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Understanding the importance of critical diameter and critical density
in the detonation process

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Abstract

This is a report on the importance of critical diameter and critical density in relation to successful detonation of high explosives. To achieve this the report consists of the analysis of one primary explosive and one secondary explosive, with a literature review of their individual performance characteristics, detonation of explosives both in an unconfined and confined environment, including the stimulus applied to the primary explosive in order to initiate a successful detonation as well as the transition from primary to secondary and the speed of detonation in which an explosive successfully propagates in order to reach detonation speeds and pressures. This report also describes an explosive train as well as a successful detonation in the form of a diagram, with clear key factors. This report does not describe nuclear or nuclear augmented explosives.

Keywords:

Critical Diameter, Critical Density, Velocity of Detonation, Primary Explosive, Secondary Explosive, Explosive Train, Unconfined, Confined, Oxygen Balance.

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List of Abbreviations

FOI	Figure of Insensitivity
mw	Molecular weight
OB	Oxygen Balance
PETN	Pentaerythritol Tetranitrate
SVHC	Substances of Very High Concern
TMD	Theoretical Maximum Density
TNT	Trinitrotoluene
VoD	Velocity of Detonation

1 Explosives

Explosives are the name of chemical substance which, when initiated via a detonation stimulus, causes an explosion. Explosions are defined as the rapid decomposition of a chemical substance with the evolution of heat and gas, of which will cause one or more of the following effects:

- Light
- Heat
- Gas
- Sound
- Pressure

They utilise these effects to cause a number of outcomes, which ranges from the colourful fireworks displays for entertainment, to the devastating damaging effects of warheads to structures, vehicles and personnel.

Explosives can be categorized under two sectors:

- Low Explosives
- High Explosives

Low Explosives are categorized as anything which detonates slower than the speed of sound within the material (typically around 5000m/s in a solid), causing either a surface burning effect (Pyrotechnics) or a deflagrating effect (Propellants).

High Explosives however fall under 3 categories known simply as primary, secondary and tertiary, and each category can be distinguished by their sensitivity to detonation, with primary explosives having a Figure Of Insensitivity (FOI) of <50 on the Rotter Impact Test, whilst secondary and tertiary explosives are >50 FOI. The distinguishing difference between secondary and tertiary explosives is that whilst secondary explosives require a primary explosive detonator to initiate a detonation, tertiary explosives also require a shock from an intermediate secondary explosive booster charge to detonate as they are extremely insensitive and cannot be detonated by a primary explosive alone [1].

1.1 Primary Explosive – Lead Azide

One such Primary explosive is Lead Azide ($\text{Pb}(\text{N}_3)_2$), which is widely used due to its better shelf life, performance when initiating secondary explosives reliably, cost and elimination of the use of mercury within its composition as a highly toxic substance in the 1900s [2].

Although in 2011 this has since been added to the candidate list of Substances of Very High Concern (SVHC) as it met criteria for classification as toxic for reproduction under article 57 of the Registration, Evaluation, Authorisation & Restriction of Chemicals (REACH) Regulation (European Commission) No 1907/2006 [3]. This is in part due to a 1991 survey showing that employees working at an FBI shooting range had in-cell blood lead levels nearly 10 times higher than the limits set by the US government [4], which lead to president Clinton issuing a series of executive orders to reduce or eliminate procurement of hazardous substances and chemicals by federal facilities in 1993 [2].

Although currently Lead Azide is exempt from restrictions due to a lack of suitable substitutes, the exemption is likely to be revoked in April 2026, prohibiting the use of lead azide in electrical detonators in the EU henceforth [3].

Lead Azide has an FOI of 20 on the Rotter Impact Test (relative to RDX), making it a fairly sensitive material [5, 11].

It is most commonly used in military ammunition, blasting caps and as a detonator or primer in explosives. When used as a detonator it may be mixed with lead styphnate and aluminium to form a composition known as ASA, whilst if used as a primer will be used in a composite mixture with tetrazene [6].

It is produced through the reaction of lead nitrate or acetate with sodium azide in an aqueous solution under basic conditions to avoid formation of hydrazoic acid, which readily explodes. Crystal size must be carefully controlled as crystalline in structure; large crystals are more hazardous due to friction as a result of breakage which can lead to ignition and detonation of lead azide [6]. Initiation of Lead Azide can be via stab, impact, friction, or electrical/static electricity discharge [7].

