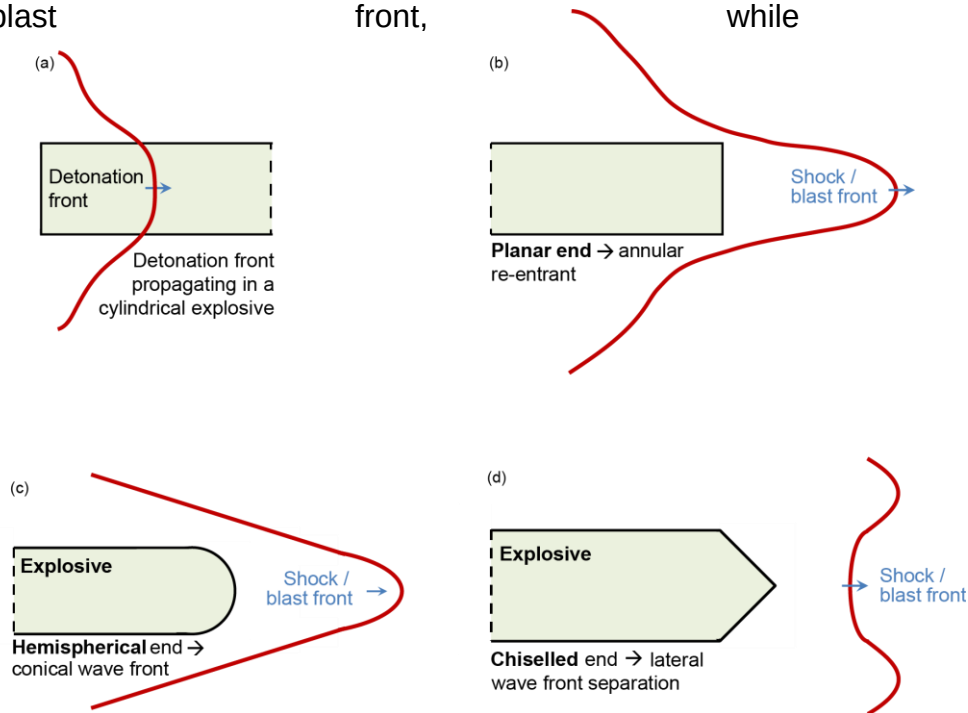


Figure 7-32(d) a wedge-shaped end section results in a laterally divergent front.

