

PRINCIPLES OF ORDANANCE MUNITIONS AND EXPLOSIVES

UNDERSTANDING THE IMPORTANCE OF CRITICAL DIAMETER AND CRITICAL DENSITY IN THE
DETONATION PROCESS

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WHAT IS AN EXPLOSIVE

An explosive substance or energetic material is defined by its ability to chemically react by itself (intra or inter – molecularly), producing gas at such temperature and pressure as could cause damage to surroundings [1]. Explosive substances do not, however, hold a monopoly on the process of ‘explosion’; which is defined as the sudden release of large amounts of energy through the dissipation of blast waves, propulsion of debris or by the emission of thermal or ionizing radiation [2]. Thus, explosions as an event can be: Physical, such as a pressurized vessel bursting; Nuclear explosions or finally, Chemical explosions in the case of Energetic materials.

Explosive substances can be defined discretely by their reaction of detonation, deflagration and burning as well as other categories such as intended use or effects:

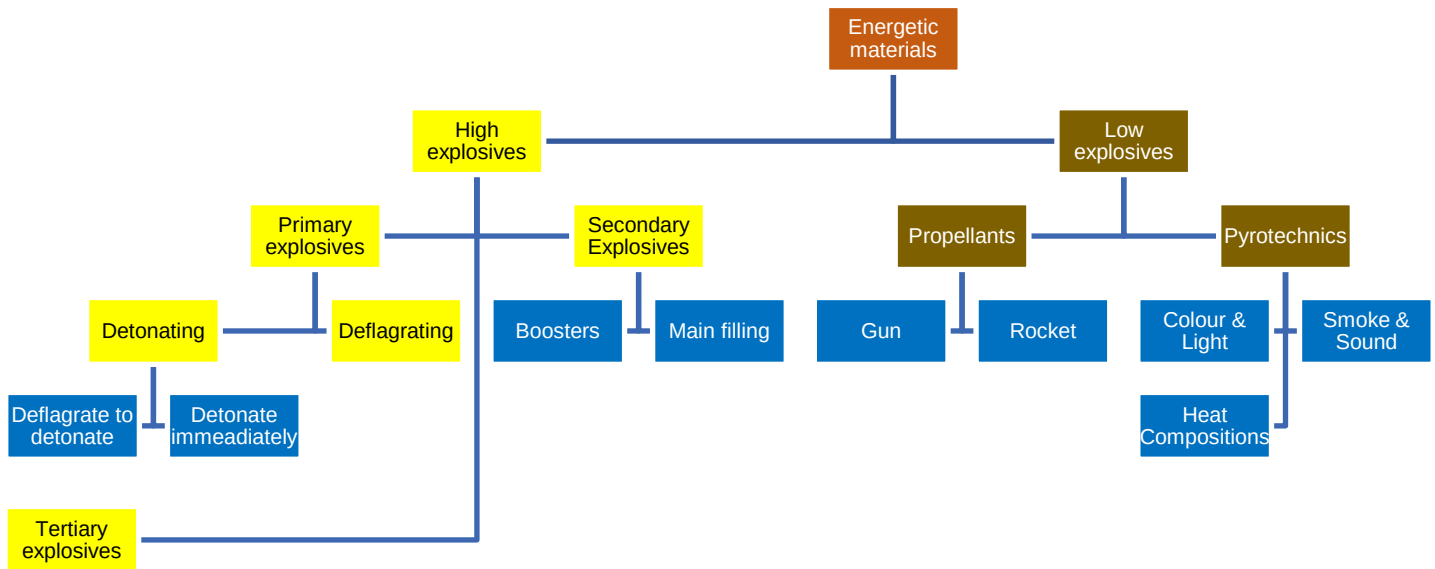


FIGURE 1 - AN OVERVIEW OF ENERGETIC MATERIAL CATEGORIES [1] [3]

Primary explosives are defined as explosives that are readily initiated by a small stimuli. Most commonly defined as a Figure of Insensitiveness (F of I) less than 50 [2]. This definition only refers to an explosives sensitiveness to impact, tested by the Rotter Impact machine, however an explosive could be considered a primary by it's response to other stimuli such as friction, heat and spark. Secondary explosives are less readily initiated by stimulus but generally have more explosive power. Explosive power is calculated by multiplying the heat of explosion $[KJ Kg^{-1}]$ by the volume of decomposition products $[dm^3 Kg^{-1}]$. As secondary explosives contain more oxygen they can produce more moles of gas products and 1 mol of gas at standard temperature and pressure will occupy $22.4 dm^3$ volume.

$$Explosive\ Power = Q \times V = Heat\ of\ Explosion \left[\frac{KJ}{Kg} \right] \times Volume\ of\ Gas\ Products \left[\frac{dm^3}{kg} \right]$$

EQUATION 1 - EXPLOSIVE POWER

Choice of explosive and munition design is tailored to the intended effect of the article. Area effect is produced by blast, fragmentation and thermal effect [4]. Penetration effects are achieved by high kinetic energy transfer of projectiles such as long rod penetrators that utilize high densities at high velocities ($>1200ms^{-1}$) to erode the target material [5]; or through shaped charges that utilize the Munroe effect to collapse a cone of ductile material into a high velocity jet (up to $10000ms^{-1}$) to laterally displace the target material [6].



