

CRANFIELD UNIVERSITY

Nicholas RW Coward

**A Study of Blast Characteristics and TNT Equivalence of
Propellants**

**CRANFIELD DEFENCE AND SECURITY
Explosives Ordnance Engineering**

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By: Nicholas RW Coward

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This thesis is submitted in partial fulfilment of the requirements for the Degree of
MSc

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ABSTRACT

Typical munitions will contain a greater quantity of propellant than of High Explosives, so it is important to identify the comparable risk posed by the propellant in both storage and transport to accurately understand the potential threat.

In this project, the detonation of a selection of double and single base small-arms propellants and a triple base gun propellant was attempted in different configurations. The purpose was to obtain peak overpressure and impulse data from detonations to determine TNT equivalence. This data can be further used in Equivalent Net Explosive Quantity (ENEQ) calculations. While some propellants are shown to detonate readily with minimal stimulus in an unconfined state, others will not without significant confinement or the use of a booster. Where full detonation was not achieved, or usable blast data could not be collected, the responses of propellants in different situations is analysed and the energetic contributions of the propellants is assessed.

Of the propellants tested, two double base rifle propellants (H335 and BL-C(2)) failed to detonate, whilst another double base shotgun propellant (Lil' Gun) and a single base rifle propellant (H322) showed signs of a partial detonation. Bullseye, a double base pistol propellant showed a full detonation in minimal confinement, with a TNT equivalence of between 0.8-1.08 found at the distances tested, and a triple base gun propellant (NQ/S42-12) was found to have a TNT equivalence between 0.16 and 0.26 based on a heavily modified air blast test. Significant variation was found in TNT equivalence values for range, and also for charge mass, with values as high as 2.32 found at close ranges from cylindrical charges.

Where a detonation failure was observed, the defining factor appears to be energetic content in double and single base propellants, with critical diameter also a likely candidate in triple base propellants.

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1.0 – Introduction

1.1 - Foreword

TNT equivalence is widely used in the explosives industry as a simple way to quantify the explosive power and performance of a material. Using this method, commonly used materials are subjected to testing to establish their TNT equivalence for simple comparison of both risk and effects, so that either a correct amount can be used for a purpose or a safety limit can be set for storage, transport, and handling. While there is sufficient information for Hazard Division (HD) 1.1 materials such as High Explosives due to their common use, relatively limited number, and high power there is very little such information available for the wide range of HD 1.2 and HD 1.3 materials, including many propellants and pyrotechnics.

While these HD 1.2 and 1.3 materials have a significantly lower risk of unintentional detonation as well as typically having lower explosive power, they are often in much greater quantities than HE in munitions such as missiles or complete artillery and naval gun shells, and thus it is important to be able to understand and characterise their response in a worst case scenario.

By improving the understanding of TNT equivalencies for these materials, limits on mass for transport, storage, and handling can be adjusted to more accurately represent the potential threat. Factors such as varying effects at range, or critical masses can also become apparent, so that optimal storage arrangements could be suggested to minimise the risk of sympathetic detonation of other stores.

1.2 – Aim

To review literature and conduct small-scale testing to determine the response and TNT equivalence of a small selection of single, double, and triple base propellants.

1.3 – Approach

In order to achieve the aims mentioned above, the following work will be done:

- A review of underlying principles and relevant literature
- Small-scale testing of a range of propellants to determine their blast parameters
- Comparison of the acquired blast parameters to TNT values from ConWep data
- Calculation of the TNT equivalence for propellants tested
- Recommendations for further work to improve the subject area

2.0 – Background

In this section basic principles and underlying theory will be explained that will be applied in later sections.

2.1 – Ideal and Non-Ideal Blast Waves

Idealised Blast Waves

Visualisation of blast waves is inherently difficult due to the short timescales involved, and the intense energies and pressures experienced. While blast waves from explosive events will vary depending on many factors including the material and its mass, as well as atmospheric and geometric conditions, a blast wave can be illustrated by defining the variations in pressure seen by an arbitrary point in space at a distance X away from a blast exhibiting spherical symmetry. A representation of an ideal blast wave can be seen in Figure 1 below.

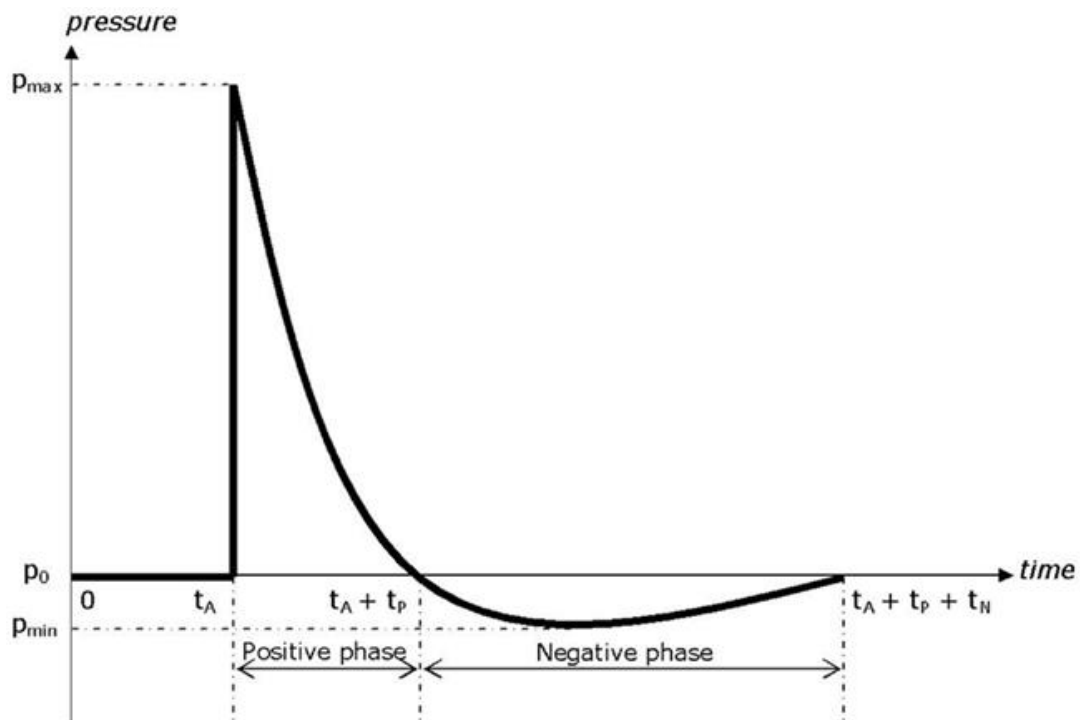


Figure 1 - Representation of an ideal blast wave [1]

An ideal blast wave from a high explosive detonation will consist of two key phases; a positive and a negative phase. From the start of detonation, the blast wave and rapidly expanding gasses create a pressure differential that travels out from the

blast epicentre at high speed. At the point in space X metres from the epicentre, this pressure differential will arrive at time t_a which indicates the start of the positive phase. At this point, the pressure at point X will rise abruptly from ambient (P_a) to a maximum pressure (P_{max}). This term can be known as peak pressure (absolute pressure) or peak overpressure (pressure above P_a). As the blast wave passes point X , pressure will usually decay exponentially, with the time taken to return to P_a defining the positive phase duration (t_p). The area under this positive phase of the curve is the positive impulse (I_p). Due to an effect known as afterflow, following the positive phase, the pressure will continue to drop to below P_a for a further period of time (t_n) known as the negative phase. The area within this curve is known as the negative impulse (I_n) [2]. For the purposes of this project, the key area of interest is the positive phase, with peak overpressure and impulse in this phase being the key parameters referred to through for the remainder of the text.

Non-Ideal Blast Waves

In contrast to an ideal blast wave, the pressure variations observed by a point in space for experimental blast waves will not always follow the idealised form shown above. Variations in pressure can occur due to slight inconsistencies in the detonation reaction and the atmospheric properties and may appear as a pressure difference (when compared to another symmetrical point in space) or as noise. Noise is a general term for an unwanted random addition to a signal, and can come from a multitude of sources, but is also inherent in electronic equipment and known as Johnson–Nyquist noise [3]. When considering high amplitude signals such as blast wave pressures, this type of noise is relatively insignificant due to the high signal strength generated by a pressure transducer compared to its noise (Signal-to-Noise ratio). A much more significant source of noise is caused by external effects on the pressure transducer itself. Simple physical effects such as vibrations in the sensor and sensor stand from the blast wave can create noise, as can meteorological variations such as wind, temperature changes or rain. During the transition of the blast wave, there are more complex and unpredictable elements that can introduce noise-like signals in to the

blast measurement, such as un-burnt material or turbulent gasses passing over or near the gauge [4]. Both of these are greatly exacerbated at close range, especially if the sensor is enveloped by the fireball. An example of typical noise seen in blast wave measurements can be seen in Figure 2 below, where clear and irregular deviation from the ideal wave shown in Figure 1 can be seen as the pressure drops away during the positive phase, and throughout the negative phase.

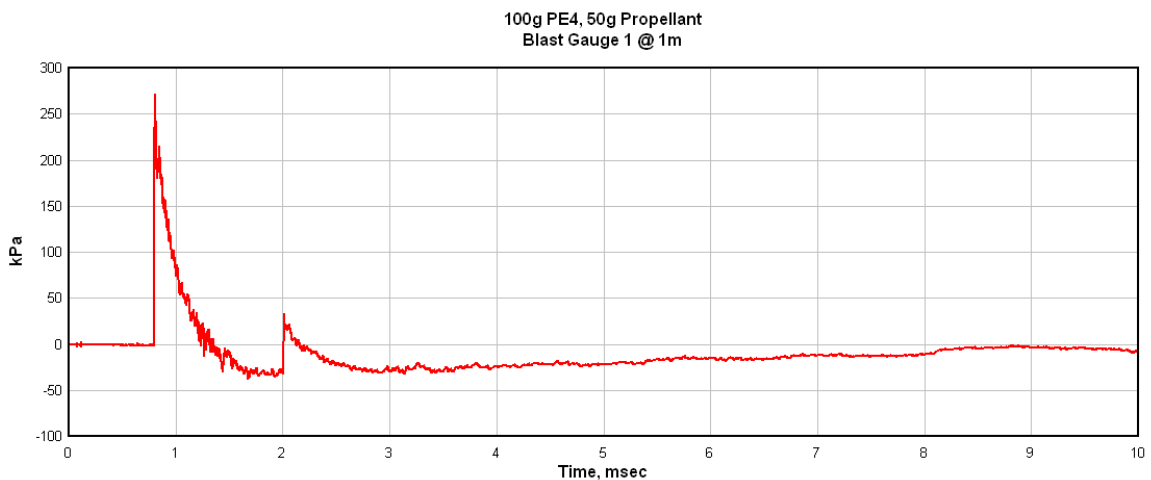


Figure 2 - A typical experimental blast pressure wave, showing a secondary wave behind the initial peak.

Other factors that can affect blast waves, particularly in different directions away from the charge, can be the point of detonation. If an explosive charge is detonated from one side (as opposed to centrally), the detonation wave will travel through the charge and increase the overpressure seen at the opposite end of the charge, compared to the overpressure seen at the side where detonation occurs. This effect can also be seen by the size of the fireball projected from each end of a cylindrical charge, as shown in Figure 3 below; a larger and more focussed fireball can be seen being projected from the right hand side of the fireball, after detonation occurred on the left.

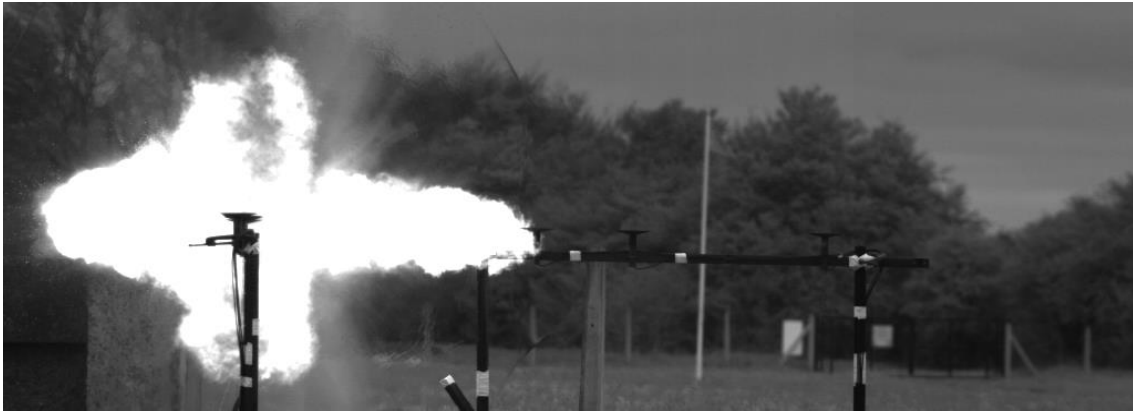


Figure 3 - Fireball projection from a cylindrical charge, opposite to the end (left) of initiation

While the shaping of an explosive charge has a significant impact on the directional variation in pressure irrespective of point of detonation, the effect of changing the point of detonation becomes more noticeable in non-spherical charges of greater length where the charge is detonated at one end [5].

Obstacles in the path of the blast wave will also affect the pressure in a multitude of ways, some of which will be covered below. For this project, interference from objects on the range, including the ground, is kept to a minimum.

Complex Blast Waves

Secondary Blast Waves

Secondary waves are often seen in pressure gauge measurements as a shock wave that travels behind the primary shock wave and typically has a lower peak pressure. The term secondary pressure waves can include a number of different waves, but most are little understood phenomenon that occur in detonations. In the case of non-spherical charges, secondary waves can be caused by interactions between primary shock waves and a bridging wave between two primary waves as described in a later paragraph. It is also thought that secondary waves occur as a result of an 'implosion wave', which formed from a reflection within the charge itself that travels out as a shock wave behind the primary wave [6].

Shock wave reflections occur when a blast wave meets an obstacle or interface that differs from the medium it is travelling in. The strength of this reflection is proportional to the rigidity of the surface it collides with, or the density difference in

the interface. In free air, the reflected shock wave that moves away from an object will accelerate as it passes through the 'pre-shocked' air, at a higher temperature and pressure, left by the movement of the primary shock wave as described by the Rankine-Hugoniot relationship [7] [8]. A shock wave is commonly seen reflected from the ground in low altitude firings; all firings for this project are done at 2m from the ground to prevent this ground reflected wave from interfering with the primary waves over the distances being measured [9] as described in section 4.4.

Blast Waves from Non-spherical charges

Due to their geometry, spherical charges have a blast wave that is uniform in all directions as the blast wave travels away from the charge perpendicular to its surface. Because other shapes do not have such spherical symmetry, a much more complex pattern of blast waves can be seen close to the charge as a shock front moves away from each different surface. For the purpose of this project, cylinders are the only non-spherical shape used.

In cylinders, a shock front will move away from each flat end, as well as a shockwave moving outwards from the curved surface. Between these two shock waves, a bridging wave is created that travels away from the charge. Where the primary waves and bridging wave interact, a reflected wave is created that will travel at a greater speed than the initial primary shock waves as described above. This wave will promptly catch up with the primary wave and coalesce, at which point the blast waves are said to have 'healed' and can be considered to be similar to a spherical blast wave. This process will occur within a few metres of a <1kg charge [6]. A pictorial representation of this can be seen in Figure 4 below.

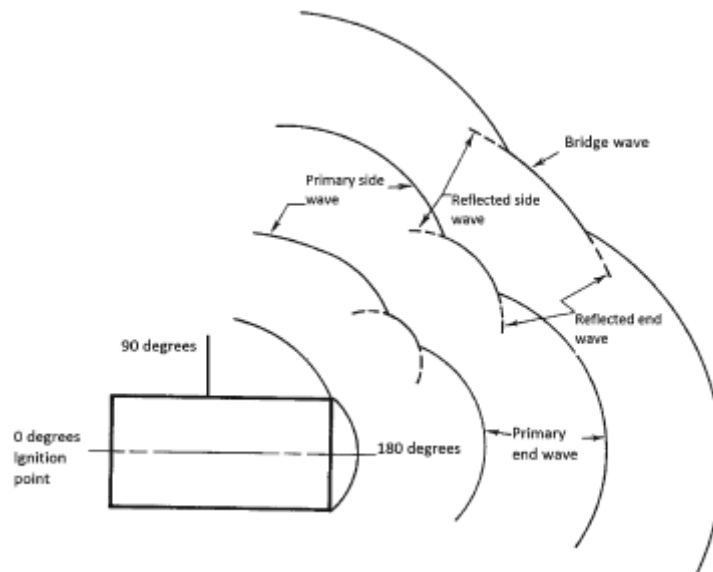


Figure 4 – Progression of shock waves from a cylindrical charge [10]

Shortly before the reflected waves coalesce with the primary waves, they merge with the positive phase of the primary wave and can make impulse of the initial primary wave difficult to determine, or essentially increase the total positive phase impulse as shown in Figure 5 below. This effect is noticeable in later analysis of the impulse from cylindrical charges, where an increase in impulse is seen after the secondary wave merges with the primary in the axial direction (see Annex F).

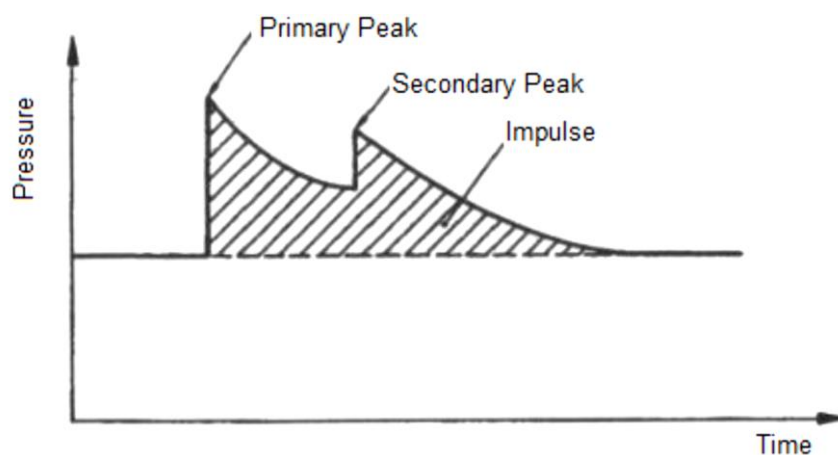


Figure 5 – Effect on impulse of interactions between primary and secondary waves [2].

2.2 – TNT Equivalence

TNT Equivalence is the most commonly used method of quantifying and comparing the effects and output of a given explosive to that of TNT. By doing this, an easily understandable ranking system of explosives can be established based on their individual TNT equivalency. Having this understanding of their destructive effects also finds uses in scaling calculations and blast or damage predictions, as well as for safety regulations for storage, transportation, handling, and siting of explosive facilities. TNT is used as the baseline due to its common historical use, and the extent of existing data available for it.