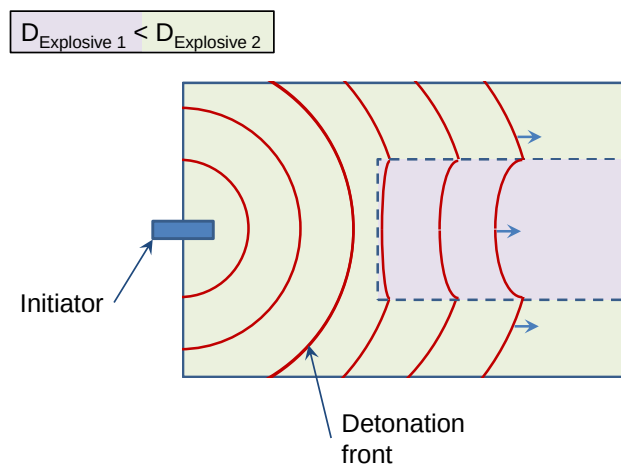


Figure 7-31 Cross-sectional illustration of a cored charge

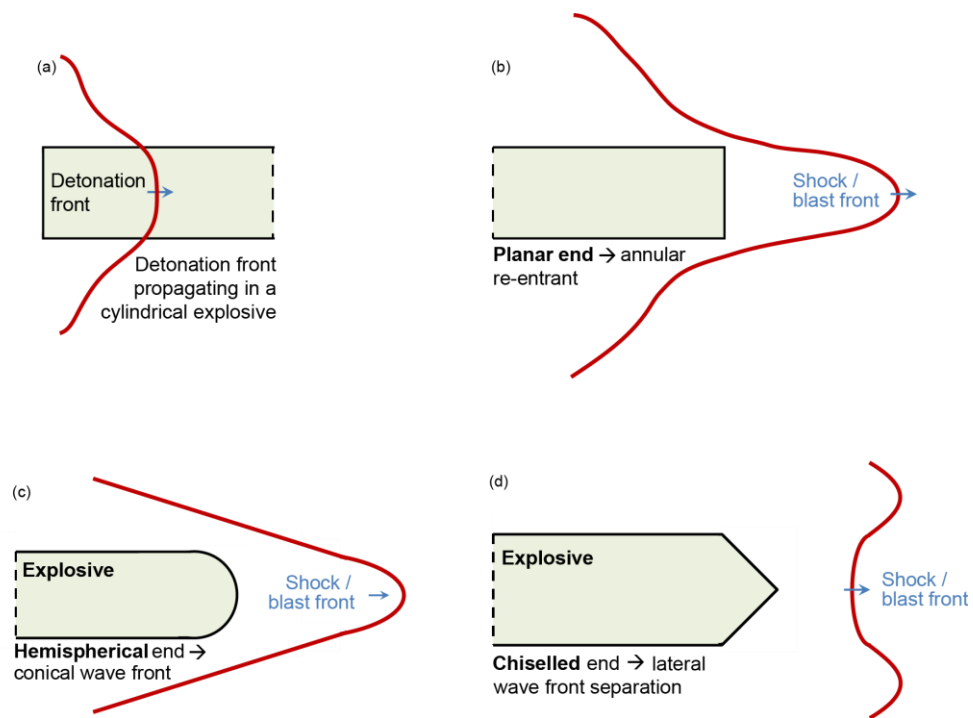


Figure 7-32 Schematic illustration of the effects of surface wave shaping (initially hemispherical detonation front in cylindrical explosive section exiting into air)

7.5 REFERENCES

- [1] W. Fickett, W. C. Davis, G. J. Appleby-Thomas, P. J. Hazell, R. P. Sheldon, C. Stennett, A. Hameed, J. M. Wilgeroth, *The high strain-rate behaviour of selected tissue analogues*, J. Mech. Behav. of Biomed. Mater., 2014, 33; 124-135
- [2] G. J. Appleby-Thomas, P. J. Hazell, C. Stennett, *The variation in lateral and longitudinal stress gauge response within an RTM 6 epoxy resin under one-dimensional shock loading*, J. Mater. Sci., 2009, 44 (22); 6187-6198
- [3] M. A. Meyers, *Dynamic Behaviour of Materials*, John Wiley & Sons, Inc., 1994 (ISBN 978-0-471-58262-5)
- [4] L. Fried, P. Souers, *CHEETAH: A Next Generation Thermomechanical Code*, Report UCRL-ID-117240, Lawrence Livermore National Laboratory, USA, 1994
- [5] G. I. Kanel, S. V. Radzorenov, V. E. Fortov, *Shock-Wave Phenomena and the Properties of Condensed Matter*, Springer, 2004 (ISBN 978-1-4757-4282-4)
- [6] J. A. Zukas, W. P. Walters, *Explosive Effects and Applications*, Springer, 1997 (ISBN 978-1-4612-0589-0)
- [7] N. Bourne, *Materials in Mechanical Extremes*, Cambridge University Press, 2013 (ISBN 978-1-1070-2375-8)
- [8] C. Stennett, G. A. Cooper, P. J. Hazell, G. Appleby-Thomas, *Initiation of secondary explosives measured using embedded electromagnetic gauges*, AIP Conf. Proc. 1195; 267, 2009
- [9] *Military Explosives*, Department of the Army Technical Manual TM 9-1300-214, US Army, 1987

BIBLIOGRAPHY

- 1) W. Fickett, W. C. Davis, *Detonation, Theory and Experiment*, Dover Publications Inc., Mineola, New York, USA, 1979 (ISBN 0-486-41456-6)
- 2) C. H. Johansson, P. A. Persson, *Detonics of High Explosives*, Academic Press Inc. (London) Ltd, 1970 (ISBN 978-0-1238-5550-3)
- 3) G. F. Kinney and K. J. Graham, *Explosive Shocks in Air* (Second Edition), Springer Science + Business Media, New York, USA, 1985 (ISBN 978-3-642-86682-1)
- 4) P. W. Cooper, *Explosives Engineering*, Wiley-VCH, Inc., New York, USA, Table 5.1, p. 79, 1996 (ISBN 0-471-18636-8)