FIGURE 2 - ENERGETIC EFFECTS: BLAST & THERMAL, FRAGMENTATION AND KINETIC ENERGY [7] [8]

Furthermore, fragmentation can be designed to fit the munitions performance, cost and manufacturability requirements as can be seen in Figure 3.

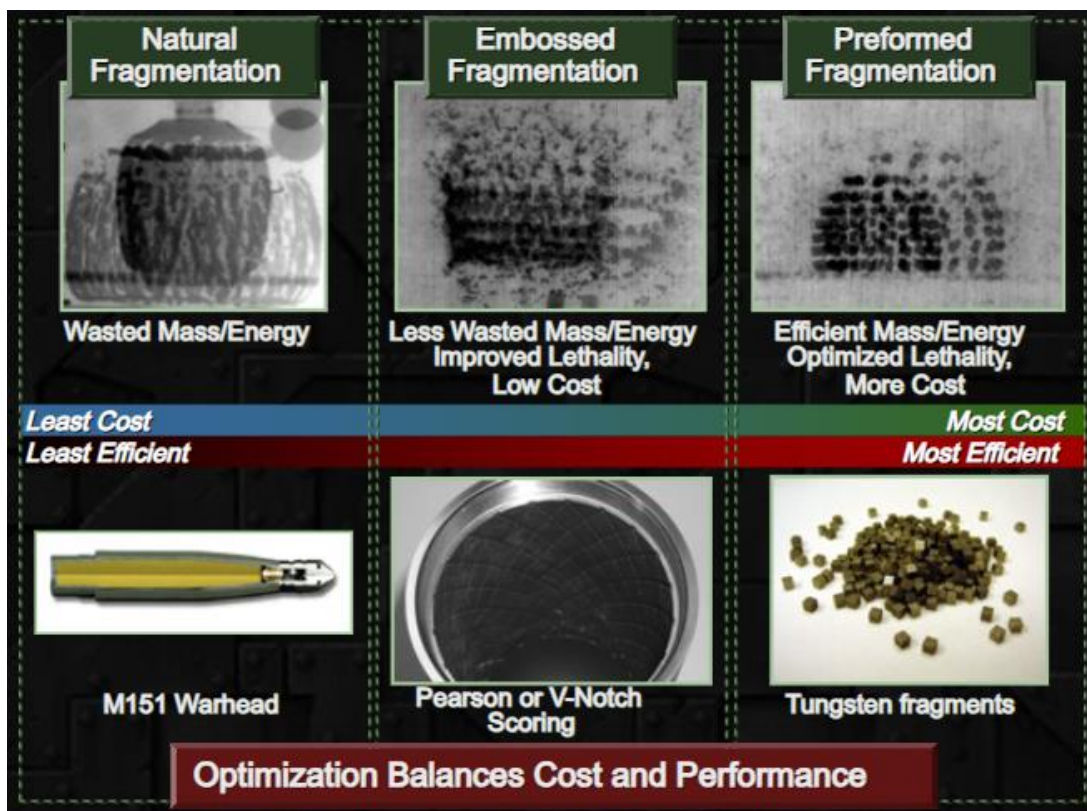


FIGURE 3 - FRAGMENTATION DESIGN CONSIDERATIONS [9]

THE DETONATION PROCESS

Combustion and deflagration as decomposition processes have more similarities than they do to detonation. Combustion and deflagration can just be considered as 'burning' but at different rates, millimeters per second compared to ~100 meters per second. Combustion also refers to explosives that burn by consuming atmospheric oxygen, whereas deflagration consumes oxygen from within the compound whether it is a mixture or homogenous compound; this internal oxygen supply is what enables this faster burn rate. Burning is a surface phenomenon in which the reaction zone consumes the explosive in a regressive manner and the combustion products (primarily hot gas) is expelled perpendicular to the direction of surface regression.