Used both in military and civilian fields, TNT equivalence can be determined using a number of different tests and can be calculated based upon a number of different explosive parameters such as overpressure or impulse. TNT equivalence of an explosive is generally established through experimental testing, which can be done using one or more of the established test methods. The most common tests include: ballistic mortar, plate dent, lead block (Trauzl), air blast, and sand crush [11]. More than one of these may be required to accurately represent the material, as the tests measure the output based on different empirical properties which can lead to a large variance in the TNT equivalence measured. P. Cooper explains that to varying extents in the plate dent test, lead block test, and sand crush test the output is directly related to the peak overpressure or Chapman-Jouguet (CJ) pressure of explosive, with little effect from other parameters [11]. Measuring TNT equivalence from CJ pressure in these tests does not properly take in to account the additional complication of energy losses to shock heating and fracturing, which scale proportionally with the CJ pressure. The ballistic mortar test on the other hand bases its result round the Pressure-volume (PV) work done by the explosive in the CJ zone; this does not reflect losses from non-ideal or aluminised explosives where chemical reactions can continue outside of the CJ zone and so not contribute effectively to the movement of the ballistic mortar [11].

The air blast test as explained by Cooper bases the result around both impulse and peak pressure at various distances to give two different equivalencies. This test however suffers from similar CJ pressure losses when metal casing is used around the charge (often weighing as much or more than the explosive) which has been calculated

to typically absorb almost half the energy available from the reaction through heating, fracturing and propelling the metal fragments, which detracts from the energy available in the blast wave. With this type of test there are also errors introduced by the different decay rates of overpressure from different explosives, meaning that TNT equivalence can vary with distance instead of remaining constant.

The effects of charge casing on blast mentioned above can be mitigated using a number of methods, many of which are discussed by Locking [12]. Due to their common use in munitions, the equations discussed by Locking are designed for use with steel or aluminium casings, and give relatively accurate results in this situation. The method outlined in the US Army engineering handbook [13] gives a slightly more generic solution, not based on casing material. This method approximates the energy taken to disrupt and accelerate the casing, and gives an equivalent case-less charge mass that would yield the same effect as the cased charge, using the equation:

Equation 1 – US Army Engineering Handbook method of compensating for case effects

$$W_b = 1.19 \left[\frac{1 + M_r(1 - M_c)}{1 + M_r} \right] c$$

Where c = actual charge mass; M_r = ratio of case mass (m) to charge mass (c); $M_c = 1$ when $M_r > 1$ and $M_c = m/c$ when $M_r < 1$

The equation makes an approximation based around the ratio of charge mass to casing mass to establish the approximate percentage of energy from the explosion that is absorbed by the casing, and gives a percentage that remains to influence the surroundings as a pressure wave. This percentage gives an equivalent bare charge mass for the charge.

Aside from the issues mentioned above, there are many other issues with TNT equivalence. Some error is expected from the ways in which it is calculated based on different explosive properties as well as slight variations between countries, facilities, their conditions, and the variability of TNT detonations [14]. Locking has reported on many of the problems associated with the theoretical methods for calculating TNT equivalence, stating a typical error in results of 20-30% when compared to experimental, with up to 50% disagreement in some cases [15]. Figure 6 below, shows

the variation in TNT equivalence reported for three different explosives (TATB, HMX, and RDX) from a wide range of sources, to illustrate how significant this disparity can be.

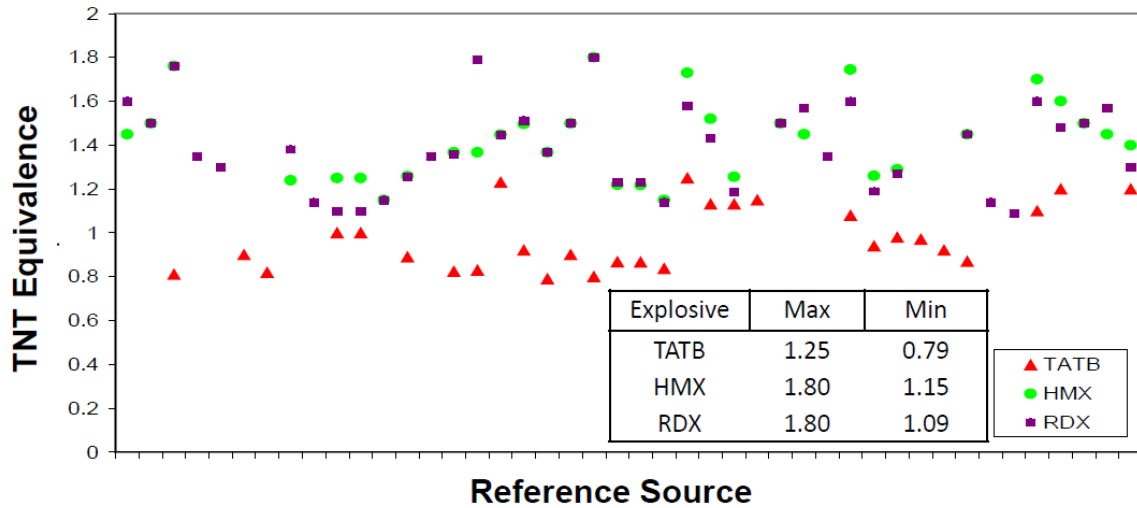


Figure 6 - Variation in TNT equivalence from three explosives, from a number of different techniques and sources) [15]

For the purposes of this project, the TNT equivalences will be calculated based on the air blast test, using the peak overpressure, and also impulse data where available. This decision is due to the equipment available for use, and the relative accuracy of the method. Specifically, TNT equivalence will be determined as the ratio of the quantity of material used, to the quantity of TNT which produces the same characteristic (overpressure or positive impulse) [13] using Equation 2 shown below [16].

Equation 2 - Calculation of TNT Equivalence

$$TNT_e = W_{TNT} / W_{Exp}$$

Where TNT_e is the TNT equivalence factor, and W_{TNT} and W_{Exp} are the masses of TNT and reference explosive (respectively) that give the same blast characteristic.

2.3 – Scaling Laws

A relevant characteristic of a blast wave, and of particular interest for TNT equivalency calculations at distance, is the decay of the blast wave over time or distance. It is clear that peak overpressure and impulse will reduce as distance from the detonation increases, and in general this can be found to follow a simple relationship, however different materials will deviate from this to different extents which can affect the TNT equivalence of a material at different ranges.

The scaling of air blast was first suggested by Hopkinson (GB) during the First World War and independently later in 1925 by Cranz (DE), with additions being made by Sachs (US) in 1944 to take in to account changes in ambient conditions [17]. Early work identified that the radius of a spherical charge can be related to its mass and energy release [18]:

Equation 3 – Initial Hopkinson Scaling Law

$$\frac{r_1}{r_2} = \left(\frac{C_1}{C_2}\right)^{1/3} = \left(\frac{E_1}{E_2}\right)^{1/3}$$

Where r is radius, C is charge mass, and E is energy released. Subscripts denote charges

This relationship requires that the two charges being compared are of the same material and packing density, and further that they are both detonated in the same configuration (including shape) and atmospheric conditions, specifically ambient pressure so that peak overpressure is not affected. The additions by Sachs allowed for variations in ambient pressure to be related for two identical charges, giving the relationship [19] [18]:

Equation 4 - Addition of pressure term by Sachs

$$\frac{r_1}{r_2} = \left(\frac{C_1}{C_2}\right)^{1/3} \left(\frac{P_{o2}}{P_{o1}}\right)^{1/3} = \left(\frac{E_1}{E_2}\right)^{1/3} \left(\frac{P_{o2}}{P_{o1}}\right)^{1/3}$$

Where P_o is ambient pressure, other variables as above

Further relationships by Sachs associate the blast wave energy with time using the square root of the ratio of ambient temperatures; however this relationship has

little significance for this project. In the late 1950's a tripartite agreement between the UK, US, and Canada suggested that these relationships be used to report all blast measurement data relative to a charge with unit mass in a STP atmosphere [20], leading to a scaled distance relationship. The validity of these laws, with a few exceptions, was confirmed by Dewey in 1964 for (equivalent) TNT charges between 25 and 10⁵Kg [21].

For the purposes of this project, there is very little variation in either temperature, or pressure between firings, with only charges of similar geometry and material being compared, so for this case only simple scaling laws need be applied. In order to plot the blast characteristics from charges of different mass on the same graph, a scaled distance based on the relationships from Hopkinson is used which can be defined by a simple relationship:

Equation 5 - Scaled Distance Equation

$$Z = R / C^{1/3} = R \cdot C^{-1/3}$$

Where R is distance from detonation in metres, and C is the mass of the charge (kg)

By using this relationship, results from charges of multiple masses and at various ranges can be related, as long as the same explosive is used with the similar density and in the same configuration.

2.4 – Equivalent Net Explosive Quantity

Net Explosive Quantity or NEQ is a term used to describe the total weight of explosive mixtures or compounds being referred to, not including casings, packaging, or non-explosive items. It can also include the mass of the TNT equivalence for the explosives [22]; however in the UK it is often just actual mass.

Equivalent NEQ or ENEQ is a term used by the maritime explosives community in the UK to more accurately represent the NEQ which is based on the TNT equivalence of the energetic material. ENEQ is also based on TNT equivalence, but takes in to

account the attenuating effects of casing and packaging, so is the equivalent bare charge weight of a munition. ENEQ is defined as [23]:

“The bare charge weight of TNT which results in the same value of the airblast parameter of interest at the same distance from the detonation source as cased munition”

The impetus for this thesis is based around the observations from several reports [23] [24] [25] on the ENEQ of naval munitions, that are unable to work out the ENEQ for various munitions containing propellants due to a lack of TNT equivalence data available for these propellants.

3.0 – Review of Relevant Literature

While the substantial majority of work in on TNT equivalencies is done for high explosives, there are examples of similar work being done for propellants. Much of the work has been conducted by the US military, and unfortunately is not approved for public release so is unavailable for reference in this project.

A report compiled in 1987 [26] contains blast parameters and calculated TNT equivalencies for a series of high explosives and pyrotechnics, as well as 14 propellants. The charges tested vary greatly in size, but are all compared at the same scaled distances (between 1.19 and 15.87 m.kg^{-1/3}). The majority of the charges are also tested in typical configurations seen during manufacture and storage. While the extent of the data in the report is too great to be covered here, a summary of the numerical data found in this report is shown in Table 1 below.

Propellant	Type	Purpose	TNT Equivalence – Overpressure [Avg. (Max, Min)]	TNT Equivalence – Impulse [Avg. (Max, Min)]	Charge Sizes (Kg)
Black Power	N/A	Igniter	0.3 (0.4, 0.2)	0.5 (0.5, 0.4)	227-2041
Benite	Single Base	Igniter	0.2 (0.3, 0.1)	0.5 (0.9, 0.2)	10.3–41.8
BS-NACO	Single Base	Naval Gun	0.2 (0.3, 0.1)	0.4 (0.5, 0.1)	22–150
DIGL-RP	Double Base	Tank Gun	1.8 (4.1, 0.8)	1.5 (2.9, 0.8)	25-74.8
JA-2	Double Base	Tank Gun	1.6 (2.6, 0.9)	1.4 (2.6, 0.8)	16-48.2
M1	Single Base	Artillery (105mm)	0.5 (0.7, 0.3)	0.6 (0.8, 0.1)	Not specified
M6	Single Base	Artillery (155mm)	0.4 (0.8, 0.2)	0.5 (0.9, 0.2)	22-26
M10	Single Base	Recoilless Rifle	1.1 (1.4, 0.6)	2.2 (5.8, 0.5)	11-45
M26E1	Double Base	Not specified	1.4 (2.5, 0.3)	1.1 (1.8, 0.7)	Up to 408
M30A1	Triple Base	Artillery	1.1 (2.0, 0.5)	0.9 (1.7, 0.4)	12.4–22.7
M31A1E1	Triple Base	Artillery (155mm)	1.2 (2.1, 0.6)	0.8 (1.6, 0.4)	27.2–55.2
N5	Double Base	Rocket Motor	0.8 (1.4, 0.4)	0.8 (1.3, 0.4)	Not specified
WC844	Double Base	Rifle Powder	1.7 (3.8, 0.5)	1.1 (2.3, 0.4)	22.7 – 45.4
XM37	Double Base	Rocket Motor	1.8 (2.8, 1.1)	1.6 (2.9, 1.0)	1.9 - 23

Table 1 - Literature based TNT equivalencies of propellants [26]

It is clear from the results that propellants can yield a wide range of TNT equivalencies, with values above 1.0 being common in higher energy propellants. What is also clear from the data in the report is that there is a notable variation in the TNT equivalence of the propellants at range, with one showing a TNT equivalence of 5.8 at close range.

As a summary, the report notes several points about propellants observed from their firings. Logically, it was stated that the pressure and impulse varied depending on the geometry and packing of the charge, and that propellants high in moisture failed to detonate. They also observed the effects of secondary waves in cylindrical charges, as discussed in Section 2.1.3 above. Of the more interesting observations is that propellants with a thickness of less than ~152.4mm (~6 inches) were failing to detonate; this may present a problem for this project, where range limits prohibit the use of this amount of material.

When TNT equivalence at range is discussed, they notice that especially for single and double base propellants tested, a much greater pressure and impulse is detected at closer range (less than $2.14\text{m.kg}^{-1/3}$) followed by lower than expected readings at further range (beyond $3.57\text{m.kg}^{-1/3}$). They also observe a higher TNT equivalence in single and double base propellants than in triple base or composite propellants.

For consideration, WC844 and M31A1E1 are broadly similar in composition to the propellants Bullseye and NQ/S42-12 respectively that will be used in this project; however the masses used in each firing in the report discussed here are significantly greater.

In another report [27], small quantities of Bullseye (1-2g) are tested with a central PETN booster. This report finds TNT equivalencies varying between 1.0 and 0.15 depending on range, with a decrease in TNT equivalence at greater ranges. This report also confirms the ability of this smokeless propellant to detonate readily without confinement; however boosters of between 0.66g and 0.97g are used which are large when compared to the mass of the Bullseye. Due to the charge set up in this case, where the Bullseye is formed as a shell around the booster, the authors use a

series of equations based on previous characterisation of the materials to determine the effect of the shell alone (without the booster) based on distance from the charge at which the peak pressure from the shell mass alone will be equivalent.

A report which was done for the US Navy [28], determines the maximum TNT equivalence of a series of naval propellants. Unfortunately a copy of this report is not freely available, however based on the abstract, a TNT equivalence of 0.7-0.75 is found for a number of double base rocket motors, with other showing lesser reactions, and equivalencies between 0.05 and 0.5. Their recommendation is that double base propellants are considered to have a TNT equivalence of 1.0, with 0.5 for composite materials and 1.25 for high energy propellants.

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4.0 – Experimental Design and Methodology

4.1 - Overview

For the purpose of this thesis as a study of the blast characteristics and TNT equivalence of propellants, the experimental phase was divided into three stages. Initially, a triple base gun propellant was subjected to a go/no-go test to determine its ability to detonate in a worst case scenario under high confinement. The second stage, based on the results of the initial test, involved the triple base propellant used in the first stage being combined in various ratios with PE4 to determine how it would act in a pseudo-realistic situation and to determine the blast overpressure provided by the propellant. Finally, the third stage involved the attempted detonation of a selection of double and single base small arms propellants, under minimal confinement to determine both their ability to detonate and their peak overpressure should detonation occur. Due to range restrictions, all tests where fragmentation was considered a threat were done within a containment building, and all charges were kept below the 454g (1lb) NEQ range limit.

4.2 – Charges and Preparation

4.2.1 - Stage 1 – High confinement Testing

As an initial test a triple base propellant designated NQ/S42-12, taken from the 105mm artillery 'charge super' L36A3 cartridge was subjected to a high stimulus under high confinement. The propellant is a slotted tubular propellant with a 3.5mm diameter. It is approximately 20.6% nitrocellulose, 20.8% nitroglycerin, 55% nitroguanidine, with 3.6% ethyl centralite, and 0.3% potassium sulphate as additives. Confinement for this stage was provided by a repurposed tubular containment vessel typically used in EMTAP testing. The EMTAP (Energetic Materials Testing & Assessment Policy) manual defines a number of tests, structured by the UK MoD, in order to characterise explosives [29]. A number of these tests use tubular steel vessels for confinement. These are 6mm thick steel pipes, 253.5mm long, with a 31.4mm internal diameter, giving an internal volume of 196.3cm³. End caps of thickness 9.1mm are

screwed on to each end with 31mm thread overlap. At one end, a 1mm flash hole was reconditioned to fit an 8mm L8 detonator for initiation of the filled device. A schematic of this device can be seen in Annex A.

Within the device, 120g of the NQ/S42-12 propellant was loaded at as high a packing density ($\sim 0.61\text{gcm}^{-3}$) as possible without compromising the tubular structure of the propellant. On top of this, 50g of PE4 was loaded and compacted in intimate contact with the propellant. Following this, the end cap with the 8mm hole was carefully screwed on to complete the charge. Figure 7 shows the composition of the device. The third charge used in firing 3 was assembled without the propellant used in previous tests but with wooden dowelling approximately 8mm in diameter used in its place as an inert replacement. By doing this, a baseline was established to determine the effect of the booster alone on the tube. This could then be compared to the two firings where propellant had been used, to ascertain the effect of the propellant, and ensure that damage was not just due to the PE4 booster.



Figure 7 - Tube arrangement used in firings 1 and 2

This phase of the firings was conducted in the range containment building due to the fragmentation that was likely to occur. This meant that no pressure or other blast data was able to be recorded as the disruptive effect of the surfaces within the

containment building on the shock waves would interfere with blast readings. Analysis of the blast was to be done using the fragments of the pipe bomb that remained and could be retrieved after each firing. Due to the nature of the containment building retrieval of all fragments proved unattainable, however enough were recovered after each firing to give a sufficient indication of the nature of the event as shown in section 5.2. Figure 8 below shows the charge in situ in the containment building, with recovered fragments shown on the right.



Figure 8 - Completed stage 1 charges in the containment building, with remaining fragments shown right

4.2.2 - Stage 2 – Combined PE4 and Propellant Testing

For this stage of the firings, following an initial assessment from the first stage results that the propellant had only partially detonated, it was decided that the energetic contribution of the propellant to a detonation should be studied as opposed to the detonation of the propellant by itself as this was judged to be unfeasible without using large quantities or confinement, neither of which could be done outside due to restrictions on NEQ and fragments on the range. In order to do this, the tubular propellant was split in to ~10mm sections and mixed as consistently as possible with PE4. This was carried out in the ratios shown in Table 2 below. This method can be seen as roughly analogous to a warhead or HE shell detonating next to propellant in a ‘worst case scenario’ type situation.

Firing #	Mass of PE4	Mass of NQ/S42-12	Ratio
7	100g	10g	10:1
8	100g	20g	5:1
9	100g	30g	10:3
10	100g	40g	5:2
11	100g	50g	2:1
12	100g	100g	1:1
13	100g	0g	1:0

Table 2 - Stage two charge compositions

Each charge was mixed by hand in a plastic dish, before being formed in to a sphere and contained within a thin clear plastic film to prevent it from separating during set-up. A detonator was inserted in to each charge to detonate it from the centre. Figure 9 below shows the mixed materials and the charges after forming.