Lead azide can exist in two allotropic forms, with the orthorhombic alpha form being the more stable of the two and the monoclinic beta form being less stable [6].

1.2 Secondary Explosive - Pentaerythritol Tetranitrate (PETN)

Pentaerythritol Tetranitrate, otherwise known as PETN, is a secondary explosive most commonly used as a booster explosive, in detonating cord and blasting caps [8].

First synthesized by German chemists working on nitrate esters of pentaerythritol in 1894, identified as more stable and easier to purify than nitro-glycerine, it quickly drew interest. Its Early military adoption was during World War I, however it wasn't widely used as it was more expensive to synthesize than readily available Trinitrotoluene (TNT).

It was later industrially produced more widely during the 1920's and 1930's as safer and more efficient nitration methods were developed, appearing in commercial blasting products used for mining, namely detonating cords.

During World War II PETN production accelerated significantly, being used in:

- Detonators and blasting caps
- Booster charges
- Bursting tubes and small bursting charges
- Early plastic explosive formulations.

This was due to its reliability, stability and high power.

Following the end of the war PETN was adopted by a range of commercial sectors including mining, construction blasting, demolition and even in medicine.

In more modern times the use of PETN as a secondary explosive has narrowed to that of only detonator cord, booster charges and transfer charges, with occasional use in military and aerospace devices, where RDX and HMX now occupy main charge formulations for high explosives in military applications [9,10].

PETN is commonly paired with lead azide as a booster charge for a main charge such as RDX or TNT, as it forms part of a highly reliable high explosive chain [8].

This is because it has a FOI of 51, putting it right on the edge of primary and secondary in terms of sensitivity, which is why it makes a good booster charge [11].

Limitations of PETN are that it can degrade under heat, moisture or extended storage, lowering shelf life and therefore reliability [8].

1.3 Explosive Train

Due to the low sensitivity of secondary and tertiary explosives, it is required that an initial explosion from a primary explosive is initiated to successfully detonate an explosive composition with an FOI >50 . For highly insensitive explosives the explosive train can include a booster charge as an intermediate for further increase the reaction enough to detonate an extremely insensitive explosive. Detonating highly insensitive explosives in turn creates a much higher energy yield from the explosive compared to primary explosives, as well as provide a much higher level of safety.

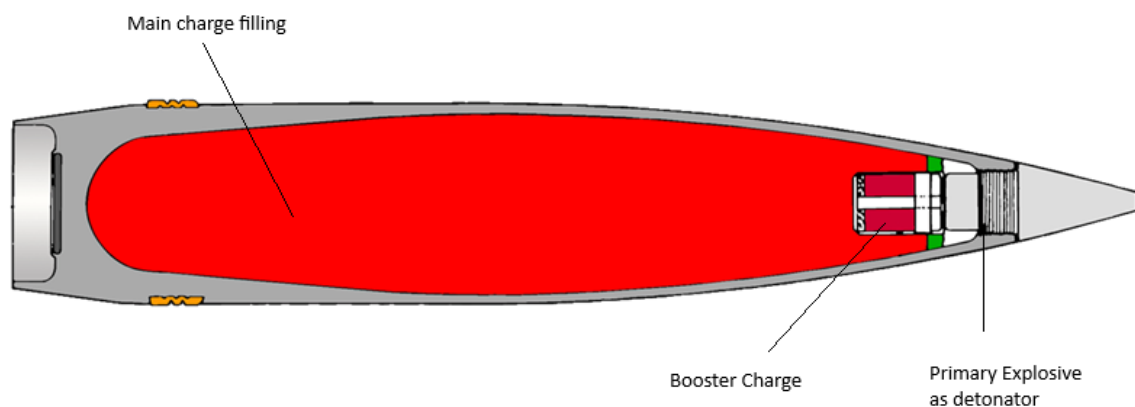


Figure 1 - Three Stage Explosive Munition

In the above figure, the stimulus of ignition would be impact on the fuse head, from the munition landing at its target.

1.4 Oxygen Balance

Oxygen balance is the amount of oxygen either required or output from a chemical reaction. This is important due to oxygen being a key part of the fire triangle and therefore crucial when it comes to combustion. As a result, the oxygen balance of a material can tell us about the efficiency of a detonation, where the closer to 0 the oxygen balance is (perfectly balanced) the more efficient a detonation is.

