

The importance of critical diameter and density in the detonation process

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Introduction

To understand the importance of charge diameter and density, two explosives have been selected. For a primary, Lead (III) azide has been selected due to its frequent use as a primary in service detonators. Typically, the α -polymorphic form is preferred due to its increased stability. For a secondary, 2,4,6-trinitrotoluene (TNT) has been chosen due to its extensive historic role as a military explosive. There are many ways to prepare TNT for an explosive charge; casting has been chosen as this was a commonly practised technique.

Performance characteristics review

Performance characteristics from several sources have been reviewed and collated in Table 1.

Much like any chemical, the performance characteristics are heavily dependent on the exact physical properties of the composition tested. Therefore, performance characteristics can vary between sources. As such, characteristics in Table 1 will be as accurate as possible to the properties reported in said table. Where this is not the case it will be noted.

Explosive Name	Lead Azide α -form	TNT
Molecular weight, g/mol	291.24 ^a	227.133 ^a , 227.1 ^d
Melting/decomposition point, °C	190 ^a (decomp), 200 (stable 6 hrs) ^c	80.7 ^a , 80.8 ^d
Ignition point, °C	327-360 ^a , 330 ^c	345-373 ^a
Typical Density g/cm ³	4.17 ^a , 4.68 ^c , 4.8 ^d	1.654 ^{a,d} , 1.5-1.6 (cast) ^b
Velocity of detonation (density), m/s (g/cm ³)	4500 (3.8) ^a , 5500 (3.8) ^b , 4550 (1.8, confined) ^c , 4500 (3.8) ^d , 5300 (4.6) ^d	6850 (1.55) ^a , 6900 (1.6) ^b , 6900 (1.6, confined) ^d
Heat of explosion, kJ/kg	1610.36 ^a , 1638 ^d	4091.63 ^a , 3646-4564 ^d
Hotspot ignition point, °C	430-500 ^a	Not reported
Friction sensitivity, N	0.1-1 ^{a,d}	>353 ^{a,d}
Impact sensitivity, N	2.5-4 ^{a,d}	15 ^{a,d}
Oxygen Balance	-5.49 ^a , -5.5 ^d	-73.96 ^a 73.9 ^d
Gas volume L/kg	231 ^{c,d}	825 ^d
Critical diameters	Varied	Varied

Table 1: Performance characteristics and properties of selected explosives. (a - Akhavan [1], b - LLNL Handbook [2] note also this source contains vastly varied data based on testing, c – Maytáš [3], d – Meyer [4])

Akhavan's book on the chemistry of explosives [1] contains mostly complete information on both lead azide and TNT, however most pieces of data are given in single instances under

specific conditions which don't always stay consistent with other values. For example, the velocity of detonation is recorded for lead azide at 3.8 g/cm^3 , but elsewhere the density sits at 4.17 g/cm^3 . This is likely a testing constraint, but it does cause uncertainty in the applicability of detonation velocities to different densities within this report.

The LLNL Handbook [2] features a wide variety of test data from different original sources, most of which are difficult to obtain. As such, knowledge of the methodology of testing for each result is quite limited, with only the occasional note about confinement or density of the explosive tested. It is not even certain in all cases if the lead azide tested was always the α -form, although it might be assumed that testing of anything but α -form would be impractical due to limited use. Similarly, very few data entries clarify if containment was used, making it a challenging source to use for this purpose. This prompts some amount of caution in using such data, however few publications are as detailed or as broad as to cover multiple densities and variations of explosives, so in some cases it is the only publication that can be relied on.

Maytáš' book on primary explosives [3] features a plethora of data for a number of primary explosives, lead azide being one. Maytáš does however often include the conditions under which the test data was acquired. This does not necessarily make the data more useful in the case of this report, but it does help to inform the validity of the application of said data.

Meyer's book "Explosives" [4] does feature extensive information on both lead azide and TNT and similar issues pertaining to changing densities persist, however there is largely agreement with Akhavan when it comes to friction and impact sensitivity. There also seems to be general agreement with other sources, so long as it is assumed that Meyer has rounded their values.

The ignition temperatures found for an explosive via hotspots generated from friction between crystals or pore collapse are higher than the typical ignition point. This is due to their transient nature; they must coalesce to overcome the activation energy to initiate a combustion reaction [1],[5]. It should be noted that in the case of TNT, hot spot ignition temperature is largely underreported, this may be due to heat dissipative effects cause by melting of TNT crystals. As a result, TNT is less impact sensitive than lead azide and therefore requires a more sensitive primary to detonate reliably.

Primary

The critical diameter of lead azide has not been conclusively studied in the public domain, however research has demonstrated detonations well below the sub-millimetre range, some reporting as low as $10 \text{ }\mu\text{m}$ [6]. This is likely due to a combination of extremely fast reaction kinetics and low activation energy enabling an easily self-sustaining reaction. The unstable nature of the azide functional group likely contributes to this behaviour. As such, diameter is not a limiting factor in lead nitrate's usage as a detonator from the perspective critical

diameter, although there may be structural issues associated with particularly thin charges [5].

However, the velocity of detonation does change with charge diameter [3], so to improve the reliability of detonation of the secondary charge, a diameter $>0.6\text{mm}$ will be used here as a worst case using the highest bound of critical diameter from the LLNL explosives handbook [2]. Additionally, charges of 1.2 mm [7] with relatively loose confinement (6 mm steel) have been shown to detonate.

As seen in table 1, the density of lead azide charges can vary greatly. In part due to the main hotspot initiation mechanism being driven by inter-crystalline friction, lead azide is not particularly prone to dead-pressing, where high density leads to reduce pored collapse [5]. As such lead azide can be pressed to its maximum theoretical density of 4.8 g/cm^3 [5], and while this would increase velocity of detonation considerably, it would likely also induce greater friction and impact sensitivity due to increased inter-crystalline friction that would naturally follow from increased compression. As such, a density of 3.8 g/cm^3 will be chosen to ensure accurate an accurate velocity of detonation.