Figure 9 - Stage two charge mixture, and completed charges

By doing this the propellant is all in intimate contact with the PE4, which can be considered as a large booster, and so has a high chance of detonating. An element of self-confinement is provided by the detonation of the PE4, and the shortened length of the propellant suggests that if any segments are separated from the PE4, the detonation will not have to be sustained over a great distance as was the case in stage 1. Combined, it is hoped that this combination will provide a suitable environment to achieve a reliable detonation of the propellant.

In order to obtain a useable measure of the overpressure from the propellant following the firings, firing 13 was conducted using a 100g charge of PE4 with no propellant. The overpressure from this charge can be used as a baseline, to be subtracted from the charges containing propellant to give an indication of the

overpressure provided by the propellant itself in each charge. Without suitable repetition, the accuracy of this method cannot be verified, however as described in section 5.3 later, the results yielded from this show consistency and scalability, especially for overpressure. This implies the method is functional for the purpose of this project.

4.2.3 - Stage 3 – Minimal Confinement Testing

This stage of testing consisted of the investigation of four double base small arms propellants, as well as one single base small arms propellant. The tests were done under minimal confinement and in quantities of 250g per firing. Testing was done to determine the TNT equivalence of these propellants, as well as the risk posed when stimulated by a detonator. Based on previous knowledge of one of the double base propellants displaying an extreme reaction to a detonator without a booster, it was decided that a booster would not be used. The propellants tested are outlined below:

Propellant Name	Quantity Used	Intended Purpose	Composition
BL-C(2)	250g	Rifle Cartridges	Double Base
Bullseye	250g	Pistol Cartridges	Double Base
H322*	250g	Rifle Cartridges	Single Base (NC w/ Dinitrotoluene binder)
H335	250g	Rifle Cartridges	Double Base
Lil'Gun	250g	Shotgun/Pistol Cartridges	Double Base

Table 3 - Small Arms Propellants Used

For clarity, the single base propellant H322 will be noted with the addition of an asterisk (*) throughout to make distinction of single and double base propellants easier.

In each case, the propellant was loaded by pouring in to a 50mm diameter PVC pipe, 250mm long, with 2mm thick walls, sealed at one end. The pipe was partially sealed at the other end using a custom-made detonator holder, consisting of corrugated cardboard attached to a foam arch, pushed in to the tube with good

contact. This can be seen in Figure 10 below. Once filled, the fill depth was measured, before being mounted centrally so that the pressure gauge arrangement would fall along both the axial and radial direction of the charge when detonated.

Charge	Fill Height (cm)	Volume (cm ³)	Mass(g)	Density(g/cm ³)
Bullseye	22	431.96	250	0.579
BL-C(2)	13	255.25	250	0.979
Lil' gun	14.5	284.70	250	0.878
H335	13.5	265.07	250	0.943
H322*	14.5	284.70	250	0.878

Table 4 - Small Arms Propellants Packing Densities

Due to the method of filling, the packing densities shown in Table 4 above are 'as is', with no compaction. It is unknown whether compaction of the propellants before firing would alter their response; as will be discussed in section 5.3 there is a correlation between density and response however it is thought this may be largely coincidental considering the inverse direction of the correlation and the granular form of the propellant.



Figure 10 - Charge set up for stage 3

The casing chosen for this stage was chosen primarily for simplicity of filling; achieving a spherically shaped charge using a fine powder without support was considered to be too difficult to be feasible. There was also an element of interest in the response of the cylindrical shape for propellants due to this being the shape found

in virtually all applications of propellant. The PVC pipe chosen was considered to provide enough confinement to hold the propellant in place long enough for the detonation to propagate, without significantly affecting the overpressure or releasing fragments large enough to travel any significant range [30].

Bullseye propellant was subjected to three firings, whereas the remaining four propellants were only used in one. This was done due to a combination of time and material constraints, with Bullseye chosen for three tests due to previous knowledge of its ability to detonate.

4.3 – Range Equipment

The equipment available on the range, and used throughout the firings, is briefly described below:

Data Recording

A Sigma 90 Digital Storage Oscilloscope (DSO) shown in Figure 11 was used to record the pressure-time histories received from each transducer. Each transducer was connected via a ~100m co-axial cable (75Ω) in to one of eight channels available in the DSO. The DSO recorded pressures in Pa, which were stored in the Nicolet time domain format (.wft) for analysis. Recording of the results for each firing was triggered using an ionisation probe in contact with the explosive charge and connected to the DSO; this causes an instant detectable signal along the probe at detonation. A transducer interface is used in-line between the DSO and the pressure transducers to provide a constant power supply to the gauges.



Figure 11 - Sigma 90 Digital Storage Oscilloscope used for data recording, with power supply unit (Right)

Blast gauges

Kistler 211B series high sensitivity pressure sensors seen in Figure 12 were used to detect peak overpressures for the experiments. These pressure gauges were protected by a steel housing, with a flat disc, approximately 150mm in diameter, flush with the sensor to detect reflected pressures or minimise interference from blast wave reflections when measuring incident pressure.



Figure 12 - Kistler Pressure Sensor, mounted in housing (right)

High Speed Camera

A Phantom V12 camera was used to record high speed footage of the majority of firings 4-17. This was done to show blast wave structure and to give a detailed image of the reaction. The camera is capable of recording at up to 1,000,000 frames per second; however the footage for these firings was taken at 10,000 frames per second (100 μ s intervals) to maintain a higher (pixel) resolution of 1024x512.

Detonators

The detonators used for all firings were commercially available 8 star electrically initiated instantaneous detonators. These detonators contain some small amounts of primary compositions, and approximately 1g of PETN as a secondary charge.

4.4 – Range Set-up

The Explosive Range Demonstration Area (ERDA) at the Defence Academy where the tests were conducted is a level open range, with concrete platforms at approximately 25m, 70m, and 100m from the preparation buildings. The equipment available at the ERDA during the firings for this thesis as described above was able to record blast pressures at 8 positions, which can be arranged in any configuration using movable supports. Unfortunately at the time of firings, there was no feasible method of recording the thermal output of the firings. There was a Forward Looking Infrared (FLIR) camera available at the time; however this proved unsuitable for recording the thermal output of the blasts.

For the second and third firing sets, the arrangement of blast pressure gauges on the range was the same; gauges were arranged at 1m, 1.5m, 2m, and 3m along two axes at 90 degrees to each other, intersecting at centre of the charge. In the case where cylindrical charges were used, one axis is aligned axially relative to the charge and one radially; this allows collection of the blast data from the side and ends of the charge, which are known to be different as described in Section 2.1.3. A depiction of this set-up can be seen in Figure 13 below.



Figure 13 - Range set-up, pictured and modelled, shown from 2 angles

Pressure gauges were placed at a height of 2m from ground level. This is to ensure that there is sufficient distance from the ground so that ground reflected waves do not interfere with the primary and secondary pressure waves that are of interest. This height is calculated based on travel time between each sensor and the charge, both directly and via the ground and taking it to account deceleration of the blast waves, 2m is found to be a suitable height. Details of the method used to determine this can be seen in past work done on the range with similar gauge distances [9] [31].

4.5 – Data Analysis

ConWep

ConWep is a well-known program, used to calculate the effects of a variety of weapons and explosives. An abbreviation of CONventional Weapons Effects Program, it was developed in 1991 by D.W.Hyde while working for the US Army Engineer Waterways Experiment Stations. ConWep derives its calculations from historical data, as well as Kingery and Bulmash curves, to give values for peak pressure, impulse and other parameters for a large range of charge masses and distances [32]. ConWep is limited to a small range of around 10 bare explosives, and can only calculate properties based on spherical (or hemi-spherical) charges, so has limited application for charges of other shapes. In this project, ConWep is used to derive TNT pressure data used in the calculation of TNT equivalence.

DPlot

DPlot software is a graphing package that allows you to interpret and manipulate a number of data formats. In the case of this project, it is used to view and clarify pressure time histories from pressure gauges used during firings. The software allows the smoothing and filtering of data in a number of ways, and allows the accurate determination of peak overpressures as well as impulse, by finding the area under the positive phase curve.

Other

Microsoft Excel was used extensively for visualisation and handling of data. This was chosen due to its simplicity and integration with the rest of the Microsoft Office suite. To a limited extent, Solidworks, a Computer Aided Design (CAD) package was also employed. This was used to construct drawings for use both as visual aids and potentially for simulations; however no software was found that would allow simulation of the complex multi-material charges used in this project, in the time available.

4.6 – Order of Firings

The firings for this study took place over the 22nd and 23rd of May 2013. The order of firings and associated daily atmospheric conditions can be seen below:

Firing	Date	Time	Material	Mass	Pressure	Temp
1	22/05/2013	10:50	NQ/S42-12 + PE4	170g	1017mBar	13°C
2	22/05/2013	11:15	NQ/S42-12 + PE4	170g		
3	22/05/2013	11:45	PE4	50g		
4	22/05/2013	12:15	Bullseye	250g		
5	22/05/2013	12:30	Bullseye	250g		
6	22/05/2013	12:42	Bullseye	250g		
7	22/05/2013	13:01	NQ/S42-12 + PE4	110g		
8	22/05/2013	13:14	NQ/S42-12 + PE4	120g		
9	22/05/2013	13:28	NQ/S42-12 + PE4	130g		
10	22/05/2013	13:42	NQ/S42-12 + PE4	140g		
11	22/05/2013	14:11	NQ/S42-12 + PE4	150g		
12	22/05/2013	14:30	NQ/S42-12 + PE4	200g		
13	22/05/2013	15:13	PE4	100g		
14	23/05/2013	10:53	Lil' Gun	250g	1011mBar	15°C
15	23/05/2013	11:07	BL-C(2)	250g		
16	23/05/2013	11:28	H335	250g		
17	23/05/2013	11:50	H322*	250g		

5.0 – Results and Discussion

5.1 – Experimental Observations

During the course of the 14 firings across stages two and three, high speed video was recorded alongside blast data at four ranges in two axes as described in section 4 above. Unfortunately, there are a number of incidences where some of this data was not recorded or is un-usable:

- For firings 11 and 16, no high speed video was recorded. In the case of firing 11, this is due to an electrical fault cutting power to the camera just prior to the firing, so no footage being recorded. In the case of firing 16, an unknown fault caused the file to become corrupted and unreadable. In both cases this does not affect analysis of the results.
- For firing 14, there is an apparent malfunction on pressure gauge 1 (radial @1m) that makes finding peak pressure unfeasible, so this result has been ignored
- Across firings 14-17, excessive relative noise due to low overpressures and significant dispersal of fragments and un-burnt powder means no accurate impulse can be determined from the pressure-time curves.

For a number of the firings, the blast gauges along the axial direction were approximately 50mm closer to the charge than intended. Where possible this has been taken in to account in all results and calculations.

For firings 1, 2, and 3, due to the conditions within the containment building where the firings were conducted, a relatively low percentage (50-64%) of fragments were able to be recovered following each firing. The possible impacts of this will be discussed later.

5.2 – Stage 1

To reiterate, stage one involved the use of steel tubes and a PE4 booster, to provide high confinement and strong stimulation to 120g of NQ/S42-12 triple base propellant used in artillery.

5.2.1 – Results

Following each of the three firings conducted for stage one, detectable fragments were collected from the containment building where the firings were conducted. The fragments were counted, inspected, and weighed in each case. It was clear after each firing that not all fragments were recovered from the containment building, notably due to the deep sandy floor and lack of lighting making them difficult to locate. Following the second firing, a Forward Looking Infra-Red (FLIR) camera was used to identify the fragments from their residual heat, however this only had a limited effectiveness. A consequence of this is that between 50-64% (by mass) of the fragments were recovered each time, likely with significant bias towards larger fragments which are easier to find. In order to produce a comparable data set from this, the number of fragments was ‘normalised’ against mass using the method outlined in the EMTAP test manual [33]. The process for this is to divide the number of fragments recovered by the fraction of the original tube mass recovered as shown in Equation 6 below:

Equation 6 - Equation for normalising recovered fragments to mass

$$\text{Normalised Fragments} = \frac{\text{Fragments recovered}}{\left(\frac{\text{Recovered Mass}}{\text{Original Mass}} \right)}$$

By doing this, the data seen in Table 5 was attained. It is recognised that adopting this method introduces an element of error in to the results; however the benefit of a quantitative and comparable data set is deemed to outweigh this.

Firing	Charge Type	Number of Fragments Recovered	Percentage Mass Recovered	Average Fragment Mass (g)	Normalised Number of Fragments
1	Propellant	17	50.4%	38.40	34
2	Propellant	38	60.0%	25.19	63
3	Inert (Wood)	16	63.7%	61.33	25

Table 5 - Fragments recovered during stage 1 testing

It is clearly visible from the normalised results that there is a difference between the firings using propellant (1 & 2) and the inert firing (3). This result is further enhanced upon inspection of the fragments from each tube, with the fragments from the third firing demonstrating significantly larger fragments along the length where the wooden dowelling was, with comparatively similar fragments where the PE4 booster was located. This can be seen in Figure 14 below.



Figure 14 - Fragments Recovered from (L-R) firings 1 and 2 (propellant) and 3 (inert)

The discrepancy between the results from the first and second firing is thought to be due to the collection of a number of fragments from the first firing that were initially missed and collected after the second firing. This may have occurred due to the use of the FLIR camera or simply a more detailed search of the containment building following the realisation that not all fragments were being collected. This suggestion is backed up by the much greater number of small fragments collected following the second firing compared to the first. It is unclear if this same problem affected the results from the third firing. It is possible that this could have been mitigated by painting the tubes to more easily identify fragments, however due to the energies

involved it is likely that much of this would separate from the metal during the blast [34].

5.2.2 – Analysis

Due to some broad similarities between these firings and EMTAP tube tests, the assessment method used in these tests can be used to approximately classify the level of reaction based on the number of fragments recovered in the three tests completed here. Unfortunately with all firings yielding between 10 and 100 fragments (when normalised) this classifies them all as ‘explosions’, described as a reaction between a deflagration and a detonation (see Annex D). This is partially expected due to the relatively large PE4 booster (50g) used in each case producing a number of fragments from the tube it is in contact with. Beyond this, the normalised number of fragments recovered is indicative of a reasonably significant reaction from the propellant. Roughly twice as many fragments are seen from the tubes with propellant compared to the tube with wooden dowelling. Based on rough reconstruction of the tubes, the fragments from the body not in contact the booster are also significantly smaller in the first two firings. What is also indicative of the level of reaction is the base of each tube; in the first two firings this has clearly separated from the threaded section implying a shockwave has travelled the length of the tube to produce the damage. In the third firing this is not seen, with a dent of approximately 2mm being produced in the base instead with no evident fracturing of the metal as shown in Figure 15 below.



Figure 15 - End cap damage from firing 3 (left) and firing 1 (right)

A potential reason for the suspected partial detonations could be the diameter of the propellants slotted tubular profile being below the critical diameter required to sustain a detonation. The propellant has a total diameter of approximately 3.5mm, or a 1.2mm ballistic size when the slotted tubular profile is taken in to account; this is far below the critical diameter of nitroguanidine (as the main detonable constituent of the propellant) of 40mm [35], and also below that of nitroglycerin at 12.5mm [36]. This suggests, in line with observations, that when the stimulation from the PE4 has diminished the detonation will cease to propagate down the propellant, and will tend towards a low order detonation or deflagration.

As no blast or other data was recorded for this stage, there is limited further investigation that can be done beyond speculation. It was decided based on the results however, that it would not be reasonable to expect the propellant to detonate without confinement with a smaller booster on the range, so that blast data could be recorded. As a compromise, the method used in stage two was employed.

5.3 – Stage 2

To recap, stage two involved the detonation of different ratios of PE4 and NQ/S42-12 triple base propellant, mixed together in single spherical charges.

5.4.1 – Results

Following the 7 firings conducted in this stage, data from the 8 blast gauges used in each firing was collected from each firing and studied using DPlot software. Using this software, a peak overpressure (in kPa) and positive phase impulse (in Kpa.ms) was determined for each gauge, as shown in Figure 16, and this data was then exported to MS Excel. The negative phase and the effects of any secondary pressure waves, while of interest, were not examined in detail or used within this project.

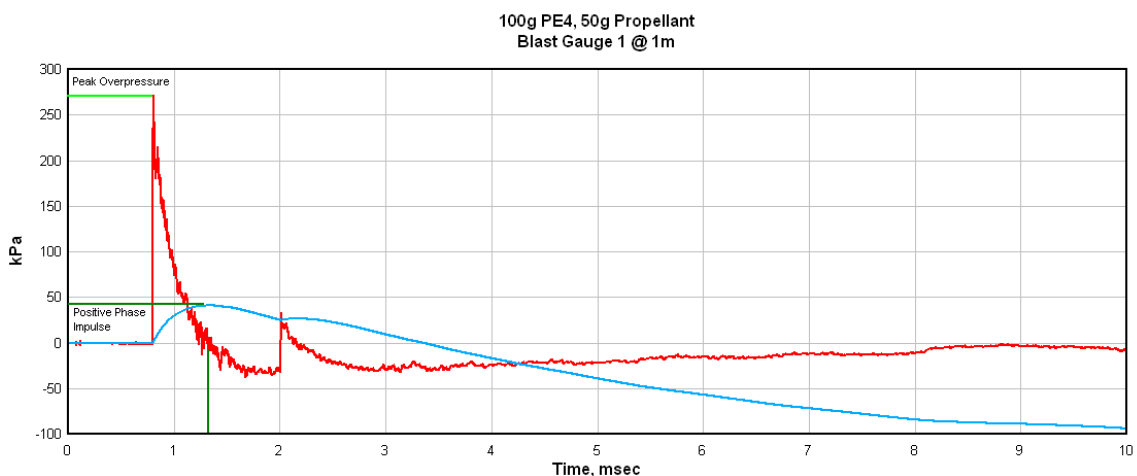


Figure 16 - Pressure-Time history in DPlot showing relevant data points

Due to the use of a spherical charge and equally spaced (within 50mm) gauges along two axes, data from duplicated gauges was averaged to give a single set of results for each firing and reduce any potential experimental errors. There is a reasonable variation (up to 40% in one case) between these results at close range, with near identical readings seen beyond 1.5m. Even in cases where significant difference is seen however, when different gauge spacing is taken in to account by plotting peak pressure against scaled distance there is a good correlation in charges above 20g. At 20g and below it is thought that experimental error accounts for the difference, especially due to the relatively low overpressures seen for these charges, and so the

values are still averaged. This method is shown to be effective, by the respectable peak overpressure vs. scaled distance trend seen in Figure 23; however it is accepted that some error may be present that could be reduced with further testing. This averaged data is used as standard throughout the analysis. Complete data is available in Section 9 – ‘Additional Data’.