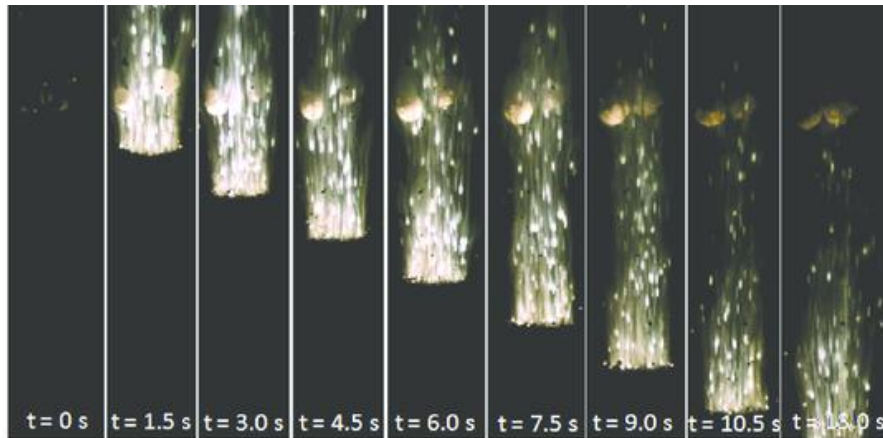


FIGURE 4 - COMBUSTION OF A PROPELLANT WITH A FLAT BURNING SURFACE [10]

Detonation occurs when the reaction zone in the explosive produces a large pressure wave that exceeds the speed of sound in the material. In the unreacted explosive, the material is heated by adiabatic compression. This is where voids in the explosive of a fixed quantity of gas have the volume they occupy reduced by compression from the shock wave, thus increasing the pressure and temperature of the gas due to the first law of thermodynamics.

Detonation can be induced either by deflagrating to detonation (DDT) or instantaneous detonation, stimulated by an initial shock.

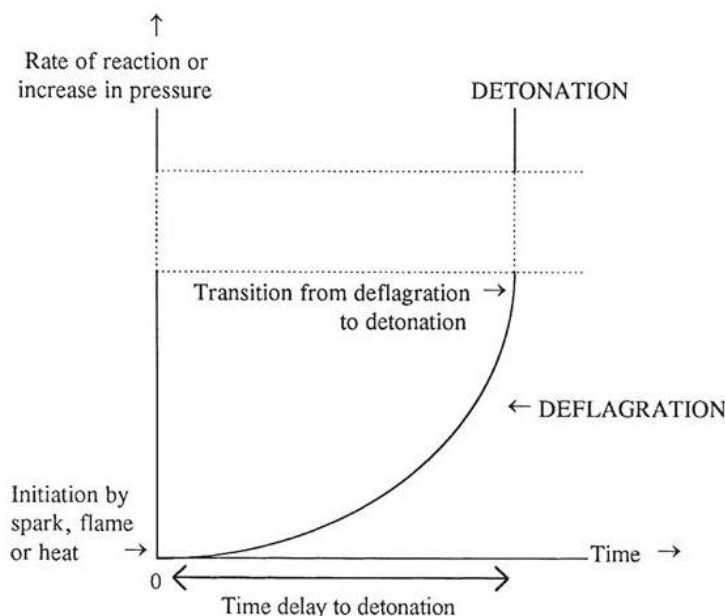


FIGURE 5 - GRAPH OF THE TRANSITION FROM DEFLAGRATION TO DETONATION [2]

The detonation driving zone consists of two sections, the induction zone and the reaction zone. In the induction zone, the explosive is sufficiently adiabatically heated to its ignition temperature, therefore decomposing into free radicals; which are atoms, molecules or ions that have unpaired valence electrons meaning they are highly reactive and tend to reduce their entropy by gaining a full valence electron shell. This zone is roughly 0.1 microns wide and is governed by the Arrhenius Rate law that states the rate which a reaction take place is related to the temperature, where increases in temperature increase the kinetic energy of the particle and therefore the number of particle collisions in which the energy is sufficient to cause a reaction.

$$k = Ae^{\frac{-Ea}{RT}}$$

EQUATION 2 - ARRHENIUS RATE LAW

The reaction zone is 1-10 millimeters wide and is the zone in which the free radicals of the induction zone are converted into detonation products, which are determined by the oxygen balance of the explosive. These detonation products determine the energy generated by the reaction by their heat of formation ($\Delta H_f = KJmol^{-1}$) with the negative oxygen balance products Carbon and Carbon Monoxide having a heat of formation of 0 and $110 KJmol^{-1}$ respectively; whereas a more positive oxygen balance explosive would form Carbon Dioxide with a much higher heat of formation of $393 KJmol^{-1}$.

