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1 Introduction

This report is an analysis of an energetic compound and how it can be integrated into a munition. This includes demonstrating the principles of explosive types and the requirements for an explosive train and a munition design process that complies with the safety standards for munitions.

2 Oxygen Balance

The explosive that has been tasked for research is a 60% RDX and 40% TNT mixture, making it a secondary explosive. For the munition this mixture would be the payload with a suitable primary and booster within the ignition train to supply the shock energy required for detonation.

Oxygen balance is a method of quantifying how well an explosive provides its own oxidant [1]. This is vital for determining how well an explosive will perform as the gaseous products of an explosive reaction that provide energy through heat of formation are oxides [2].

Most explosives consist of four elements; Carbon, Hydrogen, Oxygen and Nitrogen. During detonation, hydrogen and nitrogen both form H_2 and N_2 gases which have a 0 kJ/mol heat of formation. Therefore, they do not provide energy when formed leaving only the reaction between the carbon and oxygen to provide energy to sustain the explosive shockwave through the material.

Carbon and oxygen can form two products dependent on the available oxygen within the explosive mixture, CO and CO_2 . Carbon monoxide (CO) has an enthalpy of formation of -110.5 kJ/mol [3] and carbon dioxide (CO_2) has an enthalpy of formation of -393.5 kJ/mol [4]. The negative quantifies an exothermic reaction with carbon dioxide providing more energy than carbon monoxide. Therefore, the more available oxygen in the explosive mixture the more CO_2 is formed which results in more energy to push the shockwave through the material.

The oxygen balances for RDX and TNT are -21.61% and -73.96% respectively. From the percentages of each material in the final mixture, the oxygen balance for the explosive material can be calculated as follows:

$$\begin{aligned} \text{OB} &= (6/10 * -21.61) + (4/10 * -73.96) \\ &= (-12.966) + (-29.584) \\ &= \mathbf{-42.550\%} \text{ (3.d.p)} \end{aligned}$$

3 Velocity of Detonation (VoD)

VoD is the speed at which the detonation shockwave moves through the mixture. From the data given, the VoD of the mixture can be calculated using density (ρ) and VoD of RDX and TNT.

$$\begin{aligned} \rho_{\text{mixture}} &= 1 / ((0.6/1.793) + (0.4/1.654)) \\ &= 1 / ((0.334..) + (0.241..)) \\ &= \mathbf{1.735 \text{ g/cm}^3} \text{ (3.d.p)} \end{aligned}$$

$$\text{VoD}_{\text{Ex in mix}} = \text{VoD}_{\text{Ex}} * (\rho_{\text{mixture}} / \rho_{\text{Ex}})^n$$

Where n is the sensitivity of the VoD within the explosive to changes in density

$$\begin{aligned} \text{VoD}_{\text{RDX in mix}} &= 8440 * (1.735/1.793)^{0.4} \\ &= 8329.714 \text{ m/s} \\ \text{VoD}_{\text{TNT in mix}} &= 6850 * (1.735/1.654)^{0.4} \\ &= 6982.262 \\ \text{VoD}_{\text{mixture}} &= (0.6 * 8329.714) + (0.4 * 6982.262) \\ &= (4997.828) + (2792.904) \\ &= \mathbf{7790.732 \text{ m/s}} \text{ (3.d.p)} \end{aligned}$$

4 Brisance

Brisance is defined as the ratio between the potential of the explosive and the duration of the detonation [5]. Brisance shows the speed that the explosive reaches peak pressure which determines the effectiveness of an explosive in military applications such as fragmentation [5]. It is the factor that controls the velocity imparted on the fragments from bombs, grenades and mines [5].

Brisance is normally calculated by the sand crushing test as experimental measuring is more accurate than estimated calculations using density and VoD of an explosive [5].

Detonation pressure is the most accurate way to estimate a brisance comparison between explosive compounds, which can be calculated with the following formula:

$$P = (\rho * v^2)/4$$

Where P is detonation pressure, ρ is density of the explosive compound and v is the detonation velocity.

Using the density and VoD calculated in section 3, the detonation pressure for the mixture can be calculated below:

$$P_{\text{mixture}} = (1.735 * (7790.732)^2)/4$$

$$= 26,326,675 \text{ Pa}$$

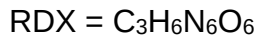
$$= \mathbf{26.3 \text{ GPa}}$$

In comparison to TNT and RDX, with a detonation pressure of 19 GPa and 31.9 GPa respectively, the detonation pressure of the mixture is greater than that of TNT but less than that of RDX. Therefore, by estimate, RDX has the highest brisance.

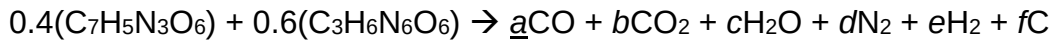
5 Detonation Products

The detonation products of the mixture can be calculated using the Kistiakowsky Wilson rules in Figure 1.

This can be done using the chemical formulas for RDX and TNT.