Using the overpressure data from firing 13, where 100g PE4 with no propellant was detonated, a baseline peak overpressure and impulse was established, from which the additional blast pressure and impulse from the propellant in each of the remaining charges could be ascertained and compared. In order to simplify this analysis, the baseline values were subtracted from the other values from each firing, at each distance. This process yielded the data visible numerically in Table 6 and Table 7 below, and graphically in Figure 17 and Figure 18 below; the baseline profile can be seen as the ‘100g PE4’ data. Figure 17 shows the overpressure from each charge before and then after the removal of the baseline pressure, and Figure 18 shows the impulse from each charge before and then after the removal of the baseline impulse.

PE4 Offset - Peak Pressure (kPa)

Distance	100g PE4	10g	20g	30g	40g	50g	100g
0.96m	187.23	18.04	34.24	46.07	80.46	90.23	143.00
1.46m	85.90	0	9.36	17.70	14.13	19.51	45.18
1.96m	51.41	0	1.47	4.43	3.95	5.78	19.91
2.96m	26.07	0.18	0.85	3.25	3.34	3.75	10.91

Table 6 - Offset Overpressures for different charge masses at each distance

PE4 Offset - Impulse (kPa.ms)

Distance	100g PE4	10g	20g	30g	40g	50g	100g
0.96m	33.83	0.00	2.83	4.69	5.09	7.57	13.73
1.46m	27.41	0.79	2.83	4.07	4.41	6.55	13.34
1.96m	20.94	0.00	2.03	2.22	2.76	5.44	10.78
2.96m	14.54	0.00	2.42	0.68	2.07	3.53	9.86

Table 7 - Offset Impulses for different charge masses at each distance

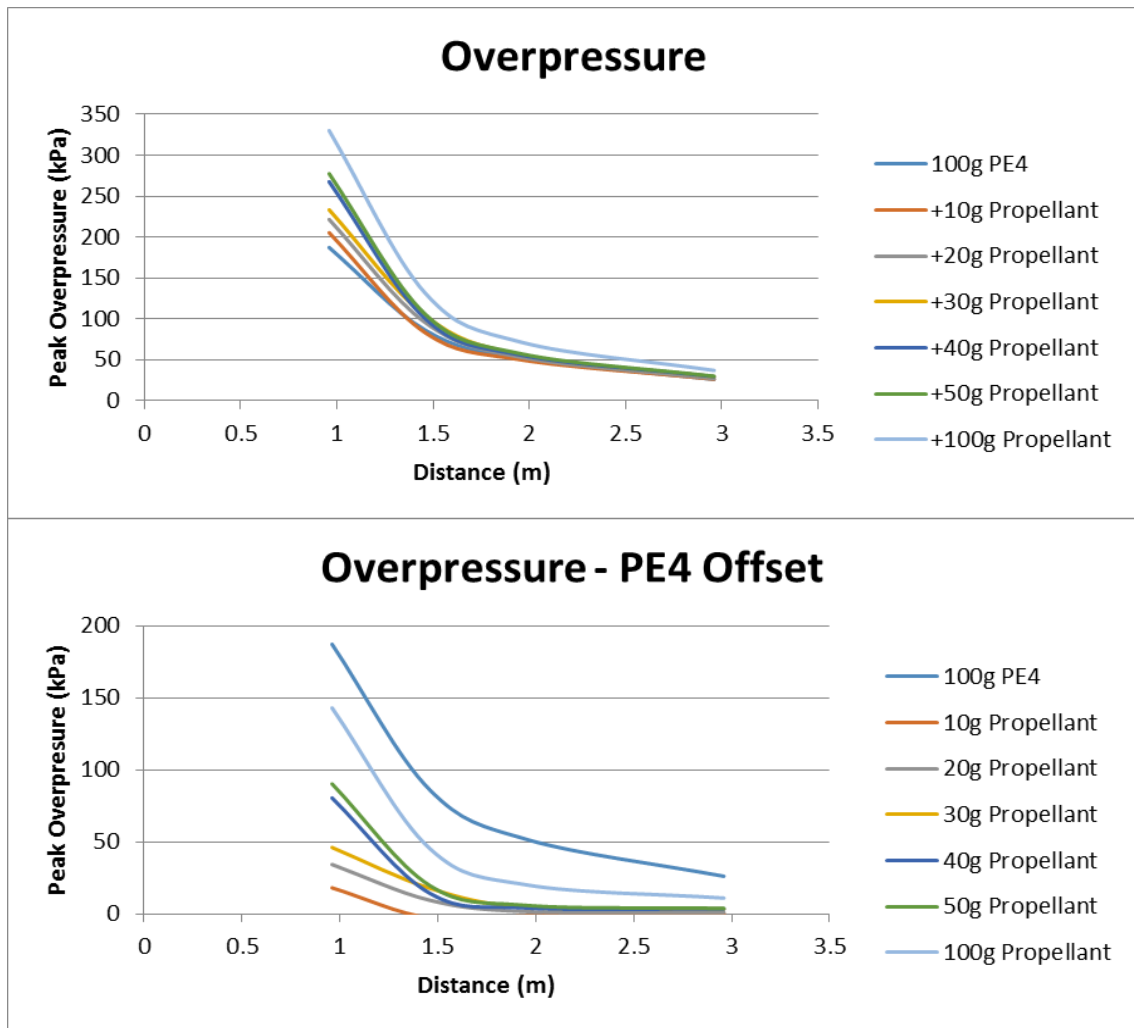


Figure 17 - Pressure vs. Distance display for Peak Overpressure before and after offset from the PE4 'baseline'

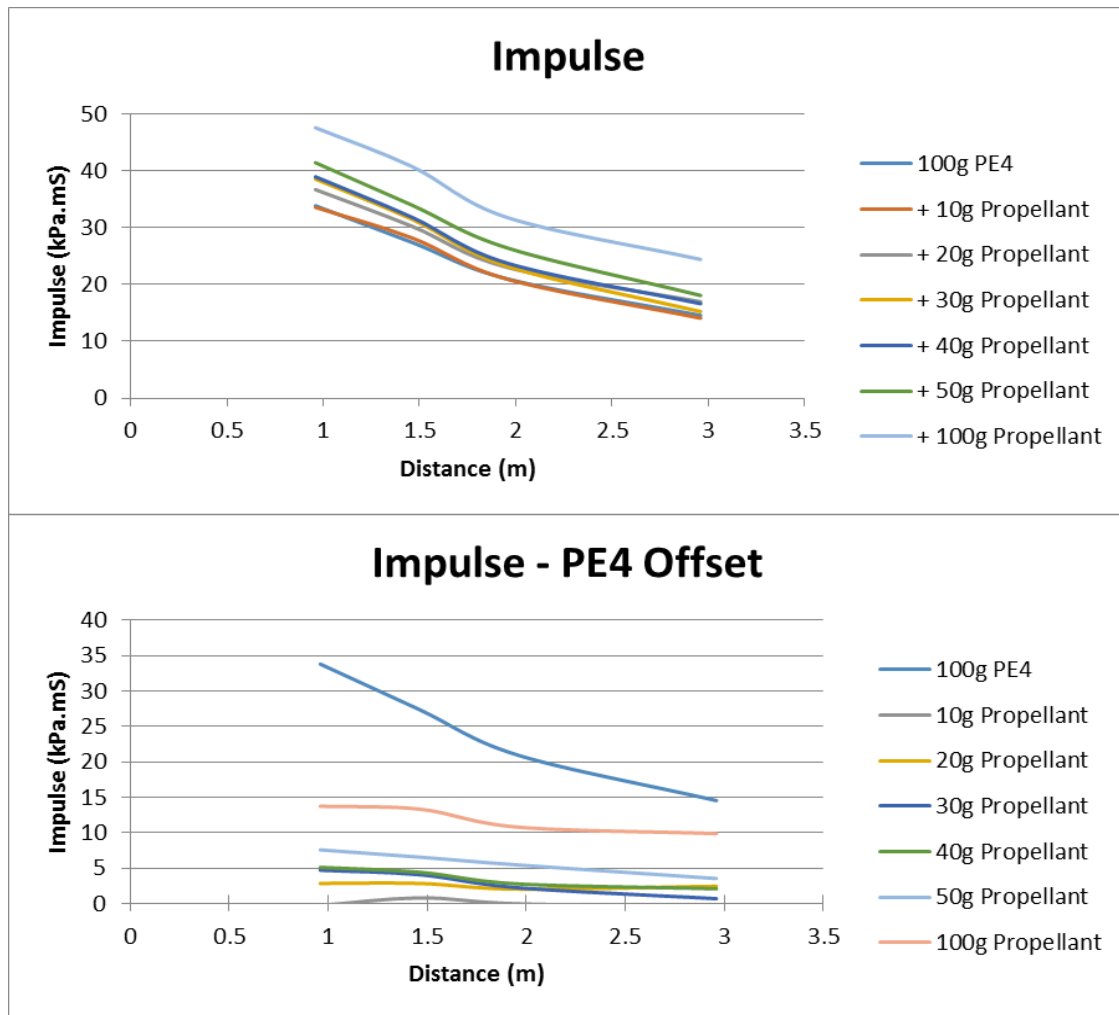


Figure 18 - Impulse vs. Distance display for Peak Overpressure before and after offset from the PE4 'baseline'

While this method is not a necessarily a perfect representation of the response of the propellant by itself, it is suitable to give an indication of the blast characteristics of the propellant in a worst case scenario. In the case of the 10g charge, at 1.5m and 2m the offset overpressure fell below zero (-2kPa); this is considered as experimental error due to the lack of repetition in the firings, so these values have been set to zero to remove confusion from the results. While it possible that the addition of the propellant can reduce the immediate overpressure of the PE4 through absorption of energy from the blast wave by potentially un-burnt propellant, for the purpose of determining TNT equivalence this is phenomenon is outside of the scope of this thesis and is ignored; accepted as an error.

By graphing the offset data, several notable points are obvious. For peak overpressure, it can be seen in Figure 17 above that while propellant has an overall lower overpressure than PE4 even at the same mass (as in the 100g propellant charge), it has a different pressure-range profile; between 1m and 2m the overpressure reduces with range at a faster rate than PE4, before settling to a roughly similar rate. When examining the impulse vs. distance graph it can be seen that the opposite holds true; impulse has a very slow reduction with range, showing that while overpressure reduces the positive phase duration increases more significantly than seen in PE4. This may be due to the propellant having a lower detonation velocity than the PE4 [37] [38], or the propellant or its products undergoing a secondary reaction shortly after the initial detonation. The oxygen balance of the propellant is approximately -29%, whereas PE4, being mostly RDX, is approximately -21% [39]. This lower oxygen balance may result in more unreacted products reacting with atmospheric oxygen after the initial detonation to provide energy and high pressure gases at a slightly later stage and prolong the impulse, largely without affecting the peak overpressure. This hypothesis is backed up by the prolonged impulse being more apparent in charges with more propellant, and thus more deficient in oxygen; Figure 19 below shows the percentage reduction in impulse between 1m and 3m, plotted for each mass of propellant tested. No data is available from the 10g charge due to a negative impulse value being found after the PE4 impulse is offset. It can be seen that aside from the 20g charge there is a good correlation showing less reduction with increased mass. It is assumed this trend would not be linear for greater masses, however over the range tested in this project a linear trend fits well; it is assumed the curve would be closer to a hyperbola if more data points were available. No reason can be suggested for the inconsistent value for the 20g charge with any certainty; the most likely reasons are due to the process of offsetting the PE4 impulse, or down to experimental error from no repetition of firings.

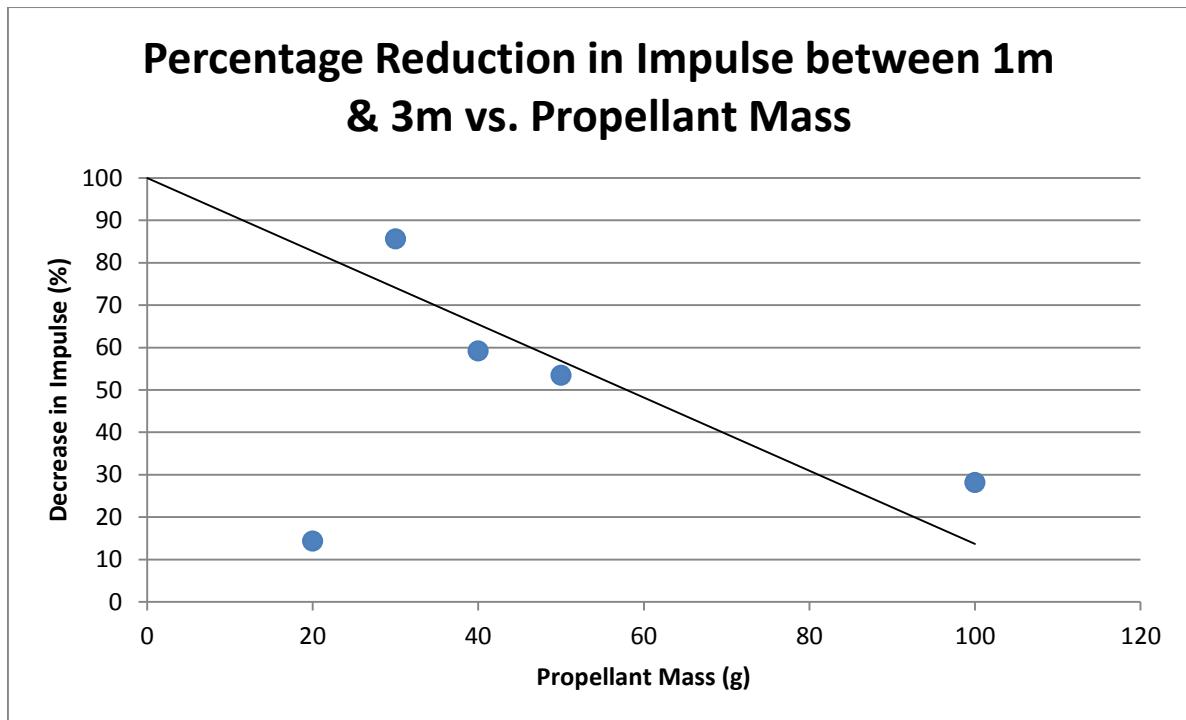


Figure 19 - Percentage reduction in impulse (1m-3m) vs. Propellant Mass

As a method of determining the suitability of the offset data, the peak overpressure was plotted against mass at each distance, with 1m and 3m shown in Figure 20 below.

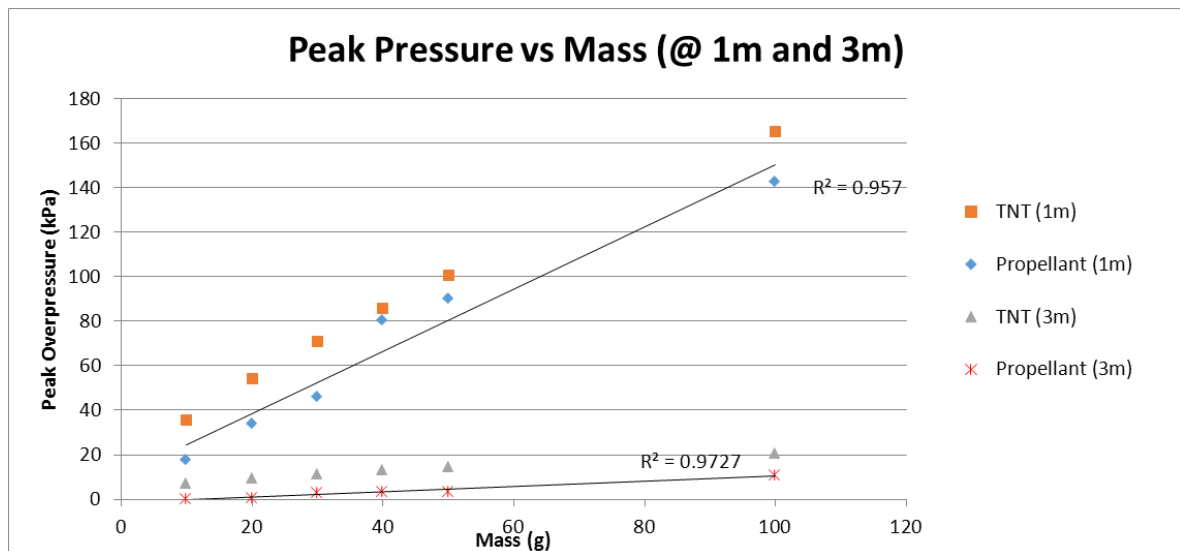


Figure 20 - Overpressure vs. Mass for TNT and TB Propellant @ 1m and 3m

The positive and accurate correlation seen when the points are plotted against each other (with forced origin intercept) is an indication that all propellant reacted consistently in each case, giving a good degree of viability to both the results and the

methods used to obtain them. The coefficient of determination (R^2 value) for lines across all masses is within the range 0.94-0.97, showing statistical significance. It is unclear whether this linear trend will continue as mass increases further however based on observations from other explosives it is considered unlikely. On the same graph, TNT overpressure obtained from ConWep has also been plotted as a comparison. It is noticeable at this point that overpressure of propellant relative to TNT varies quite significantly with mass, being almost 50% that of TNT for a 10g charge, and closer to 90% for 100g. This is clearly indicative of a variation in TNT equivalence for mass of charge.

If the same graph is plotted for impulse vs. mass, there is an equally good correlation in values from 1m-2m; however there is a noticeable decrease in the R^2 value to 0.86 at 3m. This may be a consequence of the low impulse values seen at this distance increasing relative error, or could indicate a problem with the method used to obtain the values.

5.4.2 – Analysis

In order to determine the TNT equivalence of the propellant, TNT overpressure and impulse data was taken from ConWep for all ranges and masses of propellant used. This was then compared directly to the values obtained for each mass of propellant using the previously described relationship:

Equation 7 - Determination of TNT Equivalence

$$TNT_e = W_{TNT} / W_{Exp}$$

Where TNT_e represents TNT equivalence, and W represents the mass of each charge, producing the same peak overpressure or positive impulse at the same distance. By using this method, a TNT equivalence can be established for each mass of propellant at each distance, as shown in Table 8 and Table 9 below. Where the value of overpressure fell below a threshold level, ConWep is unable to give an equivalent mass of TNT, so the value has been left blank.

TNT Equivalent at Range – Peak Overpressure

Distance	10g	20g	30g	40g	50g	100g
1m	0.250	0.414	0.453	0.803	0.759	0.726
1.5m	-	0.106	0.282	0.1323	0.206	0.463
2m	-	-	0.031	0.018	0.034	0.259
3m	-	-	0.055	0.043	0.045	0.249

Table 8 - TNT Equivalence of NQ/S42-12 based on Peak Overpressure

TNT Equivalent at Range - Impulse

Distance	10g	20g	30g	40g	50g	100g
1m	-	0.074	0.108	0.091	0.135	0.170
1.5m	0.040	0.136	0.160	0.136	0.197	0.300
2m	-	0.131	0.096	0.103	0.236	0.329
3m	-	0.306	0.031	0.120	0.219	0.522

Table 9 - TNT Equivalence of NQ/S42-12 based on Positive Impulse

Based on these results, the average TNT equivalence of NQ/S42-12 was found to be **0.26** for peak overpressure, and **0.16** based on positive impulse. The standard deviations for these figures are 0.2 for peak overpressure and 0.08 for positive impulse, which are significant considering the values themselves. The data from the above tables can be seen graphically in Figure 21 and Figure 22 below.