It can be derived from the following formula:

$$OB(\%) = \frac{(d - (2a) - (\frac{b}{2}))}{mw} \times 16 \times 100$$

Equation 1 - Oxygen Balance Rule

Where:

OB = Oxygen Balance

a = no. of carbon atoms in molecule

b = no. of hydrogen atoms in molecule

d = no. of oxygen atoms in molecule

mw = molecular weight of one molecule

What this formula explains is how a detonation would transition between states understanding the rapid chemical decomposition, using Hess' law, where carbon forms carbon dioxide (CO₂) and hydrogen forms water (H₂O), and the oxygen used from the material (or atmosphere) to make up these decomposition compounds.

note: there is no c given in this equation as c refers to nitrogen atoms which require no oxygen and always form nitrogen gas (N₂), however it is important to understand how many nitrogen atoms make up a molecule as it forms part of the mw.

There is an addition to this, where an explosive device is not based on a CHNO composition and instead a metal, which decomposes to form a metal oxide:

$$OB(\%) = \frac{(d - (2a) - \left(\frac{b}{2}\right) - (x \times e))}{mw} \times 16 \times 100$$

Equation 2 - Revised Oxygen Balanced rule to include Metals and Metal oxides in composition [24]

Where:

x = typical oxidation state of the metal oxide

e = number of metal atoms in molecule

This information can explain the oxygen balance of lead azide ($Pb(N_3)_2$)

Azide is N_3 and lead is Pb therefore the mw is:

$$mw = 207.2 + 2(3 \times 14.01) = 291.26g/mol$$

Leads typical oxidation state in the oxide is +2.

Plug these figures into the formula:

$$OB(\%) = \frac{(0 - (2 \times 0) - \left(\frac{0}{2}\right) - (2 \times 1))}{291.26} \times 16 \times 100 = -10.99\%$$

The oxygen balance of PETN can also be calculated, where PETN is $C_5H_8N_4O_{12}$, therefore the mw is:

$$mw = (5 \times 12.01) + (8 \times 1.008) + (4 \times 14.01) + (12 \times 16) = 316.154g/mol$$

As there are no metals in this material, equation 1 can be used to calculate the oxygen balance:

$$OB(\%) = \frac{(12 - (2 \times 5) - \left(\frac{8}{2}\right))}{316.154} \times 16 \times 100 = -10.12\%$$

Using both of these values, it can be surmised that an explosive train comprised of these explosives would have to absorb some oxygen from its environment, or to achieve greater efficiency it could be balanced with a positively balanced tertiary explosive (where PETN may be used as a booster).

2 Critical Diameter and Critical Density in an Unconfined Environment

To understand critical diameter and critical density, it is first important to understand how an explosive propagates into a successful detonation wave to cause all of the material within an explosive to combust rapidly.

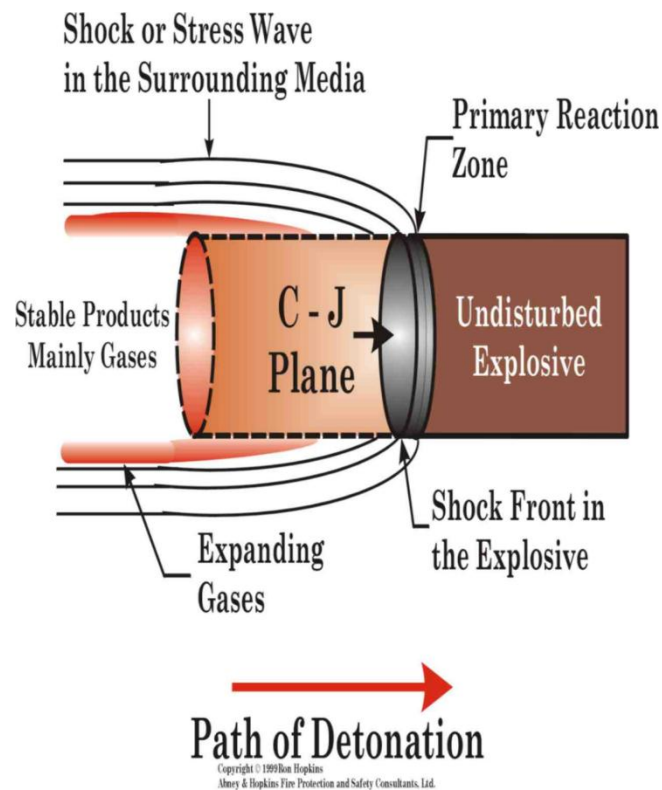


Figure 2 - A Schematic Diagram Showing a Successful Detonation Through an Explosive Composition [12]

This diagram describes partly the requirements for a successful detonation, such that there is a shock front within the explosive during detonation, creating forward pressure to compress explosive material slightly ahead of the primary reaction zone. The reaction is pushed forward by the expanding gases behind the reaction zone, along what is labelled as the “C-J Plane”.