Lead azide is highly friction sensitive, with sensitivity ranging from $0.1\text{-}1\text{ N}$ (see table 1) [1],[4]. This wide range is attributed to variation in crystal structure during testing [3]. Regardless, a friction-based stab initiation would be an effective initiation mechanism for this primary explosive.

Secondary

TNT's critical diameter can vary significantly depending on the conditions under which it's prepared. For this report, an assumption has been made that the TNT has been cast to 1.62 g/cm^3 , leaving it with a critical diameter of 14.5 mm unconfined [2].

Increasing the density of the TNT charge would also increase the velocity of detonation and shock sensitivity, as supported by the findings that a difference of just 0.02 g/cm^3 resulting in a halving of reaction time for TNT [8]. However, as compression increases beyond this point, pores would likely get smaller, with some being eliminated entirely, reducing the number of viable hotspots within the charge. Furthermore, as the density of a substance increases, the ability to disperse heat increases, limiting the effect of hotspot ignition. This combined effect is known as dead-pressing [4].

Confined case

Because detonation waves are convex, in an unconfined explosive detonation some energy is lost from the sides of the charge rather than contributing to sustaining the reaction of the explosive substance. The critical diameter marks the point at which those losses are low enough that a detonation can be sustained [1]. When an explosive is confined, it's burn rate will increase substantially [1] due to an increase in pressure and a reduction of heat losses to the outside, making detonation almost guaranteed with a strong enough confining material

[4]. TNT for example has been reported by Meyer [4] to have a critical diameter of 5 mm under steel sleeve confinement. Jung's work [6] found that at a 0.050 mm diameter weakly confined with glass capillary tubes, lead azide will detonate at a velocity of 2670 m/s.

This indicates that confinement of both the primary and secondary explosives in this report would be beneficial in improving reliability of detonation and increasing velocity of detonation which in turn may assist in explosive charge performance.

Summary of the explosive chain

An explosive chain can therefore be constructed in two cases:

The first would be unconfined, with a stab sensitive lead azide detonator >0.6 mm in diameter laid against a >15 mm diameter charge of 1.6 g/cm³ cast TNT. This would successfully detonate with a velocity less than the maximum confined velocity of 6900 m/s.

The other would be inside a steel confinement as seen in Fig. 1, using lead azide (3.8 g/cm³) as a primary with a gap in the casing ready for stab initiation. The lead azide of a diameter >0.05 mm will then detonate, causing initiation of the secondary explosive main charge consisting of casted TNT at >5 mm diameter. Due to the confinement via steel casing, rapid detonation will occur with velocity of detonation approaching 6900 m/s. It should however be noted that the shock produced by lead azide of this diameter likely would not be enough to detonate the TNT, so a wider diameter should be used in practice.

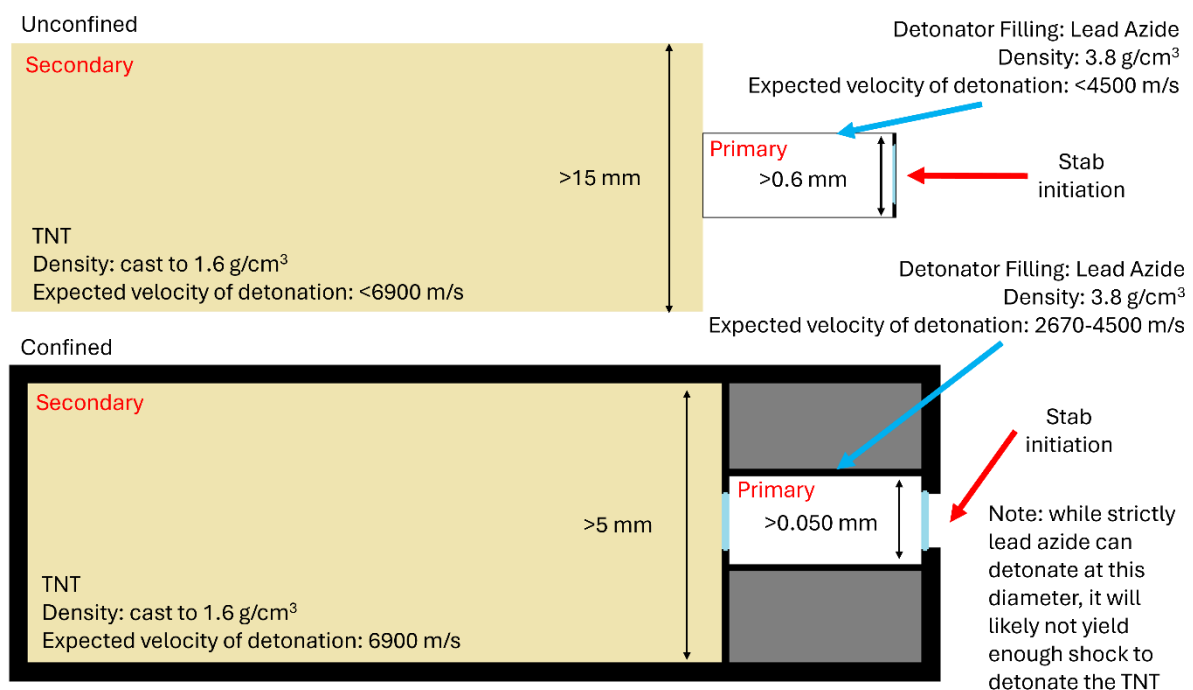


Figure 1: Showing the two cases of successful explosive chains, note: diagram not to scale.

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