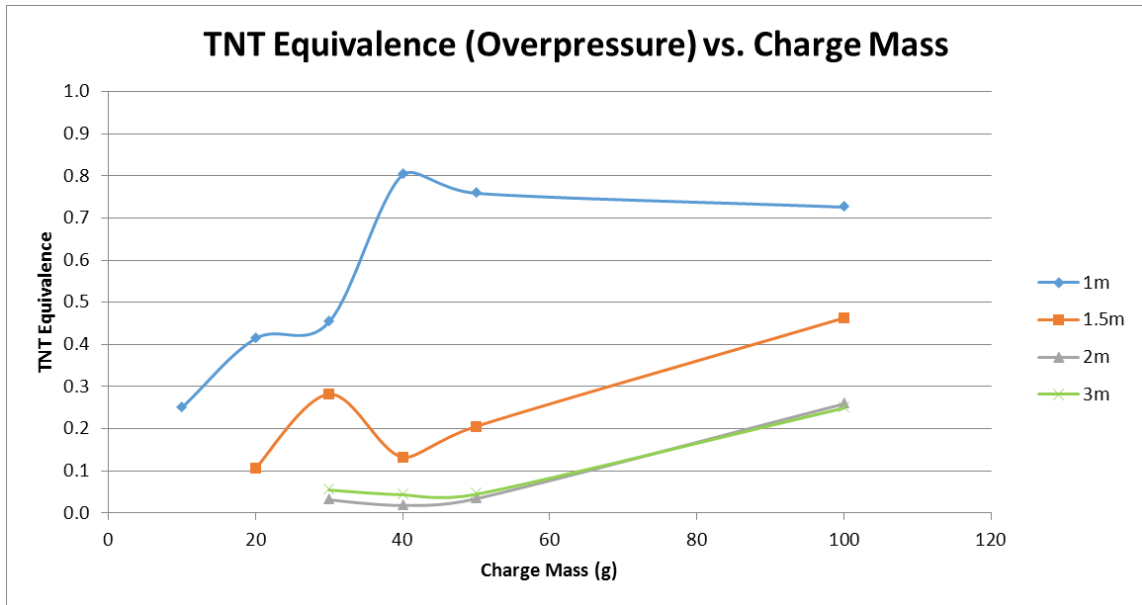


Figure 21 - TNT Equivalence (Overpressure) vs. charge mass for each distance

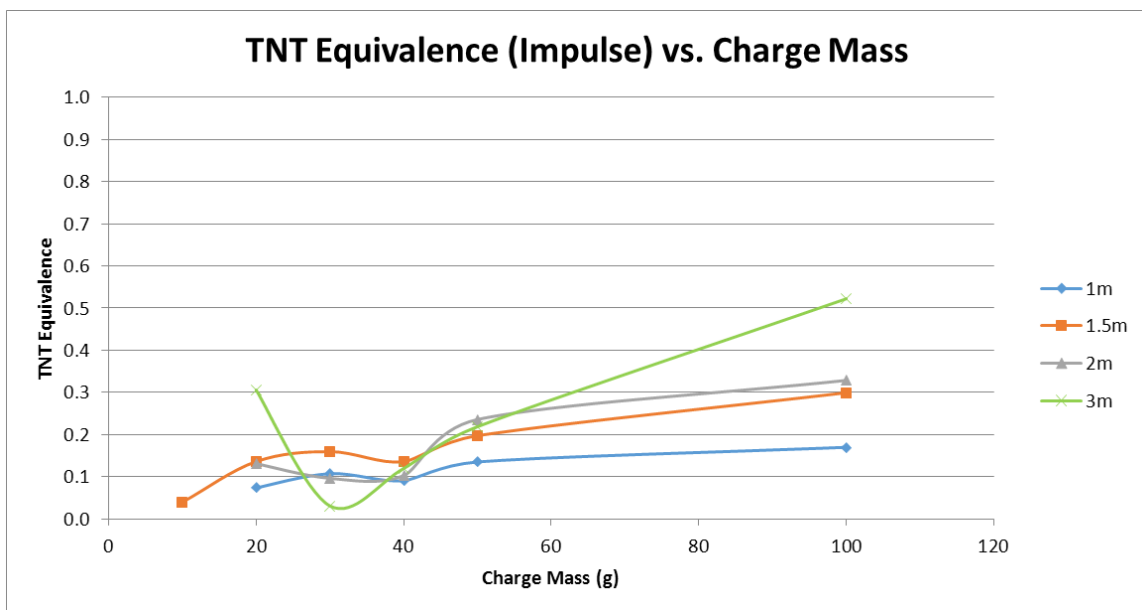


Figure 22 - TNT Equivalence (Impulse) vs. charge mass for each distance

Two trends are visible from this data which are logical continuations of observations above; for both peak overpressure and positive impulse the TNT equivalence increases with mass of propellant however while TNT equivalence for peak overpressure decreases with distance, the opposite is true of TNT equivalence for Impulse where TNT equivalence is seen to increase with distance. The coherence of the trend for this is notably clearer for peak overpressure than with impulse however,

which may be a consequence of the method of obtaining the impulse data from the propellant. No literature has been found which reports on a trend showing a change in TNT equivalence with mass; it is possible that the trend is apparent over the limited range of charge masses tested and does not continue over a wider range, or that it is a product of mixing the propellant with PE4 before offsetting the result.

Moving on to scaled distance; If we look at the values of overpressure and scaled impulse vs. scaled distance, we can see that while peak overpressure is seen to scale effectively, scaled positive impulse (positive impulse divided by scaled distance [13]) is not. Each line in the following two figures represents a single firing from each material.

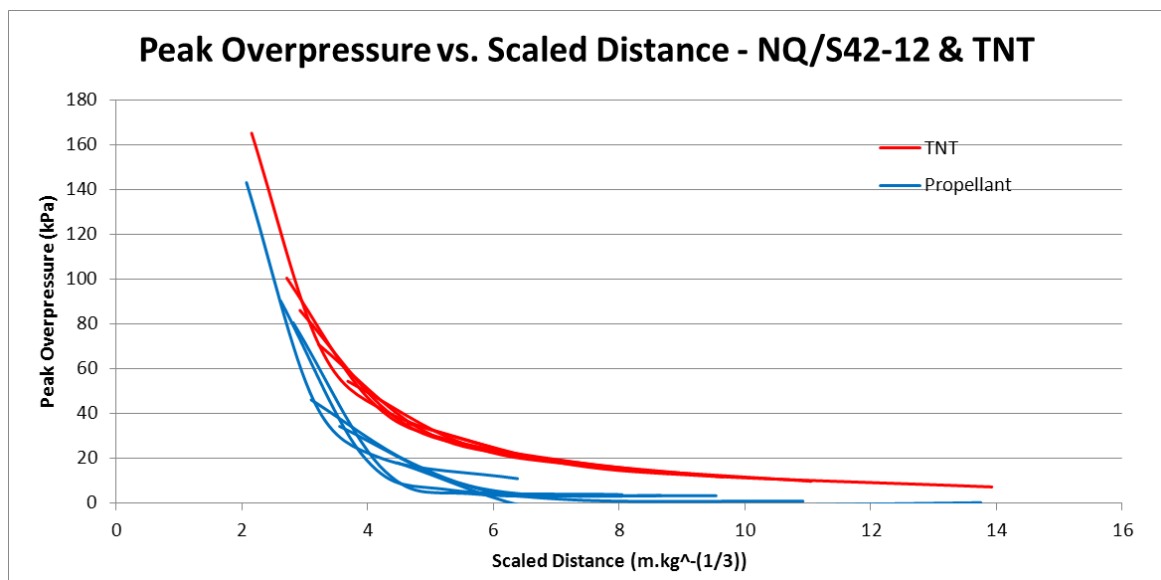


Figure 23 - Peak Overpressure vs. Scaled Distance of NQ/S42-12 and TNT

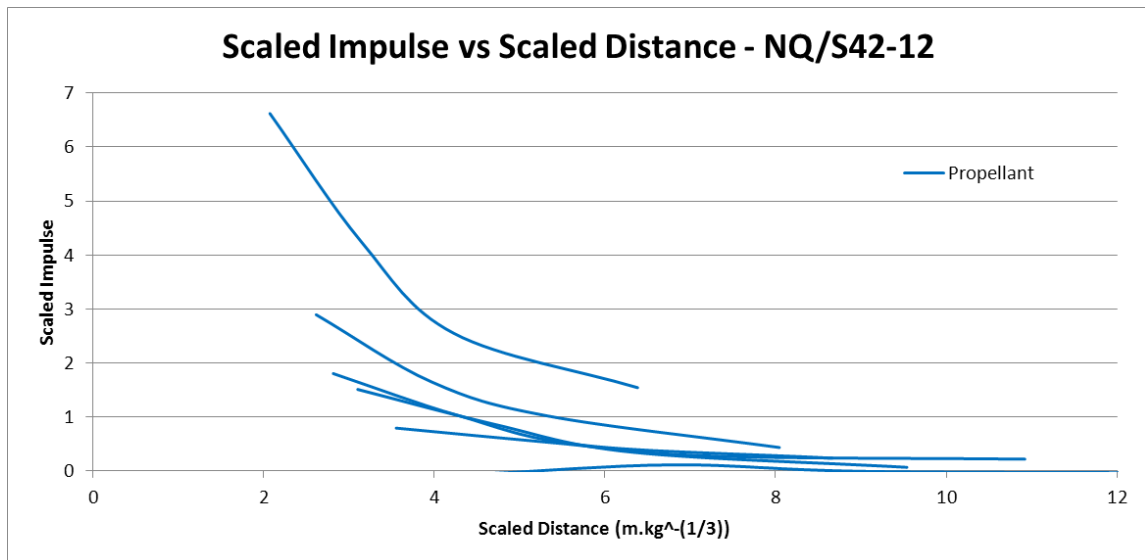


Figure 24 - Scaled Impulse vs. Scaled Distance of NQ/S42-12

It is suggested that the method of deducing impulse of the propellant from the combined PE4-NQ/S42-12 charges may not be as simple and effective as it is for peak overpressure, and thus the data may become skewed by this method. There may also be experimental errors due to lack of repetition that are not apparent in overpressure data.

5.4 – Stage 3

Stage three entailed the attempted detonation of a selection of four double base propellants and one single base propellant, in thin tubular PVC vessels.

5.4.3 – Results

Due to a number of factors, some of which are discussed in section 2.1.2, as well as large amounts of dispersed material; there is a significant amount of noise seen in the results for this stage. When combined with the low overpressures seen in four of the firings for this stage, determination of peak overpressure is made difficult and determination of positive impulse is unworkable. In order to diminish the noise so that overpressure readings could be made, the Dplot data was post-processed; this involved a series of smoothing operations being carried out on the pressure-time curves. All the operations are built in to DPlot, and involved the removal of any random spikes, the filtering of fixed frequency noise, and smoothing of points by averaging until a reasonable blast profile could be identified with minimal disruption to the raw data. Typically this processing was required significantly more on gauges in the radial direction than in the axial direction, most likely due to greater interference from the casing fragments in this direction. Figure 25, Figure 26, and Figure 27 respectively show an axial gauge reading, a radial gauge reading, and the same radial gauge reading after processing.

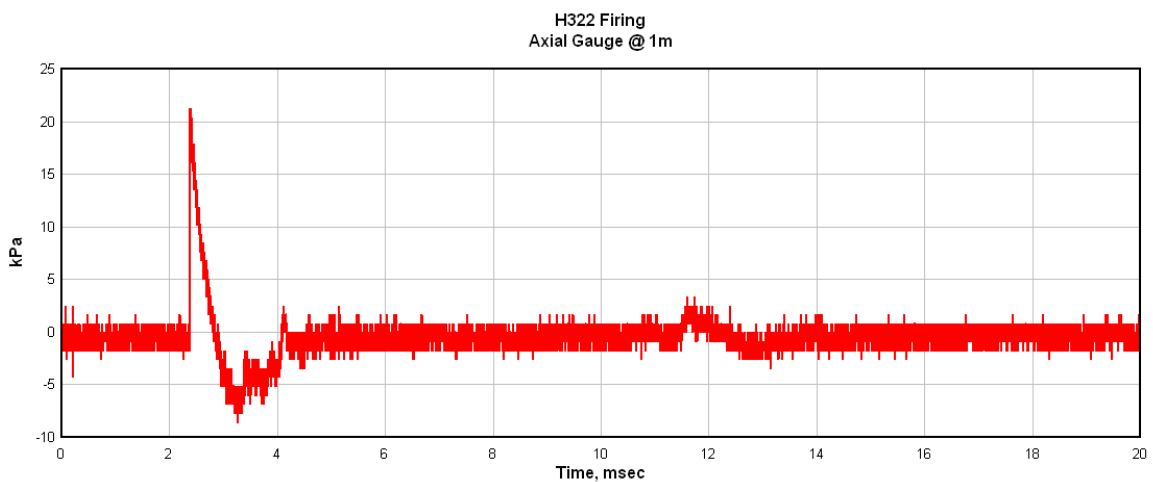


Figure 25 - Axial pressure time history for H322*

For the firing in Figure 25 above, in the axial direction, it can be seen that while there is significant noise it does not greatly affect the values in the positive phase. This means minimal processing is required to retrieve accurate values for peak overpressure and impulse.

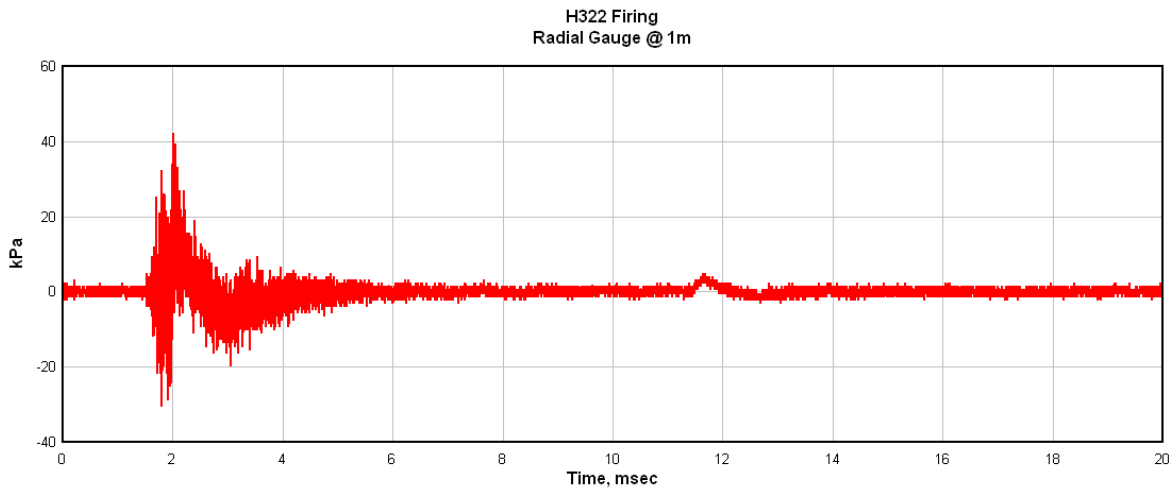


Figure 26 - Radial unprocessed pressure time history for H322*

Conversely, in Figure 26 above, it can be seen that there is significant noise, concentrated in the positive phase. Because of the 'random' spikes in overpressure, a reliable maximum cannot be determined, and the positive impulse (as area under the curve) is also considerably affected.

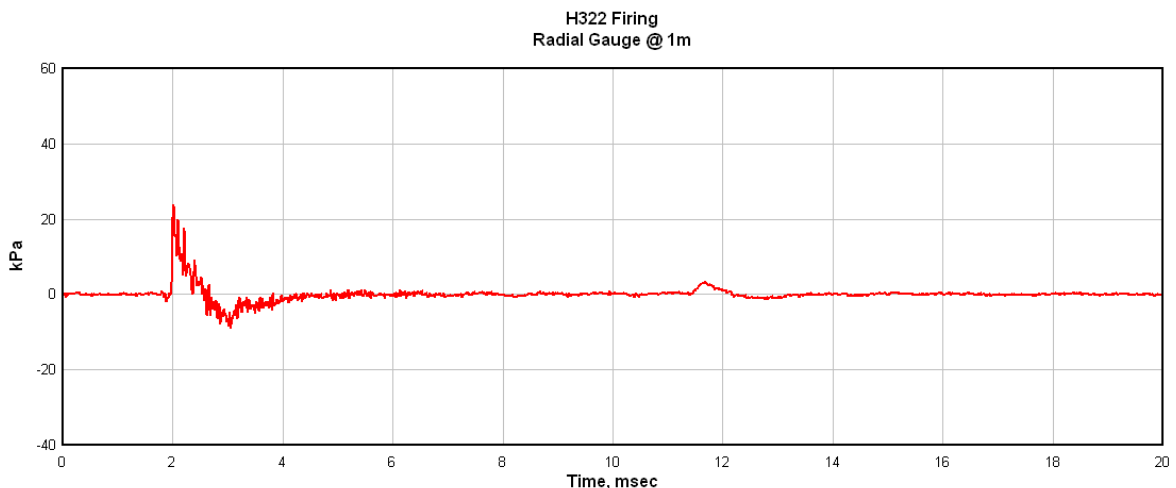


Figure 27 - Radial pressure time history for H322* after processing

Figure 27 shows the same data seen in Figure 26 following processing. It can be seen by comparison that the majority of signal noise has been reduced, but significant

details such as the positive phase and ground reflection have been maintained. The positive phase is now considerably clearer, albeit with notable noise still present on the curve. This allows a reading of peak overpressure to be taken, however it was considered that taking an impulse from this would still be too inaccurate.

In each case where it was considered necessary, processing was done to the extent where a peak pressure could be taken with a reasonable degree of certainty without compromising the initial data too much through over-manipulation. This process resulted in the overpressures seen in Table 10 below. The results from the three Bullseye firings were averaged, with a standard deviation of ~10% of the average.

	Approx. Overpressure (kPa)					
	Distance	Bullseye	Lil' Gun	H322*	BL-C(2)	H335
Radial Pressure	0.95	696.47	0.00	29.36	15.73	9.50
	1.45	181.78	21.13	11.05	8.47	5.68
	1.95	86.12	11.65	8.09	5.52	3.46
	2.95	40.57	7.77	4.77	3.15	2.42
Axial Pressure	0.99	388.17	27.21	20.28	9.54	10.59
	1.49	82.46	16.88	12.79	5.87	5.97
	1.99	37.63	12.36	9.94	4.07	4.62
	2.99	17.50	6.87	5.09	2.34	2.39

Table 10 - Peak Overpressure data from small arms propellant firings

Based on observations from the firings, and backed up by blast data and high speed video, it was found that four of the five propellants tested did not detonate. Two of those were determined to give a minimal partial detonation one of which was the single base propellant, with the remaining two double base propellants showing no reaction whatsoever beyond deflagration of particles close to the detonator as shown below.