Explosive	Oxygen Balance [%]	Heat of Explosion [Kj/Kg]
TNT	-73.9	3646
Tetryl	-47.4	4166
Nitromethane	-39.3	4299
Nitrocellulose	-28.7	3991
HMX	-21.6	5249
RDX	-21.6	5297
Lead Styphnate	-18.8	1453
Mercury Fulminate	-11.2	1735
PETN	-10.1	5850
Urea Nitrate	-6.5	2455
Lead Azide	-5.5	1638
EGDN	0	6743
Nitroglycerine	3.5	6214
Ammonium Nitrate	19.9	1441
Ammonium Perchlorate	34.4	1972

TABLE 1 - OXYGEN BALANCE AND HEAT OF EXPLOSION OF PRIMARY AND SECONDARY EXPLOSIVES [3]

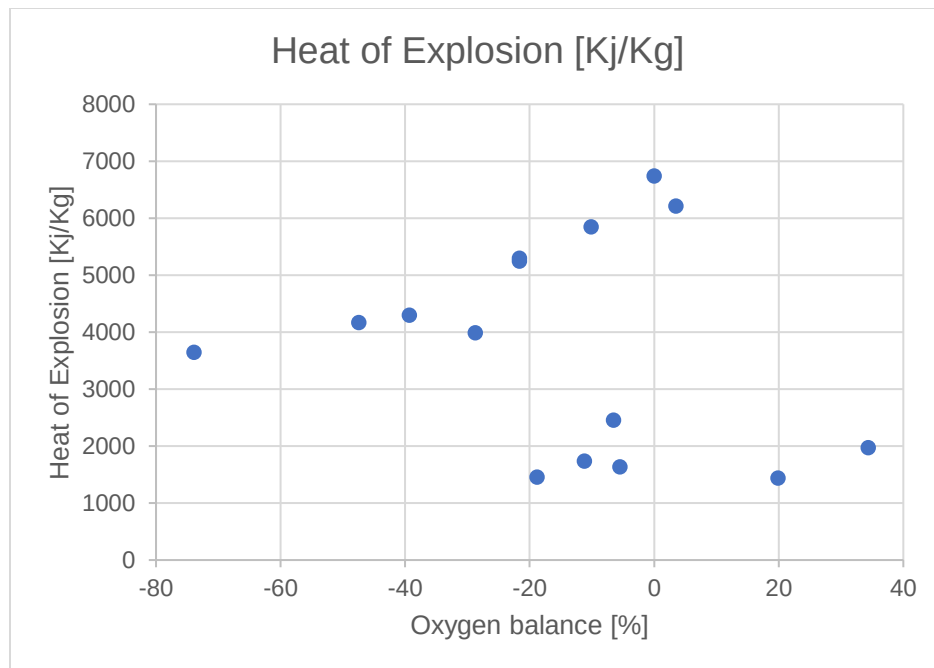


FIGURE 6 - HEAT OF EXPLOSION INCREASES PROPORTIONALLY TO OXYGEN BALANCE (DISREGARDING PRIMARY EXPLOSIVES WITH A HEAT OF EXPLOSION <2500 KJ/KG)

Due to the high pressure differential between the non-driving and driving zones, the decomposition products are 'sucked' along the same direction of the reaction (at a much slower rate than the shockwave) in its turbulent wake. In this non-driving zone, secondary reactions will occur between various additives and the detonation products. The most common example of this occurs as a result of aluminized explosive compositions. Flaked or spherical Aluminium is added to increase the blast profile of a given explosive by reacting with atmospheric oxygen to combust and form Aluminium Oxide with it's high heat of formation $1669.8 \text{ KJmol}^{-1}$. The addition of Aluminium has the effect of decreasing the peak overpressure of the blast but increasing the overall impulse due to the elongation of the blast profile.

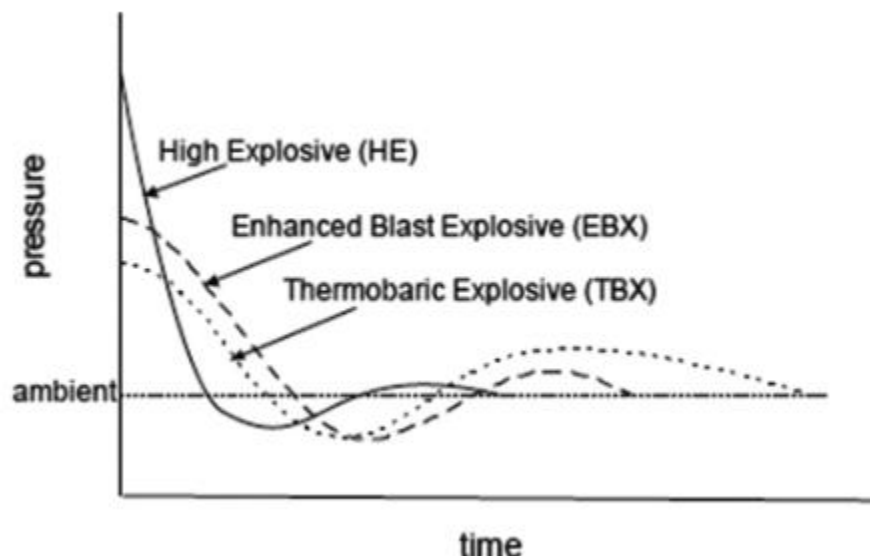


FIGURE 7 - BLAST PROFILE OF HIGH EXPLOSIVE, ENHANCED BLAST AND THERMOBARIC EXPLOSIVES [11]