Therefore for 1 mole of the mixture, the formula is:



$$\text{C: } (0.4 \cdot 7) + (0.6 \cdot 3) = 4.6$$

$$\text{H: } (0.4 \cdot 5) + (0.6 \cdot 6) = 5.6$$

$$\text{N: } (0.4 \cdot 3) + (0.6 \cdot 6) = 4.8$$

$$\text{O: } (0.4 \cdot 6) + (0.6 \cdot 6) = 6.0$$

Order	Condition	Reaction
1	Oxygen atoms oxidize 'H' atoms to H ₂ O molecules	$2\text{H} + \text{O} \rightarrow \text{H}_2\text{O} \text{ (gas)}$
2	Remaining 'O' atoms oxidize all 'C' atoms to CO molecules.	$\text{C} + \text{O} \rightarrow \text{CO} \text{ (gas)}$
3	Remaining 'O' atoms oxidize all 'CO' molecules to CO ₂ molecules	$\text{CO} + \text{O} \rightarrow \text{CO}_2 \text{ (gas)}$
4	Excess of O, H and N atoms are converted to O ₂ , H ₂ and N ₂ . Any excess C stays as C _{solid} .	$2\text{H} \rightarrow \text{H}_2 \text{ (gas)}$ $2\text{N} \rightarrow \text{N}_2 \text{ (gas)}$ $2\text{O} \rightarrow \text{O}_2 \text{ (gas)}$

Figure 1: Kistiakowsky-Wilson Rules [6]

1: All N $\rightarrow$ N₂

2.4 N₂

2: All H $\rightarrow$ H₂O

2.8 H₂O

Leaving 3.2 O remaining

3: $C \rightarrow CO$ with remaining O forming CO_2

3.2 CO

Leaving 1.4 C remaining

4: Remaining C $\rightarrow$ solid C

1.4 C

Therefore, the products of detonation for 1 mole of the mixture are



In comparison to TNT, the detonation products suggest that the mixture is a more efficient explosive as the oxygen balance is much higher. This means that as water and carbon monoxide are formed, more energy is released than that of TNT during detonation.

6 Explosive Train

The explosive mixture is a secondary, high explosive as it is made from TNT and RDX which are both also secondary explosives. High explosives detonate due to their chemical formula and have a figure of insensitiveness of ≥ 50 , meaning they can be fairly insensitive. Due to being insensitive, they require a booster or donor pellet in order to detonate. This setup is known as an explosive train which normally contains three explosives; a detonator filled with a primary explosive; a booster or donor pellet made from a secondary explosive with a low figure of insensitiveness; and a main fill made from an insensitive secondary explosive.

FOI is a measure of a materials sensitivity to impact and indicates how much shock is required to detonate an explosive [8]. RDX has a FOI ≈ 80 and TNT has an FOI ≈ 100 so the mixture would have an estimated FOI of 80-100. Explosives within this region are considered moderately insensitive but they can still be used in detonators and boosters, such as Tetryl which has an FOI of ≈ 85 .

From the data collected about the explosive mixture, an assumption can be made that it is Composition-B3. This can be assumed due to the makeup of 60% RDX and 40% TNT as well as the estimated brisance and detonation velocity [10][11]. Composition-B is a versatile, melt-cast HE which has been used in artillery projectiles, rockets, landmines, hand grenades, and various other munitions [11].

For this munition, a shock detonation would be the most appropriate as it allows for more control on when the munition detonates and has a lower risk of misfire and ineffective firing. Therefore, the explosive train will contain a detonator and a booster pellet for a successful detonation [7]. For the FOI region of 80-100, the shock required for detonation is approximately 8-15 GPa so a booster with a detonation pressure of 15 GPa or higher is required otherwise the mixture in the main fill will not have sufficient shock to reliably initiate detonation. The shock sensitivity of an explosive can vary due to conditions such as temperature and confinement but by including a booster with a higher shock output, these factors are nullified.

For initiation of the explosive train, a variety of detonator types can be used such as a low voltage L2A2 for experimental initiation or a stab detonator for initiation within a munition. L2A2 detonators consist of a primary charge, made up of aluminium, lead azide and lead styphnate, and a base charge of PETN [12]. Lead azide is the primary of highest mass within an L2A2 making roughly 68% of the primary charge. By total mass of the detonator, it is roughly 15.7% of the energetic material [12]. Within a stab and percussion detonator, lead azide is also the most common primary used, with a stab detonator also requiring an igniferous composition to ignite the azide [15]. The grain length for lead azide differs, but the most common range is 5-15 μm [14]. The most common form of lead azide is in grain or powder due to it being very sensitive and its critical diameter being <1mm with a density of 4.71 g/cm³ [13][14].

The booster for the explosive train must be detonator sensitive to be universal for both experimental and munition detonation. PBXN-5 has been chosen due to this factor as it is detonator sensitive and that its shock output is $\approx 27\text{GPa}$, which is high enough to reliably initiate detonation within Composition B3 [16].

For experimental firings, an L2A2 detonator is used as it can be electrically initiated and aligned with the instrumentation required for data collection. The setup would consist of the L2A2 in contact with the PXBN-5 booster which is also in contact with the Composition B3.