Propellant	Purpose	Reaction
Bullseye	Pistol Power	Detonation
BL-C(2)	Rifle Powder	Deflagration/No Reaction
Lil' Gun	Shotgun/Pistol Powder	Partial Detonation/No Reaction
H322*	Rifle Powder	Partial Detonation/No Reaction
H335	Rifle Powder	Deflagration/No Reaction

Table 11 - Reactions from small arms propellants

Once peak overpressure data had been exported for all firings it was compared in Excel. As expected there was significant difference between the overpressures seen from the Bullseye detonation and the other four propellants of at least an order of magnitude. For this reason it is unfeasible to display them fully on the same graph and maintain clarity, although this is done for comparison in Figure 32 and Figure 33 later. The four non-detonating propellants will be considered first, followed by the Bullseye data. Figure 28 and Figure 29 below show the initial overpressures recorded for the non-detonating propellants.

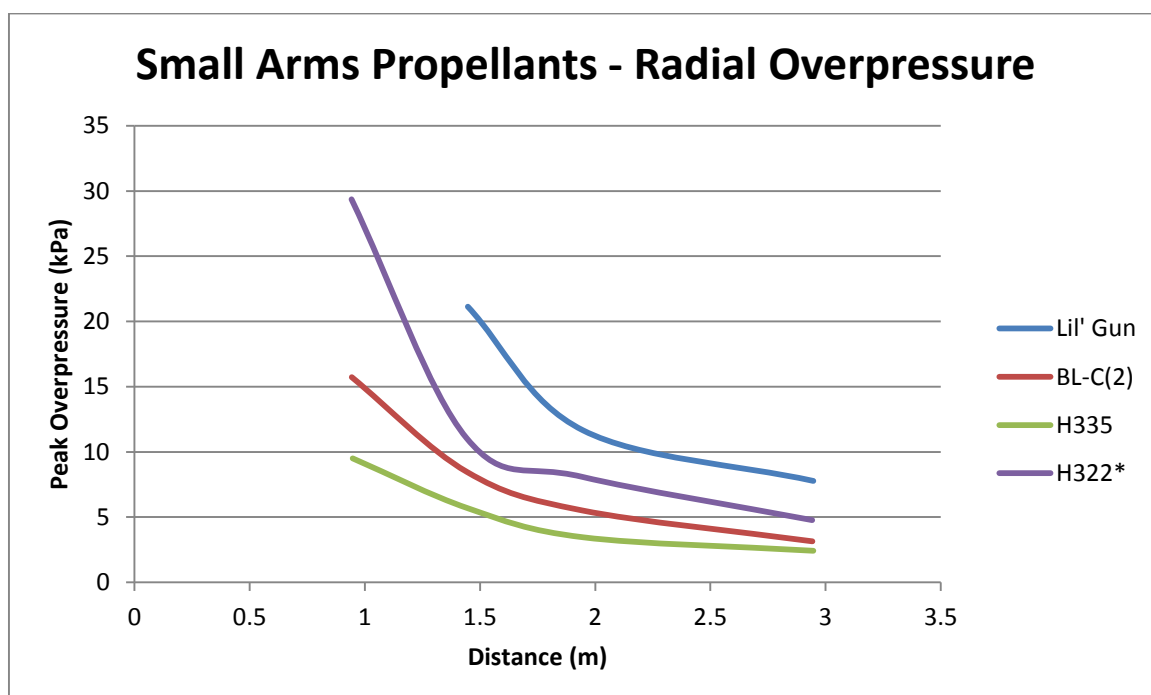


Figure 28- Radial Overpressure from small arms propellants

No data is available for Lil' Gun at 1m in the radial direction due to a sensor problem giving excessively noisy results, making inference of a peak overpressure unfeasible.

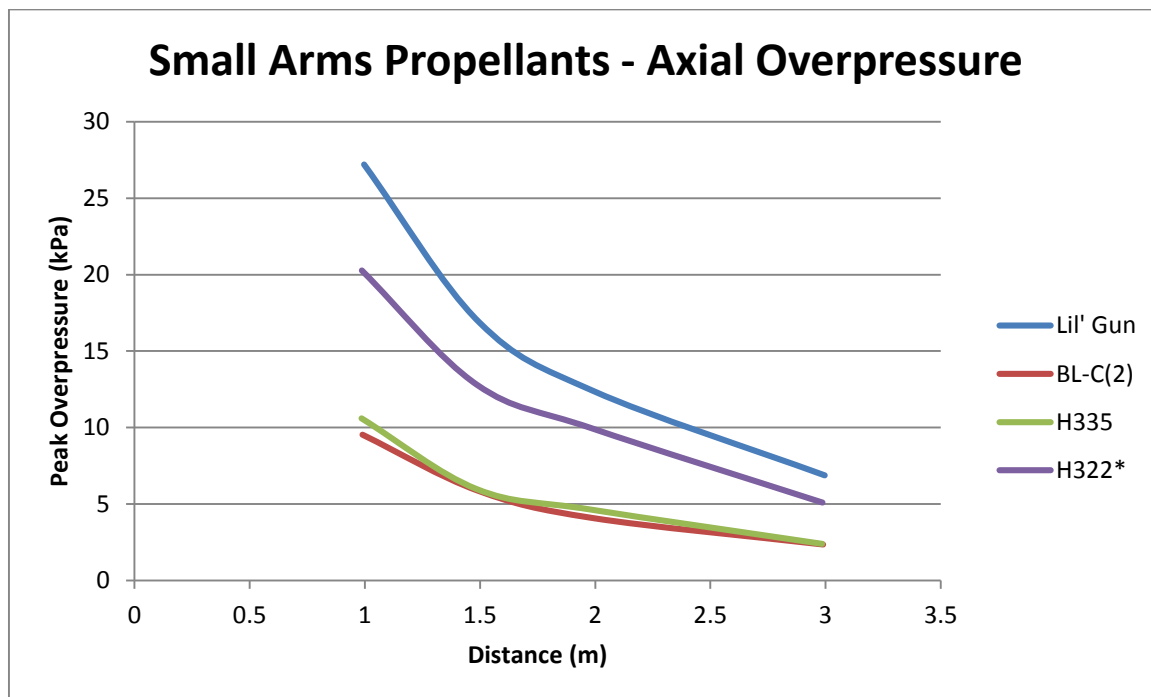


Figure 29 - Axial overpressure from small arms propellants

Due to the low overpressures seen in the data from these propellants, it was decided that the effect from the ~1g of PETN in the detonator could account for a significant amount of the recorded overpressure. In order to combat this, the overpressure from 1g PETN was subtracted from the results. This was done by taking the overpressure from 1.33g of TNT at each range (based on PETN's TNT equivalence for peak overpressure of 1.33 [40]) from ConWep and subtracting it from the values obtained experimentally. By doing this, a representation of the reaction from the propellant was clarified. In a number of instances, the subtraction of the overpressure from the detonator took the value slightly below zero. This may be due to experimental or post-processing error, or could be due to blast energy losses in to dispersal of the un-reacted propellant. In this occurrence, the value was set to zero.

Figure 30 and Figure 31 below, show the results of this subtraction.

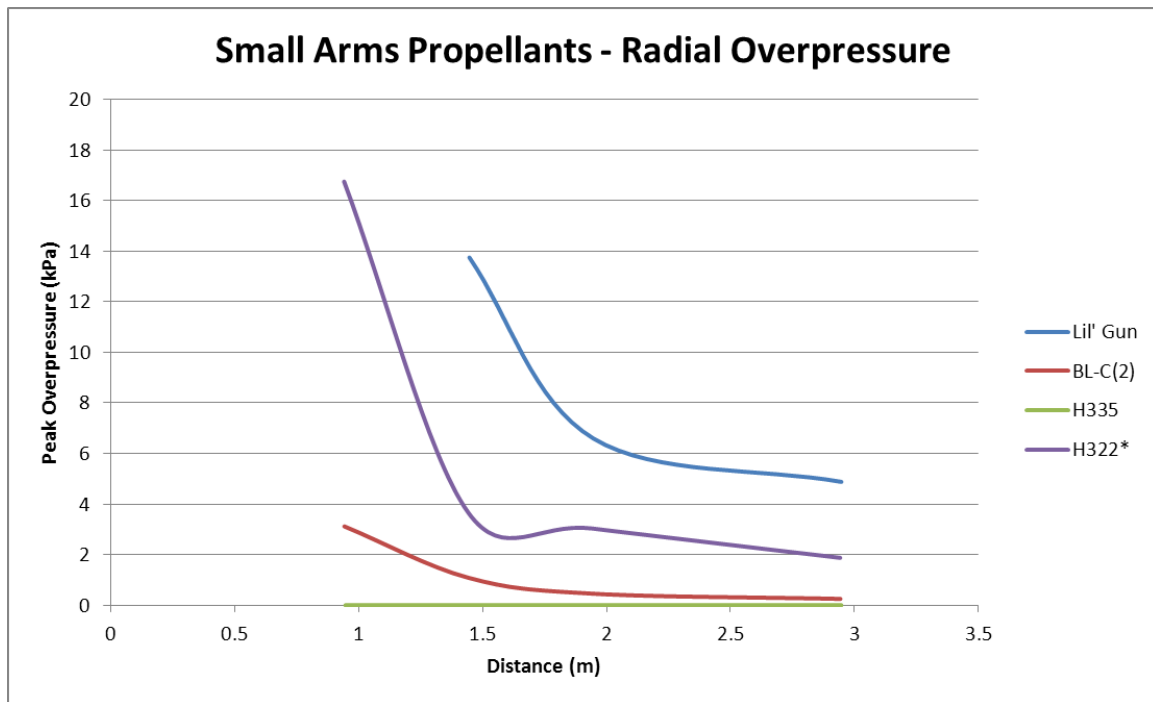


Figure 30 - Radial overpressure from small arms propellants, with detonator effects removed

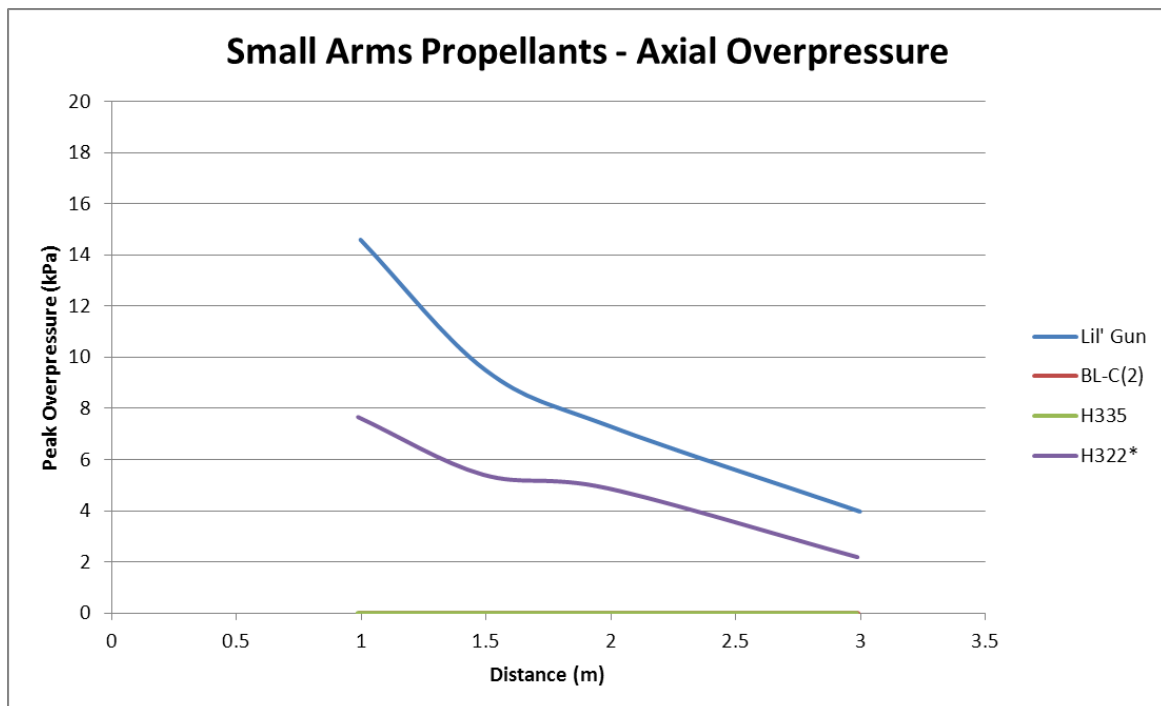


Figure 31 - Axial overpressure from small arms propellants, with detonator effects removed

It can be seen following removal of the effects from the detonator that, as in Table 11 above, H335 and BL-C(2) displayed no detectable reaction, while Lil' Gun and H322* displayed a minimal contribution to overpressure. Table 12 below has been updated from Table 10 to reflect the removal of the overpressure from the detonator. Suggested reasons for these reactions will be made following discussion of the Bullseye firing data.

	Approx. Distance	Pressure (kPa)				
		Bullseye	Lil' Gun	H322*	BL-C(2)	H335
Radial Pressure	0.95	696.47	-	16.75	3.12	0.00
	1.45	181.78	13.75	3.67	1.09	0.00
	1.95	86.12	6.59	3.03	0.46	0.00
	2.95	40.57	4.88	1.87	0.25	0.00
Axial Pressure	0.99	388.17	14.60	7.67	0.00	0.00
	1.49	82.46	9.50	5.41	0.00	0.00
	1.99	37.63	7.30	4.88	0.00	0.00
	2.99	17.50	3.97	2.19	0.00	0.00

Table 12 - Overpressure data from small arms propellant firings, updated to reflect removal of detonator overpressure

As stated, Bullseye was determined to have undergone a full detonation; Figure 32 and Figure 33 below show peak overpressure vs. distance, compared with the four other double and single base small arms propellants for comparison.

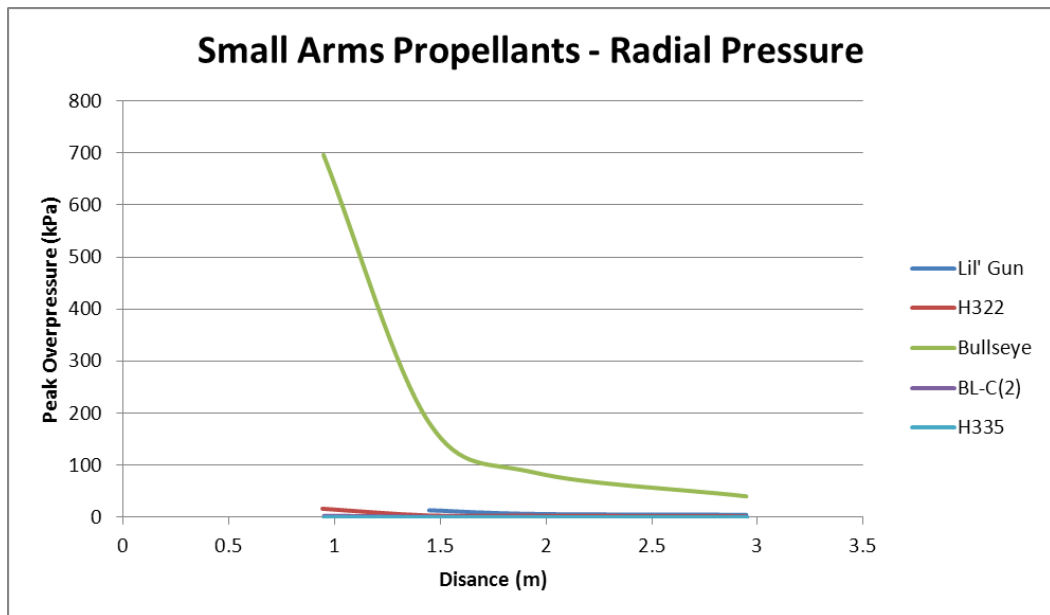


Figure 32- Radial Overpressure from Bullseye propellant

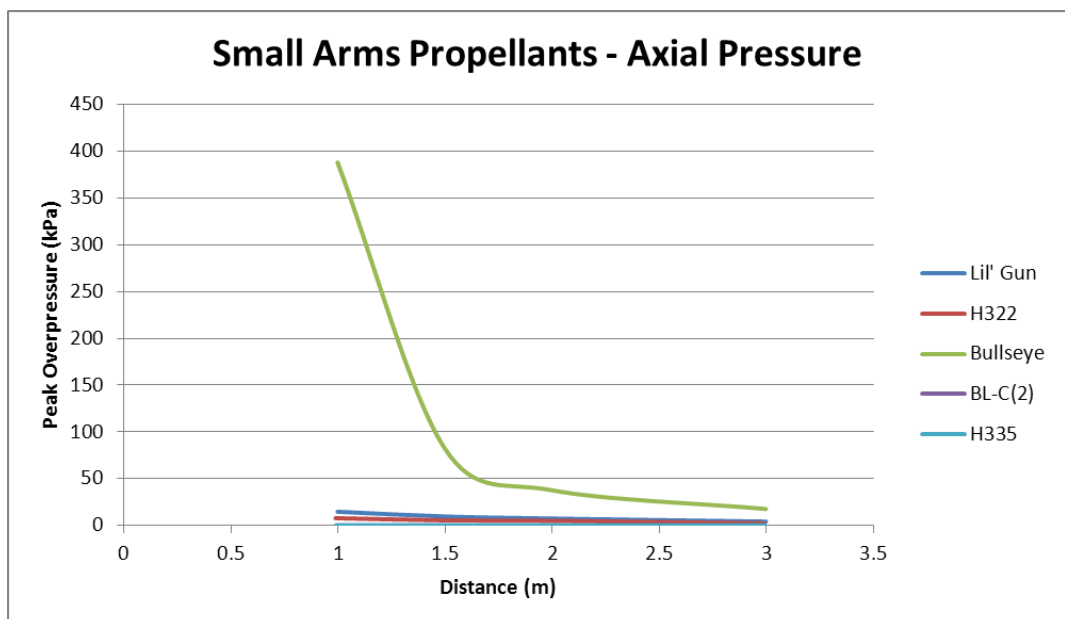


Figure 33 - Axial Overpressure from Bullseye propellant

Based on these results, only the Bullseye firings are considered to have provided usable blast data to be used in TNT equivalence calculations, so this will be the only numerical data taken forward.