In part, this helps understand critical diameter, which is in definition the minimum diameter required to successfully detonate an explosive composition, as there is enough surface area of the explosive material detonating to cause pressure from expanding gases behind the reaction zone to push it forward through the material.

Below the critical, an explosive charge will not reliably sustain a detonation wave due to lateral expansion and edge effects, which is to say energy escapes faster than the reaction can propagate due to energy input from the shock front.

Too small of a diameter does not provide enough of a pressure wave and therefore the detonation stalls, where some of the explosive material is likely to remain in its initial state.

Density within an explosive has 2 notable boundaries, the critical and theoretical maximum, where critical density is defined as the minimum density required for a detonation to propagate, and theoretical maximum density is the limit in which a material may still detonate for a given diameter.

Critical density, alongside critical diameter, plays a crucial role in successful detonation, due to “hotspots” within the explosive material during detonation. These are formed when density in the material is between the upper and lower limits, where there are pockets, pores or voids of gas/air within the explosive material, as these pockets are compressed at by the shock front and expanding gases they rapidly heat up to temperatures hot enough to assist in the propagation of the temperature transfer through the material by outpacing energy-loss, causing a chain reaction [13]. This is forms deflagration to detonation.

Critical densities for Lead Azide and PETN can be found in [Appendix 1](#).

3 The Effect of Confinement

Confinement, as first reported in experimental work by A.W.Campbell, W.C.Davis and J.R.Travis, decreases the critical diameter as the acoustic impedance of the confiner wall increases [21]. What this means is that if the container wall is thicker or made of a material more resistant to sound wave penetration, it reflects soundwaves generated by the detonation back into the material, which proves to amplify the compression wave caused by the shock front and propagate more uniformly throughout the material.

This can also be seen in theoretical framework, even though the critical diameter is directly proportional to the reaction zone, confining the detonation reduces the effective loss rate [22].

Similarly, when analysing critical density, it can be seen that confining the material mitigates against “dead pressing” – the term used when an explosive material surpasses its Theoretical Maximum Density (TMD) and voids which would enable hotspots would be reduced and spread further apart. This is because the inertia of the confiner, if strong enough, can maintain higher pressure for an extended period. This extended pressure ‘pulse’ allows bridging between larger gaps over fewer hotspots, increasing the reaction [16].

Data to support this can be seen in Appendix 1 as well as a diagram of these effects can be seen in [Appendix 2](#).

4 The Effect of Density on Velocity of Detonation

For primary explosives, such as lead azide, there is an optimal window for Velocity of Detonation (VoD), where exceeding it can cause failure to detonate as a result of hot spot dependence. Specifically for lead azide, its peak VoD is reached when its density is just below critical [18, 19].

For secondary explosives however, VoD increases almost linearly with density up to between 95-98% of TMD, however, in order for this to happen the initiation stimulus needs to be near perfect, and the explosive is required to be confined [14, 16, 23].

This can be seen in the tables in [Appendix 3](#).

This can also be captured by the following equation:

$$D = A + B\rho$$

Equation 3 - Modified Kistiakowsky-Wilson Rule

Where: D is VoD, ρ is density, and A , B are explosive-specific constants [14, 16].

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6 Appendices

6.1 Appendix 1 - Data Table for Explosive Materials

Explosive Compound	Critical Diameter (unconfined) (mm)	Critical Diameter (confined) (mm)	Critical Density (and TMD) (g/cm ³)	Velocity of Detonation at Critical Density (m/s)
Lead Azide (Pb(N ₃) ₂)	0.5 – 1.0 [14, 15]	≤ 0.1 [15, 17]	3.8 – 4.0 (TMD 4.8) [18, 19]	4,500 [17, 18]
PETN (Pentaerythritol Tetranitrate)	3 – 5 [16, 17]	1.0 – 2.0 [16, 20]	1.6 – 1.7 (TMD 1.77) [16, 18]	7300 – 7600 [14, 16]