As can be seen in Figure 7, the instantaneous overpressure rise decays exponentially; following the inverse cube law. This is the principle upon which the scaled distance equation is based upon, where the scaled distance is equal to the distance from the center of the explosion is multiplied by the inverse cube of the charge weight.

$$Z = \frac{R}{\sqrt[3]{W}} = RW^{-\frac{1}{3}}$$

EQUATION 3 - SCALED DISTANCE EQUATION

This calculated value can then be used with data tables such as those from Kingery-Bulmash to estimate the incident overpressure of a blast. When the incident pressure reflects off a surface, the reflected wave will constructively interfere with the incident wave leading to reflected pressure acting on the surface far greater than the incident overpressure. Severe lung hemorrhage occurs above 550 Kilopascals [12], making blast in the proximity of hard structures particularly deadly.

HOT SPOTS

The key driving force in the above detonation process, particularly with energetic materials that have plastic mechanical properties [10]; is the formation of hot spots. Hot spots can form in cracks, voids or impurities as small as 0.1-10 microns within the explosive composition [13]. Hot spots occur when said imperfections reduce in size by compression from the initial reaction pressure and adiabatically heat the surrounding explosive. The compression can be induced by friction, electro-static discharge, crystal fracture, visco-plastic work, shear bands and bubble collapse. If the explosive is heated in excess of its ignition temperature; the reaction will be maintained and cascade eventually up to a shock front. This is referred to as linking whereas a failure to link is referred to as quenching.

The primary mechanism for hot spot formation within primary explosives is inter-crystalline friction and heating in contrast to secondary explosives where the air and adjoining explosive in imperfections is adiabatically compressed, up to exceeding the explosives ignition temperature.

STIMULIS

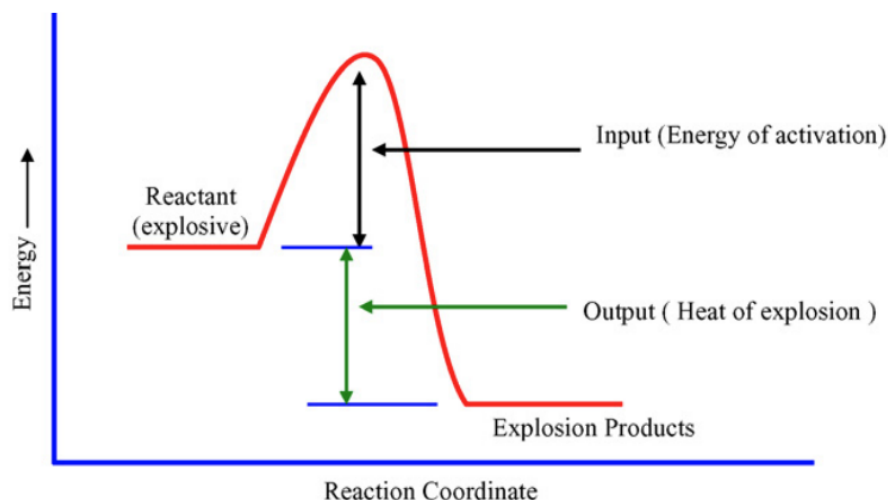


FIGURE 8 - ACTIVATION ENERGY AS IT PERTAINS TO AN EXPLOSIVE REACTION [11]

An Explosive material can be initiated by a variety of means, all relying upon the principle of overcoming the activation energy of the reaction, Figure 8. The activation energy being less than the overall heat of explosion output as all explosive reactions are exothermic.

The various stimuli to initiate an explosive reaction depend upon the concentration of heat in the explosive to overcome the ignition temperature while energy is dissipated to the surrounding material or container. This heat

is induced by: Heat from hot wires, gas, particles or conduction; impact such as firing pins on percussion caps; friction in the case of stab detonators; electric spark and finally shock in the case of exploding bridge wires.

FACTORS AFFECTING DETONATION

Explosives can react in three different modes: thermal decomposition, deflagration and detonation. These modes are dependent upon the initial temperature and pressure of the reaction; but as the reaction will increase both factors, a reaction is able to transition to a more vigorous mode [12].

CRITICAL DIAMETER

The critical diameter of an explosive material refers to the smallest diameter a charge can be to propagate a stable detonation shock wave [16]. Below the critical diameter, sufficient shock energy is dissipated external to the material such that the reaction cannot self-sustain. This critical diameter is independent of the initial shock pressure induced in the explosive. The critical diameter is simply a threshold for stable detonation, as the diameter increases up to the minimum diameter (Figure 9); the velocity of detonation will increase. Past the minimum diameter, the detonation velocity will be constant.