5.4.4 – Analysis

An interesting observation from results of all the small arms propellant firings is the relationship between the intended purpose of the propellant, and its reaction to detonation; the two propellants which gave the highest overpressure are Bullseye, which is designed for pistols, and Lil' Gun, which is designed for shotguns and pistols. The remaining propellants are all rifle propellants, and showed little or no reaction. Propellants designed to be fired from shorter barrelled and lower pressure weapons (pistols) will be required to have a much faster burn rate than those fired from longer barrelled higher pressure weapons (rifles) to accommodate the shorter duration before the optimal all-burnt position in the barrel is reached. Burn rate is determined by the chemical composition of the material as well as the local pressure and temperature. In the firings conducted here, all the initial conditions such as confinement and atmospheric conditions can be considered to be the same; therefore it is appropriate to focus on burn rate variations caused by composition as the main cause of the different reactions observed in the firings.

Burn rate modifiers can be added to compositions to alter and typically reduce the burn rate, however conversely to what would be expected based on the results, only the propellants that yielded full or partial detonations are shown to contain any (see Annex B). It would be expected that the addition of these compounds would reduce the rate of reaction and thus make detonation more unlikely, however it may be that when subject to detonation these compounds do not act as they do during deflagration, and actually contribute to the reaction. DNT for example, seen in H322* (<10%) is used as a burn rate modifier, but is also an insensitive detonable explosive [41] so is likely to react differently in response to a detonation wave. Further work would be needed to determine if this is the case in each propellant.

Another factor for consideration is the amount of nitrocellulose and nitroglycerin in each composition; while the specific percentages of each are kept purposefully vague in documentation for commercial reasons, in the data sheets for each composition there is a noticeably lower percentage of additives in the form of stabilisers, plasticisers, and smoke/flash suppressants in both Bullseye and H322*. As

the data sheet for Lil' Gun covers a range of propellants it is impossible to say with certainty which of the compounds mentioned it contains, however based on the absence of further evidence the only credible conclusion that can be drawn is that the propellants with higher detonability contain lower amounts of (non-energetic) additives and thus have a higher net energetic mass.

Having a higher energetic mass, and thus energetic density, will mean more energy is liberated per amount burned, and this additional energy will allow the reaction to propagate faster through the material, and may allow the propellant to sustain a detonation for a greater period of time. This difference (of up to 30%) in energetic material is suggested as the primary reason for the difference in reaction seen between the propellants. Table 13 below, shows the potential amount of non-energetic material in each propellant. The DNT binder (~10%) in H322* is considered as an energetic material due to its ability to detonate, however it is not known if this occurred experimentally.

Propellant	Purpose	Reaction	Maximum Non-Energetic Material (%)
Bullseye	Pistol Power	Detonation	6
BL-C(2)	Rifle Powder	Deflagration/No Reaction	37.5
Lil' Gun	Shotgun/Pistol Powder	Partial Detonation/No Reaction	51
H322*	Rifle Powder	Partial Detonation/No Reaction	5
H335	Rifle Powder	Deflagration/No Reaction	37.5

Table 13 - Maximum Non-energetic material in each small arms propellant

With the exception of Lil' Gun, there is a good correlation between lower non-energetic material and severity of reaction to detonation. As mentioned, these values are the maximum values specified in the Material Safety Data Sheet (MSDS) for each propellant, with the MSDS's for H335, BL-C(2), and Lil' Gun covering a range of propellants, so it is probable that these values are actually lower than presented. Up to 25% of Lil' Guns composition is proprietary and not specified; it is assumed this is non-energetic.

It is also worth noting that based on Table 4 in section 4.2.3, there is a correlation between packing density and detonability, with propellants exhibiting lower packing densities giving a more severe reaction. While it is known that high explosives with lower packing density are more likely to undergo Deflagration to Detonation Transition (DDT), this is due to lower packing density and associated increased granularity allowing formation of hot spots as well as convective movement of gasses through the material [42]. Since granularity is evident in all the propellant due to their form anyway, it is suggested that packing density is not a major factor in the response of the propellants.

Sample images of the firings, taken from high speed footage, can be seen below, with visible blast waves highlighted in red. Complete videos can be seen at the links provided in Annex C.

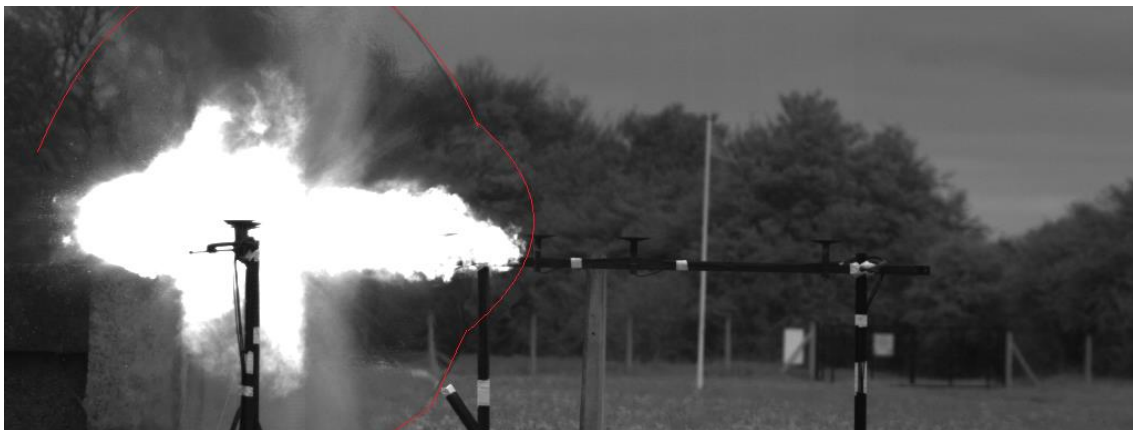


Figure 34 - Still from Bullseye detonation @1.4ms showing fireball and primary shockwaves



Figure 35 - Still from Lil' Gun firing @1ms, showing distortion of a primary blast wave, with initial reaction and dispersal of propellant



Figure 36 - Still from BL-C(2) firing @1.2ms, showing dispersal and burning of propellant away from the charge

The blast waves in Figure 34 and Figure 35 do not appear to show any signs of secondary waves seen in cylindrical charges; this is either due to the shape of the small amount of detonating material being closer to spherical, or the amount being so small that the wave has ‘healed’ over a much shorter distance (see section 2.1.3). It is also noticeable that the blast waves for Lil’ Gun and (more so) BL-C(2) are significantly less visible compared to the Bullseye.

With respect to the large amount of un-burnt propellant dispersed from the non-detonating firings; this is caused by the relatively slow burn rate not being fast enough to transmit to the neighbouring grain and propagate through the material before it is scattered by the fast moving high pressure gases from the initial reaction of the PETN in the detonator or the propellant before detonation failed. With greater confinement holding the propellant in place, the entire mass would deflagrate or possibly detonate.

As discussed, Bullseye was the only propellant to yield useable data for the calculation of TNT equivalence. In order to do this, the method outlined in Section 2.2 was used. In order to compare the results to an appropriate mass of TNT, the effect of the case on the overpressure was considered. Using Equation 1, the equivalent mass of a case-less charge of Bullseye (to give the same overpressure) was found to be 241.5g. The overpressure and impulse at each distance from each of the three Bullseye firings was then averaged to give the values seen in Table 15 below. A full list of results can be seen in Section 9 – ‘Additional Data’.

	Distance (m)	Peak Overpressure (kPa)	Impulse (kPa)
Radial	0.94	696.47	59.57
	1.44	181.78	51.74
	1.94	86.12	31.87
	2.94	40.57	25.29
Axial	0.99	388.17	49.26
	1.49	82.46	33.74
	1.99	37.63	36.10
	2.99	17.50	25.38

Table 14 - Peak Overpressure and Impulse from Bullseye Firings

The results seen above had a standard deviation of approximately 10% of the final averaged value in each case, with a slightly larger deviation seen at close range. Following accumulation of the results, ConWep was used to find the corresponding mass of TNT that would provide the same overpressure as the Bullseye. The case-less equivalent mass of Bullseye (241.5g) was then divided by the corresponding mass of TNT at each distance (as shown in Equation 7 to arrive at a TNT equivalence as shown in Table 15 below.

	Distance	Overpressure	Impulse
Radial	0.94	2.32	0.71
	1.44	1.41	1.04
	1.94	1.21	0.73
	2.94	1.31	0.92
	<i>Average Radial</i>	<i>1.56</i>	<i>0.85</i>
Axial	0.99	1.25	0.57
	1.49	0.52	0.55
	1.99	0.36	0.93
	2.99	0.29	0.95
	<i>Average Axial</i>	<i>0.61</i>	<i>0.75</i>
Average	-	1.08	0.8

Table 15 - TNT Equivalence of Bullseye from each gauge

A standard deviation of 0.52 was found for the average TNT equivalence based on overpressure of **1.08**, and a standard deviation of 0.16 was found for the average

TNT equivalence based on impulse of **0.8**. These standard deviations are high due to the significant variance in TNT equivalence with range that can be seen above. This is a recognised problem that occurs with TNT equivalence calculations [15] [43], which may be further exacerbated in this case by the use of cylindrical charges, which are known to enhance directional blast effects. This can be seen in Figure 37 and Figure 38 below, where TNT equivalence for impulse and overpressure are shown against distance.

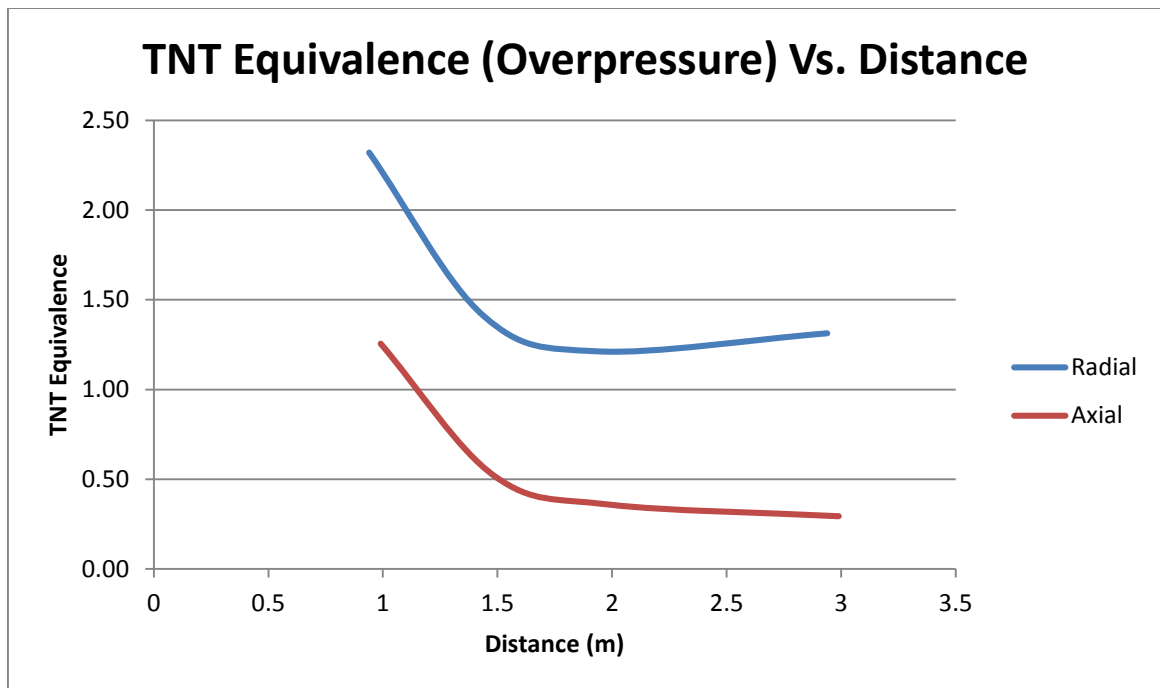


Figure 37 - TNT Equivalence (overpressure) of Bullseye at distance

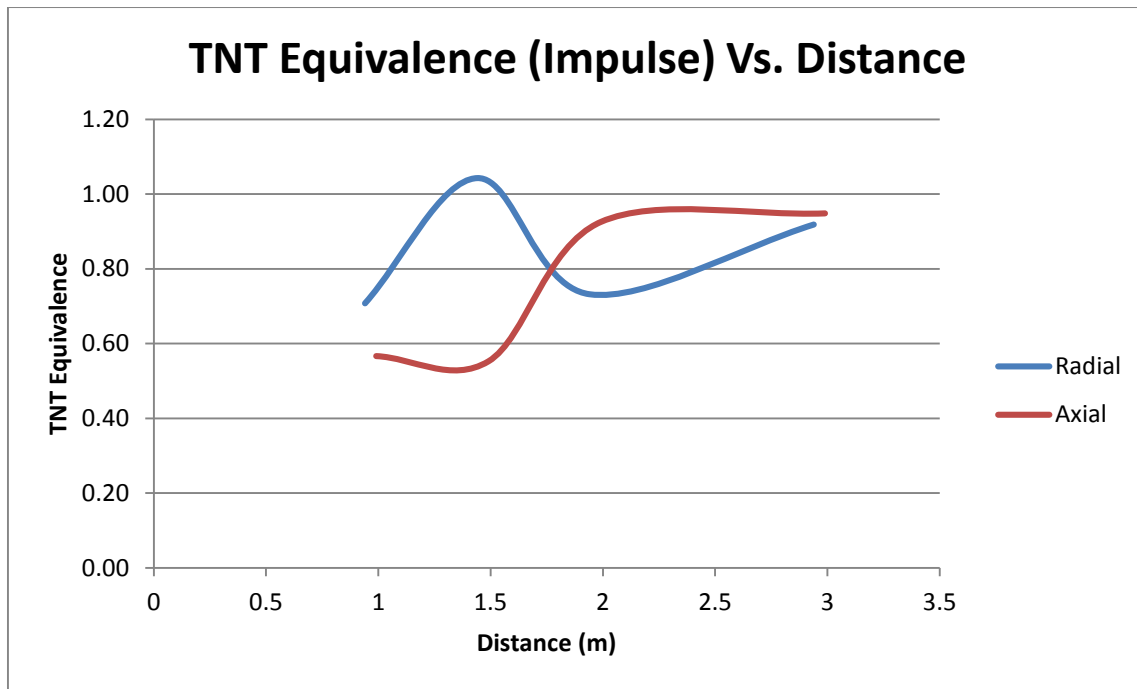


Figure 38 - TNT Equivalence (Impulse) of Bullseye at distance

This highlights the effects of both the different overpressures seen from cylindrical charges, as well as the difference seen in TNT equivalence at range. While there is a clear trend for TNT equivalence to reduce with distance for overpressure, for impulse there is more unpredictability. In the axial direction the sudden increase is due to the secondary waves from the bridging waves starting to merge with the primary wave past 2m, and thus significantly increasing the impulse in the positive phase. The peak in TNT equivalence in the radial direction at 1.5m cannot be caused by the interactions from the same secondary waves, as based on the raw data these do not interact in the positive phase until the 3m gauge. The root of this discontinuity is considered as error caused by the excessive noise at close range (1m) causing the impulse to be estimated too low.

Based on the failure of four of the five propellants to detonate, it cannot be said from the results seen here that a TNT equivalence value of 1.08 or 0.8 can be applied to all double base propellants. Results from literature indicate that Bullseye broadly aligns with typical values, with results from a propellant with similar composition to Bullseye giving a close agreement when compared over scaled distance

as shown in Figure 39 below. The radial data collected for Bullseye is compared, due to the literature test also being measured in the radial direction [26]. TNT equivalence for Bullseye in both radial and axial direction vs. scaled distance can be seen in Annex G.

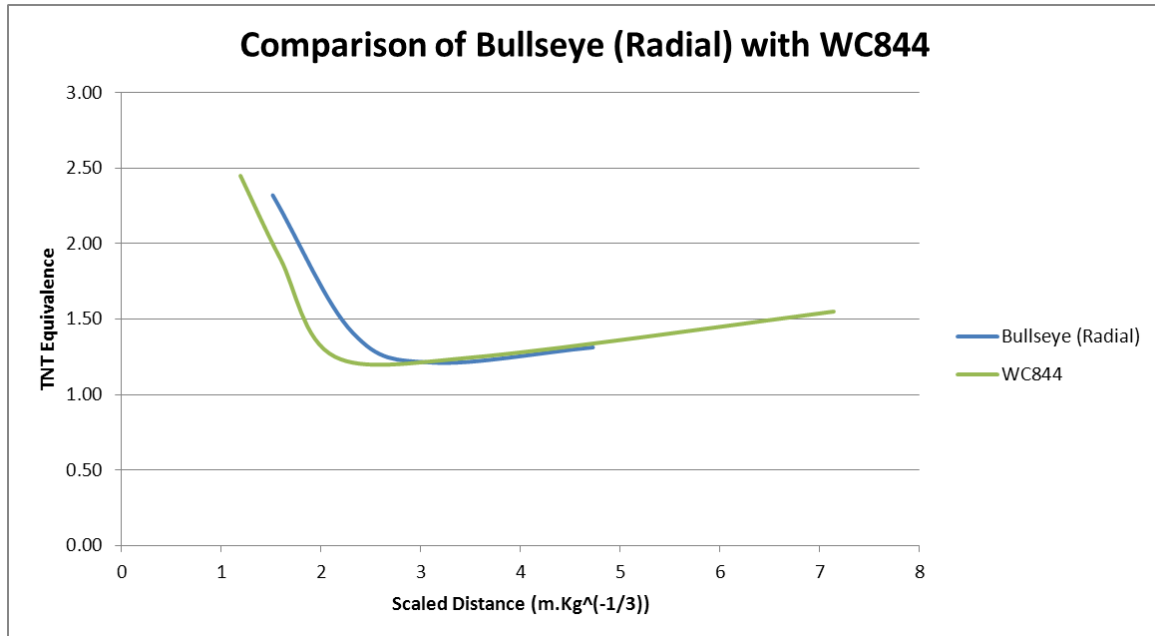


Figure 39 - Comparison of Radial TNT equivalence data from Bullseye firings and Literature WC844 firings [26]

If the differences in directional data are to be considered, it can be seen that the effect from a cylindrical charge (as most propellants are) is significantly greater in the radial or sideways direction. This may be a problem for the storage of munitions, where they are typically stacked or stood side by side where the effects will be greatest for the transmission of the reaction to other munitions. As there is no space efficient method of storing munitions end-to-end, there must be sufficient mitigation in place to limit blast from travelling sideways between munitions.

6.0 – Summary and Conclusions

6.1 – Summary

6.1.1 – Stage 1

The intention of stage one was to determine the ability of NQ/S42-12, a triple base propellant, to detonate or find the severity of its reaction. The propellant in this stage comes from the 105mm ‘charge super’ cartridge, the composition of which can be seen in Annex B. Based on the results seen, it was determined that the propellant partially detonated, with the failure of the detonation being caused by the sub-critical diameter of the propellant being unable to sustain the detonation after the PE4 had detonated. Because of this, it was decided that it would not be possible to find the blast characteristics of the propellant by detonating it alone.