Table 1 - Data Table for Lead Azide and PETN

6.2 Appendix 2 - Diagram of the Effects of Confinement

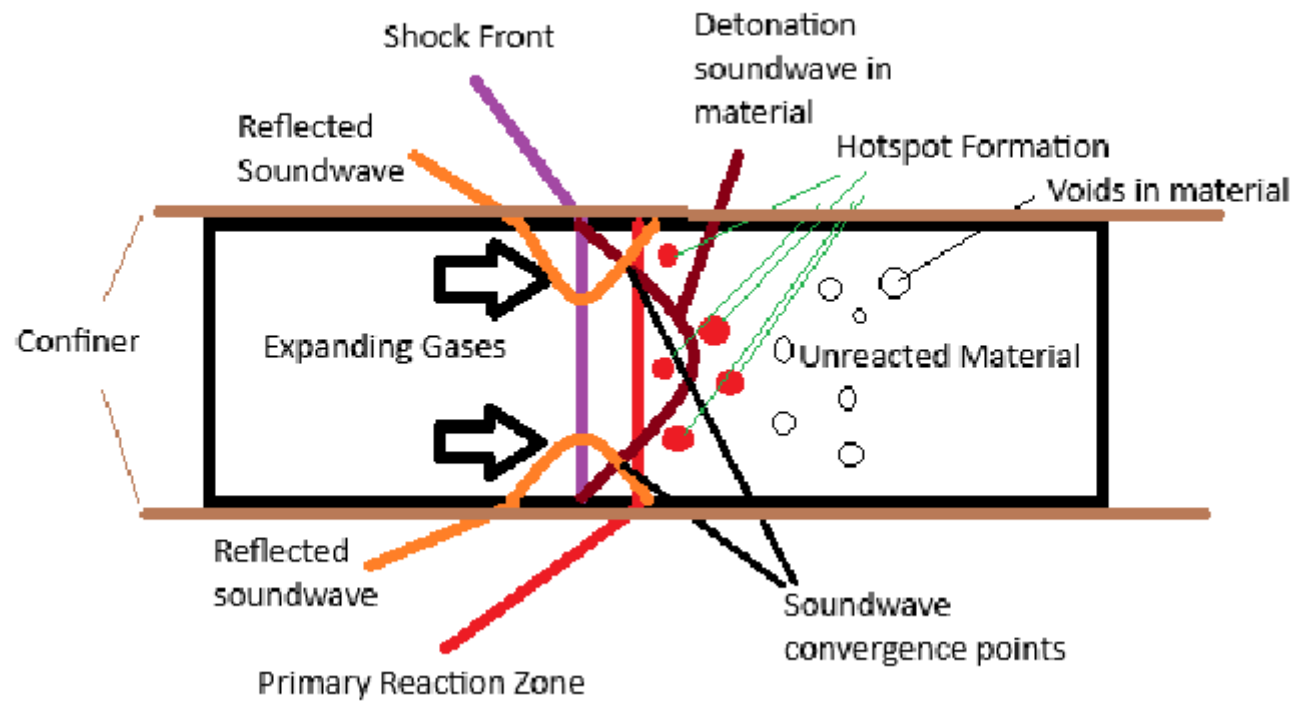


Figure 3 - Detonation in a Confined Environment

6.3 Appendix 3 – Velocity of Detonation Change with Material Density

Density Range	VoD Trend	Notes
Low (< 2.0 g/cm³)	Increases rapidly	Poor performance, unstable detonation.
Optimal (2.5 – 3.5 g/cm³)	4,500 – 5,200 m/s (peak)	Standard for detonators. Good balance between performance and sensitivity.
High (> 4.0 g/cm³)	Sharp decline to failure	At critical density (4.0 g/cm ³), VoD is 4,500 m/s or lower and highly unstable.

Table 2 - Effects of Density on VoD for Lead Azide [18, 19]

Density (g/cm ³)	Approximate VoD (m/s)	Notes
1.0 (loose powder)	5,500	Unconfined, large critical diameter.
1.5 (pressed)	7,200	Common pressing density for boosters.
1.65 (highly pressed)	7,800	Requires strong confinement and initiation.
1.70 (near TMD)	7,300 – 7,600	At critical density - VoD is slightly reduced from peak due to initiation strain.
1.77 (TMD, ideal)	8,300	Theoretically maximum - requires perfect initiation and confinement.

Table 3 - Effects of Density on VoD for PETN [16, 23]