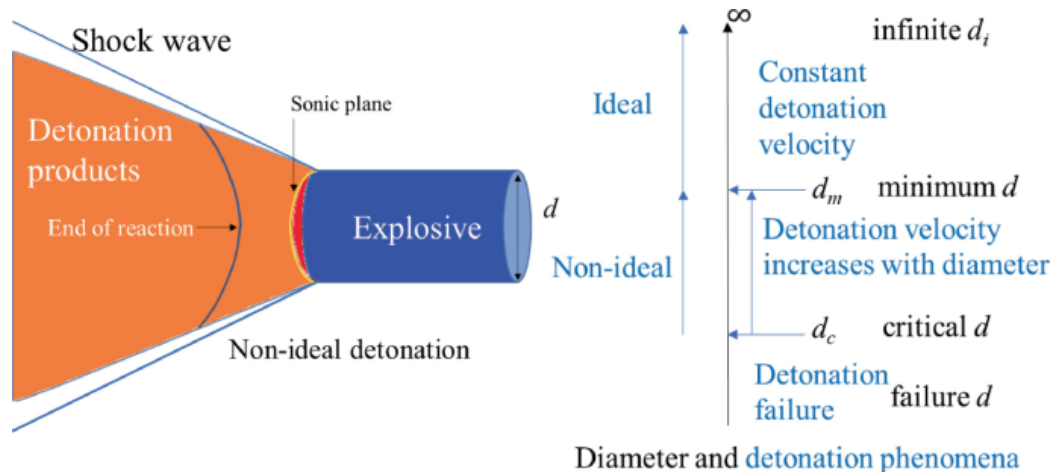


FIGURE 9 - DETONATION DRIVING ZONE AND CRITICAL DIAMETER [17]

Critical diameters are typically referenced as values in unconfined explosive material. Confinement, for example steel shell cases, will reduce the critical diameter. In the case of PBXW-115, an RDX based polymer-bonded explosive, the critical diameter is reduced from 80mm to 26mm (67.5% decrease) by confinement with a 3mm thick brass tube [16].

CRITICAL DENSITY

The critical density of an explosive refers to the minimum density required for a stable propagation of the detonation shockwave. In the case of powdered explosives, insufficient density can result in the explosive being 'blown' away. Above the critical point, increasing the density of an explosive results in an increase in the detonation velocity up to the point of the theoretical maximum density. At this point, the material is so densely packed that the aforementioned process of hot spot formation is impossible. This is also referred to as 'dead-pressing' and is a consideration within the commercial mining industry with regards to tertiary heterogeneous blasting agents such as Ammonium Nitrate-Fuel Oil (ANFO) [18].