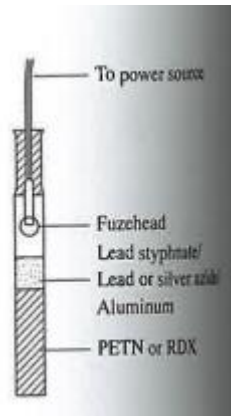


Figure 1 – L2A2 Detonator Diagram [15]

Figure 1 shows an L2A2 detonator that is used for experimentally firing the explosive mixture in Figure 2.

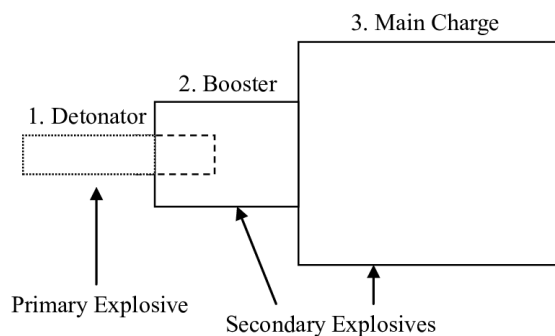


Figure 2 – Electrically initiated explosive train [17]

Figure 2 clearly demonstrates the intimate contact between the three explosives used within the explosive train to achieve successful detonation. If the contact is not intimate, the detonation shockwave loses energy as it travels in the air gap between the explosive compounds and would therefore make the detonation unreliable. This is due to the shock wave energy input into each section being variable due to energy loss.

Within a munition, a stab detonator is used which is found at the base of the munition and is initiated by a firing pin exerting force onto the cap [15].

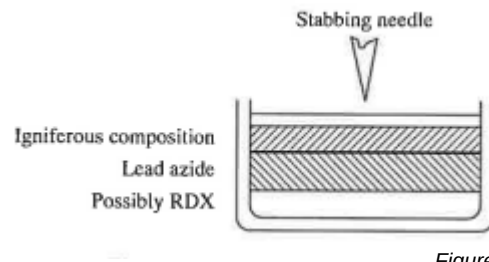


Figure 3 – a stab detonator diagram [15]

The igniferous composition in Figure 3 is required to ensure that enough hot particles are ejected onto the primer, which in this case is lead azide, to initiate the composition.

7 Grounded Sea Mine Application

Grounded sea mines have been used for centuries in ocean warfare and have been developed over the years to remain effective with the newer naval ships [21]. They were first used in 14th century China for defence against pirates and were filled with gunpowder [21]. The main development of sea mines stemmed from World War I to hinder the movement of German U-boats [21]. Grounded/bottom sea mines rest on the seabed in typically shallower waters and are triggered by magnetic or acoustic signature of ships as they pass by [21]. Due to their low profile, they are harder to detect especially at ground level which made them key in both World Wars for an initial line of defence [21].

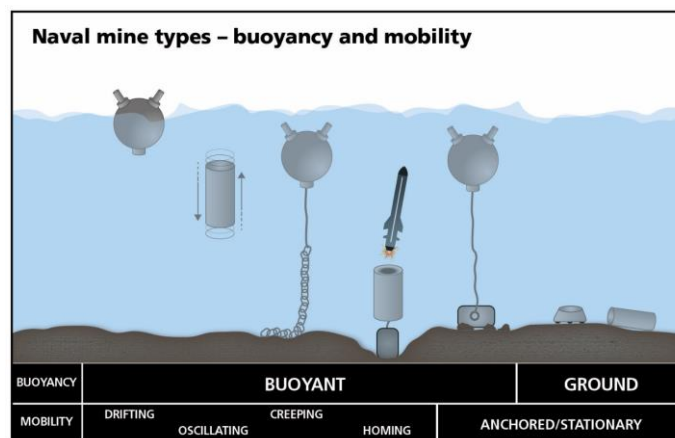


Figure 4 – Naval mine types [22]

For the application of a grounded sea mine, aluminium can be added to the mixture for increased underwater performance. In an underwater explosion, the gaseous products are confined by water which allows the aluminium to react more completely with the detonation products [18]. Adding an additional oxidant can further increase the reaction rate of the aluminium which increases the energy output [18]. The aluminium reacting with the detonation products creates a large number of bubbles that significantly increase the bubble energy of the detonation [19]. Aluminium also increases the duration of a blast wave, both underwater and in air, due to its reaction with the detonation products. As the explosive needs to detonate initially prior to the aluminium reaction, which sustains high temperature and pressure [20]. This is particularly effective when underwater as the pressure within the bubble increases exponentially through the prolonged reaction and can create a far more devastating impact when the pressure is released [20][19].

8 Conclusion

This report covers an explosive mixture of 60% RDX and 40% TNT with calculated VoD, density and oxygen balance. These calculations determine the mixtures effectiveness in an explosive application for both experimentation and munition uses. Additives can also be added to the mixture to alter its application to be more effective within underwater mines which have been proven to improve performance.

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