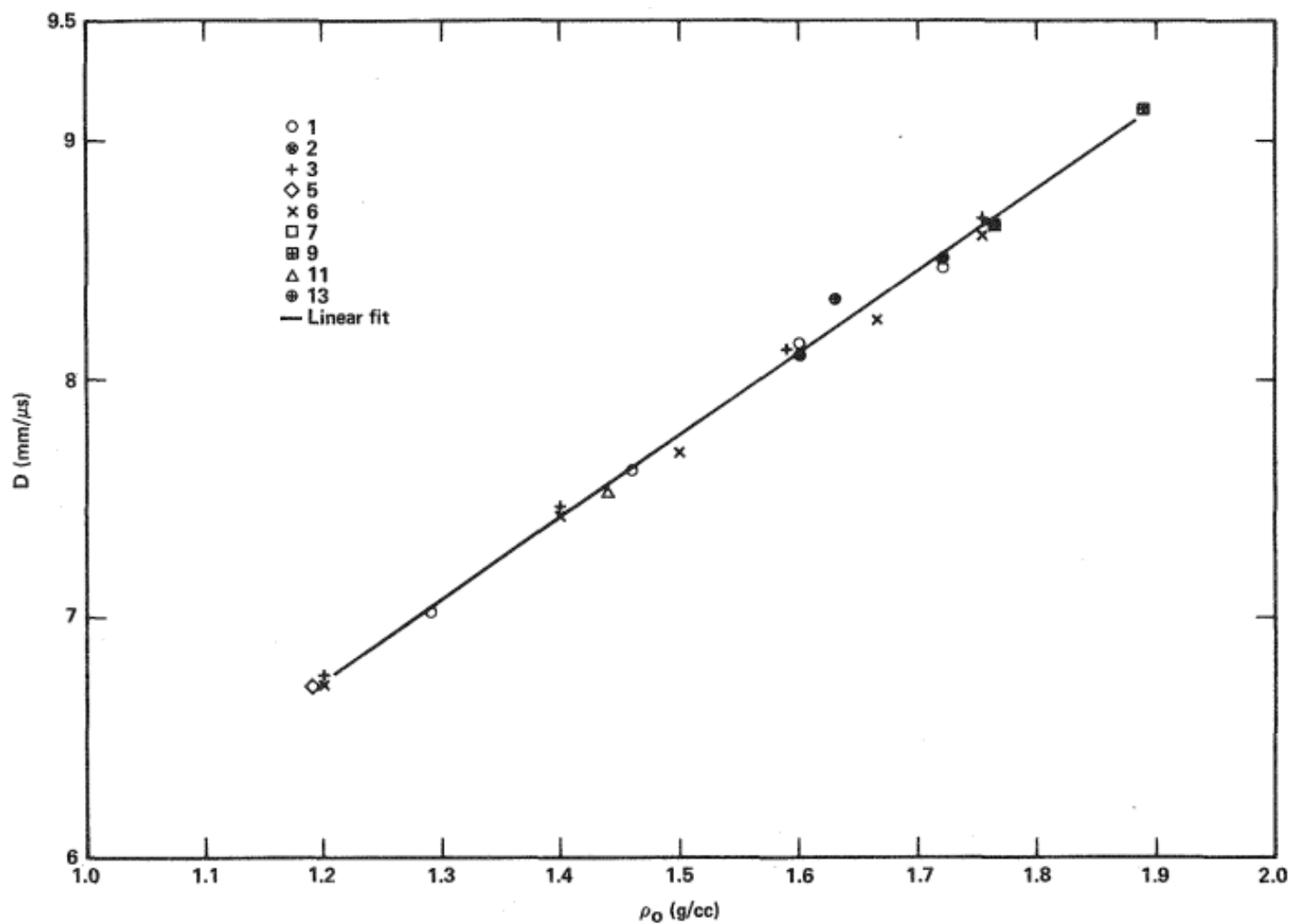


FIGURE 10 - GRAPH OF DETONATION VELOCITY VS DENSITY OF RDX [19]

EXPLOSIVE TRAINS

Explosive trains are designed such that the main charge is able to detonate in a stable and optimally performant manner with the minimum quantity required of sensitive primary explosives to initiate it. Developments in exploding bridgewire and slapper detonators allow for the complete removal of primary explosives from explosive trains not just for handling and storage safety but also for environmental factors as most primary explosives contain toxic substances such as lead and mercury.

Standard detonators are by themselves, a small explosive train and can either be electric or non-electric. A pyrotechnic delay element is ignited by either a fuse-head rapidly heating up a priming composition (or match-head) in the case of electric detonators; or an external shock or flame from detonating cord or safety fuze in the case of non-electric detonators. This delay will then initiate a primary charge such as Lead Styphnate or Azide which will 'run up' and deflagrate to detonate, instantaneously detonating the output charge which typically consists of Pentaerythritol tetranitrate (PETN) [20].

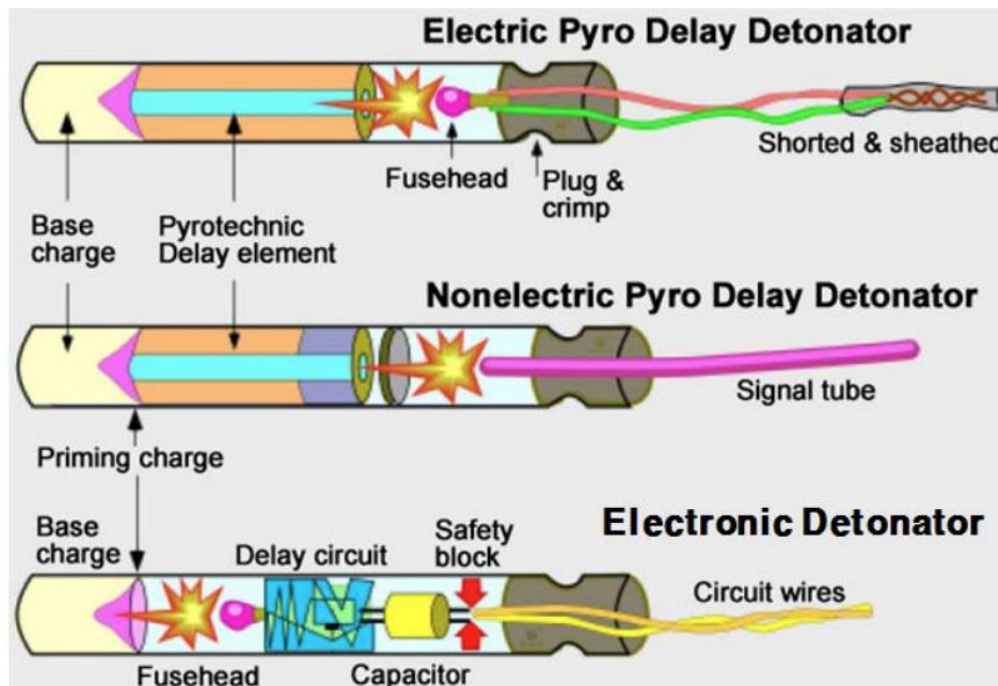


FIGURE 11 - CROSS SECTION OF STANDARD DETONATORS [20]

After the detonator output, a booster element with a smaller critical diameter than the main charge is utilized. This ensures the detonation shock front is stable and reaches a sufficient detonation velocity and pressure to guarantee the takeover to the main charge. Each element of the train will maintain intimate contact with the next to ensure takeover of the shock front; although in specialist applications such as fuzes, stand off distance and even attenuating material is employed to enhance safety as only the precise shock pressure that is required will initiate the next stage of the explosive train.

MUNITION DESIGN

The proposed munition is that of an Insensitive Munitions compliant, enhanced blast warhead that is lightweight and cost effective for use on FPV drones. The Russian invasion of Ukraine has seen the return of trench warfare to this century alongside fighting in built-up areas, therefore the need for a user targetable blast munition that could be directed inside structures or key command points in trench is imperative. Current FPV munitions are repurposed in-service RPG or various other submunitions that are of a high-explosive anti-tank design, therefore, there is need for more specialized munitions for purposes other than anti-vehicle.



FIGURE 12 - UKRAINIAN FPV DRONES CARRYING MUNITIONS UP TO 2KG [23]

The proposed explosive train will consist of an exploding bridgewire detonator such as the RP-80 from Teledyne which contains PETN as the initiating explosive that will deflagrate to detonate upon a high voltage signal vaporizing the bridge wire and RDX as the output composition [24]. Capacitor based firing packs are of reasonable size weight and power that they could be integrated onto a drone. The high voltage requirement of the EBW also enhances operate safety in noisy EMC environments where there is interference from RF signals, radios and electronic warfare.

The main charge will be based upon IMX-104 with the addition of aluminum. IMX-104 is a melt-castable insensitive composition intended to replace TNT based compositions and consists of NTO, DNAN and RDX in a 53/31.7/15.3 ratio [25]. Due to the insensitiveness of the main charge, a booster consisting of the HMX based pressable PBXN-9 is required [26].

Explosive	Unconfined Critical Diameter [mm]	Optimum Density [g/cm ³]	Detonation Velocity [km/s]
PETN	1.5	1.73	8.35
RDX	2	1.8	8.798
HMX	5.4	1.91	9.1
IMX-104	30	1.724	7.352

TABLE 2 - DETONATION CHARACTERISTICS OF CHOSEN EXPLOSIVES TAKEN FROM REFERENCED LITERATURE

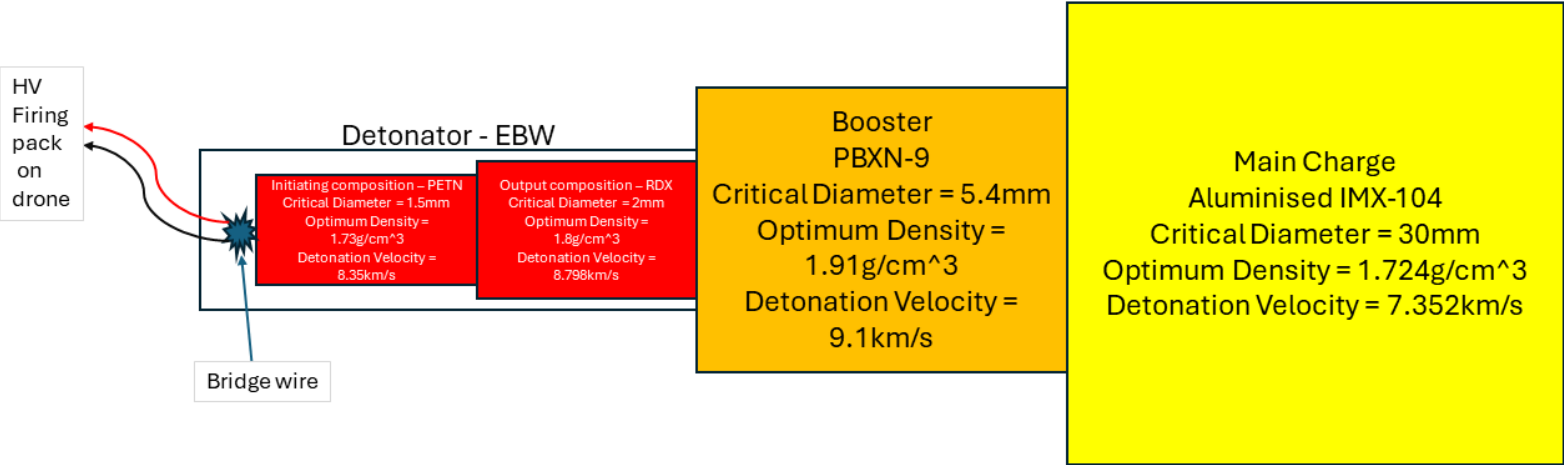


FIGURE 13 - DIAGRAM OF PROPOSED EXPLOSIVE TRAIN

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