6.1.2 – Stage 2

The purpose of this stage was to determine the blast characteristics and TNT equivalence of the same triple base propellant used in stage 1, by detonating it in combination with PE4 to achieve a full detonation. By removing the effects of the PE4 from the resulting data, it was found that in this configuration the propellant had an average TNT equivalence of 0.26 when overpressure was used or 0.16 when impulse is used. There was significant variance seen for both mass of propellant and distance however. By using the method described to obtain the data, overpressure was found to scale well, but impulse was not. It is not clear if this is due to the method or other factors.

The TNT equivalences found for this propellant are lower than expected when compared to the literature where similar propellants have been used. It is thought this is due to the small charge sizes used compared to the literature; this is supported by the upwards trend in TNT equivalence with mass as shown in Figure 21 and Figure 22.

6.1.3 – Stage 3

Stage three involved the attempted detonation of a series of single and double base small arms propellants in thin cylindrical tubes. Following the failure of four of the five to detonate, it is suggested that total energetic mass of the propellant is the most likely differentiator, with non-detonating propellants having a lower energetic mass. The double base propellant that did detonate (Bullseye) was used to determine a TNT equivalence of 1.08 based on overpressure or 0.8 based on impulse. Again a significant variation in TNT equivalence with range was observed, partly exacerbated by the use of cylindrical charges.

This TNT equivalence is comfortably within the range found in literature for double base propellants. A propellant with a similar composition was found to have a slightly higher TNT equivalence [26]; however this was being tested in quantities two orders of magnitude greater, which may account for some of the difference.

6.2 – Conclusions

To summarise, 17 firings were conducted using 6 propellants, one triple base, four double base, and one single base. Following three stages of testing to determine the response of the propellants only one triple base propellant (NQ/S42-12) and one double base propellant (Alliant Bullseye) were shown to detonate in the configurations and charges sizes tested.

Using the overpressure and impulse data acquired from these firings, TNT equivalencies of 0.26 for overpressure and 0.16 for impulse were determined for NQ/S42-12, and TNT equivalencies of 1.08 for overpressure and 0.8 for impulse were found for Bullseye. These figures were found to have a high standard deviation due to large variance in TNT equivalence for both range and charge mass observed.

The most substantiated reasons for the remaining propellants not detonating is due to low energetic content and small quantities tested ($\leq 250\text{g}$), and the subsequent thickness of the samples being sufficiently below the critical diameter found in other reports [26]. It is thought a better rate of detonation may also have been achieved with the use of a larger booster.

6.3 – Recommendations

Based on the conclusions of this project and the results obtained from it, a number of recommendations for further work are suggested:

- Testing on a larger scale should be conducted in order to determine the response of propellants in greater quantities, as critical mass is known to be a key factor in detonability and energetic response, especially in propellants.
- Testing of complete munitions is recommended to determine the actual threat of detonation from propellant in a real life scenario. If possible, this should be compared to small scale testing done in this project (specifically stage 2) to determine its effectiveness as a simulant of this situation.
- A series of tests should be carried out on higher energy propellants, as well as those propellants typically used in rocket motors, to determine their responses to a detonation.
- For future tube (or similar) tests, where fragments are to be collected, it is suggested that tubes are either painted with a durable paint, and/or the testing is done in a purpose built containment set up, one of which is available at COTEC at the time of writing. Unfortunately this was discovered after testing had been completed.
- Further research is needed to determine a TNT equivalence for a range of double and single base propellants in order to corroborate or improve on the limited data found in this thesis.

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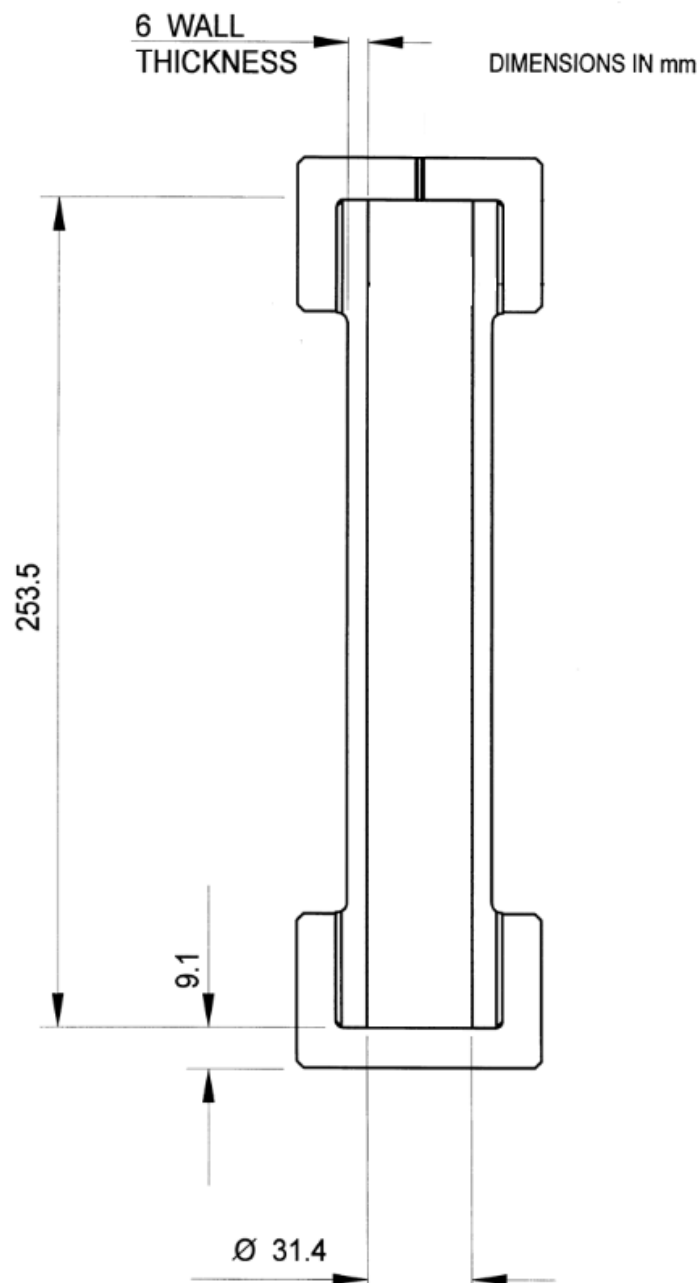
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8.0 – Appendices

- A. Tubular containment vessel schematic. Diagram modified from EMTAP test no.35 [29]



B. Propellant Compositions

Propellant (and Source)	Constituent	Percentage Range
BL-C(2) <i>(http://tinyurl.com/k8u6jaj)</i>	Nitroglycerin (NG)	0-40%
	Nitrocellulose (NC)	'Remainder'
	Dibutyl phthalate	0-10%
	Polyester Adipate	0-10%
	Rosin	0-5%
	Ethyl Acetate	0-1.5%
	Diphenylamine (DPA)	0.3-1.5%
	N, Nitroso diphenylamine	0-1.5%
	Potassium nitrate	0-1.5%
	Potassium sulphate	0-1.5%
	Tin dioxide	0-1.5%
	2-Nitro diphenylamine	0-1.5%
	Graphite	0.02-1%
	Calcium Carbonate	0-1%
Bullseye <i>(http://tinyurl.com/lycfdwz)</i>	Nitroglycerin (NG)	4-40%
	Nitrocellulose (NC)	'Remainder' (>54%)
	Diphenylamine (DPA)	~1%
	Ethyl Centralite (EC)	~1%
	Rosin	0-4%
Lil' Gun <i>(http://tinyurl.com/lfwbhe2)</i>	Nitroglycerin (NG)	0-42%
	Nitrocellulose (NC)	'Remainder'
	Dibutyl phthalate	0-10%
	Polyester Adipate	0-10%
	Akardite II	0-3%
	Ethyl Centralite (EC)	0-10%
	Rosin	0-5%
	Ethyl Acetate	0-2%
	Diphenylamine (DPA)	0-1.5%
	N, Nitroso diphenylamine	0.02-1%
	Potassium nitrate	0-3%
	Potassium sulphate	0-3%
	Tin dioxide	0-1.5%
	Graphite	0.02-1%
	Calcium Carbonate	0-1%
H322* <i>(http://tinyurl.com/k5xvcko)</i>	'Proprietary ingredients'	0-25%
	Nitrocellulose (NC)	>90%
	2,4-dinitrotoluene (DNT)	<10%
	Diphenylamine (DPA)	1%
	Graphite	1%
	Calcium Carbonate	<1%
	Potassium sulphate	<1%
	Potassium nitrate	<1%
H335 <i>(http://tinyurl.com/k8u6jaj)</i>	Nitroglycerin (NG)	0-40%
	Nitrocellulose (NC)	'Remainder'
	Dibutyl phthalate	0-10%
	Polyester Adipate	0-10%
	Rosin	0-5%
	Ethyl Acetate	0-1.5%
	Diphenylamine (DPA)	0.3-1.5%
	N, Nitroso diphenylamine	0-1.5%
	Potassium nitrate	0-1.5%
	Potassium sulphate	0-1.5%
	Tin dioxide	0-1.5%
	2-Nitro diphenylamine	0-1.5%
	Graphite	0.02-1%
	Calcium Carbonate	0-1%
NQ/S42-12 <i>(Communication with manufacturer)</i> <i>[BAE Systems]</i>	Nitroglycerin (NG)	~20.8%
	Nitrocellulose (NC)	~20.6%
	Nitroguanidine (NQ)	~55%
	Ethyl Centralite (EC)	~3.6%
	Potassium Sulphate	~0.3%

C. Links to high speed videos

Firing #	Propellant	Mass	URL
4	Bullseye	250g	http://youtu.be/VUnehH0DFqs
5	Bullseye	250g	http://youtu.be/7zwX2C_MWLM
6	Bullseye	250g	http://youtu.be/hP_ZEW68WwU
7	NQ/S42-12 + PE4	100g + 10g	http://youtu.be/i1ryLS8KBKI
8	NQ/S42-12 + PE4	100g + 20g	http://youtu.be/SDr87xzqglg
9	NQ/S42-12 + PE4	100g + 30g	http://youtu.be/y__BfRAecnY
10	NQ/S42-12 + PE4	100g + 40g	http://youtu.be/S04gFBwbGMM
12	NQ/S42-12 + PE4	100g + 100g	http://youtu.be/bkGHafagzgc
13	PE4	100g	http://youtu.be/uYdA-LGBTek
14	Lil' Gun	250g	http://youtu.be/hR0Yt61iJ6I
15	BL-C(2)	250g	http://youtu.be/QyMUoJtC8D8
17	H322	250g	http://youtu.be/-_Ms2nCATqw

D. – EMTAP tube test guidance

EMTAP

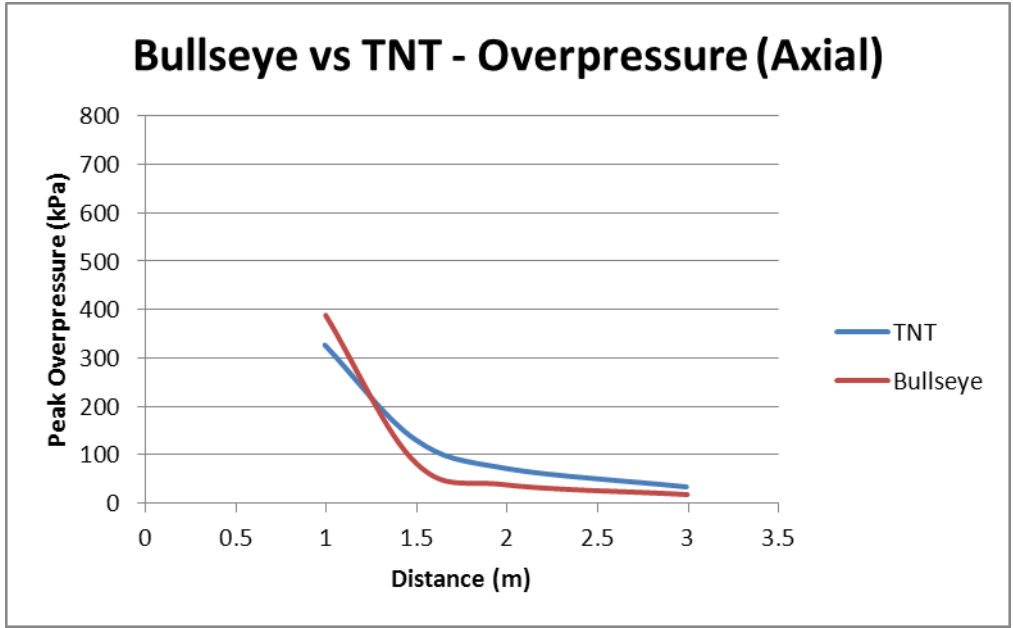
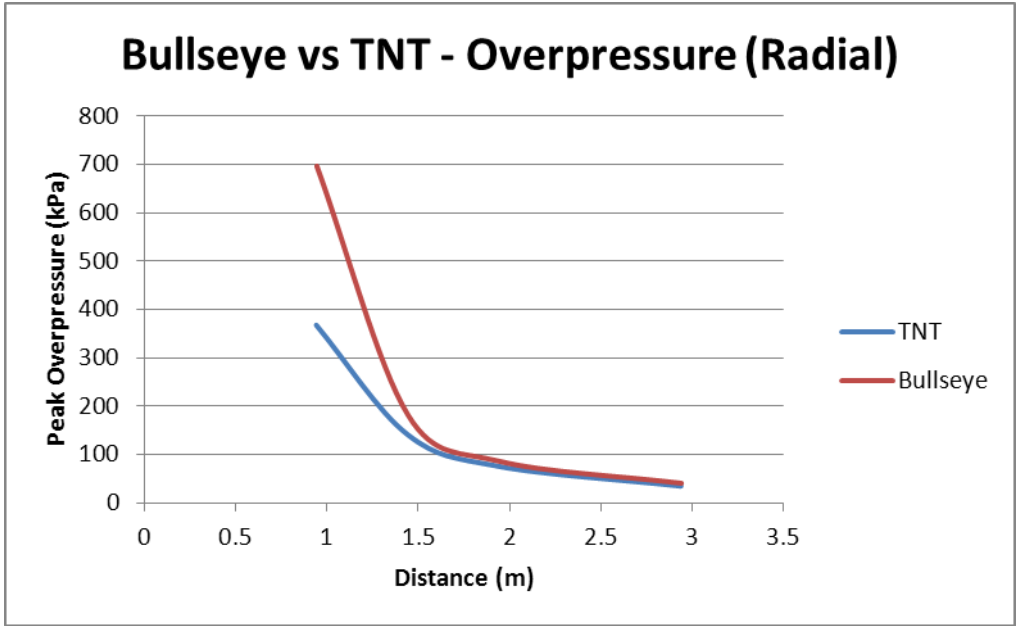
Test No 35
April 2005

TABLE 2 Description of Reaction Categories

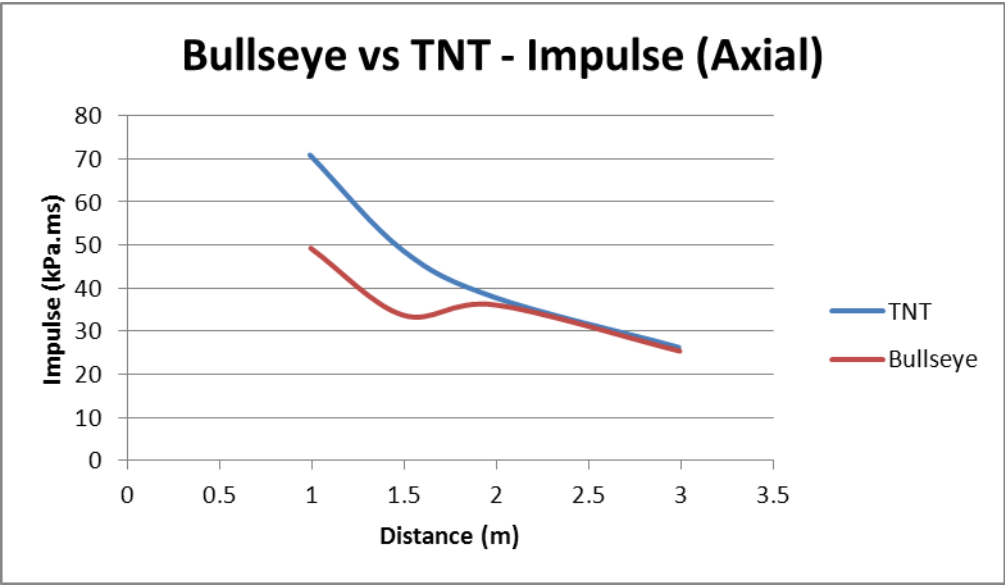
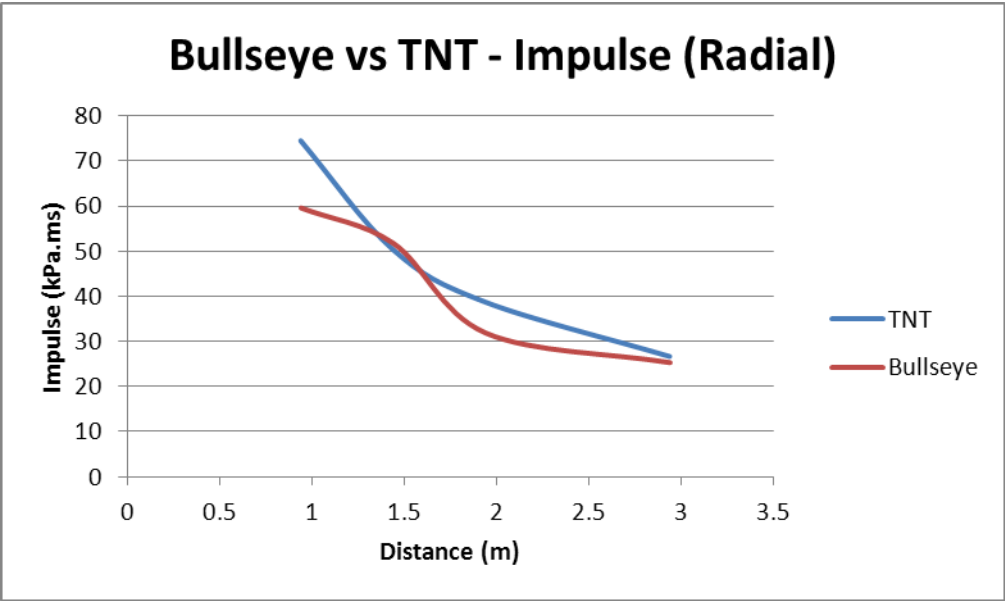
Category	Reaction Description	Observation
0	No reaction	From weighing
0/1	Burning decomposition	No disruption of test vehicle
1	Pressure burst due to burning/decomposition	Assembly ruptured but one fragment approximates to original weight
2	Deflagration	2 to 9 body fragments
3	Explosion	10 to 100 body fragments
4	Detonation	>100 test vehicle body fragments showing evidence of detonation

"In those experiments where less than 100% of the test vehicle is recovered, the number of body fragments recorded in Table 1 may be divided by their fraction of the intact vehicle to give a "normalised number of body fragments".

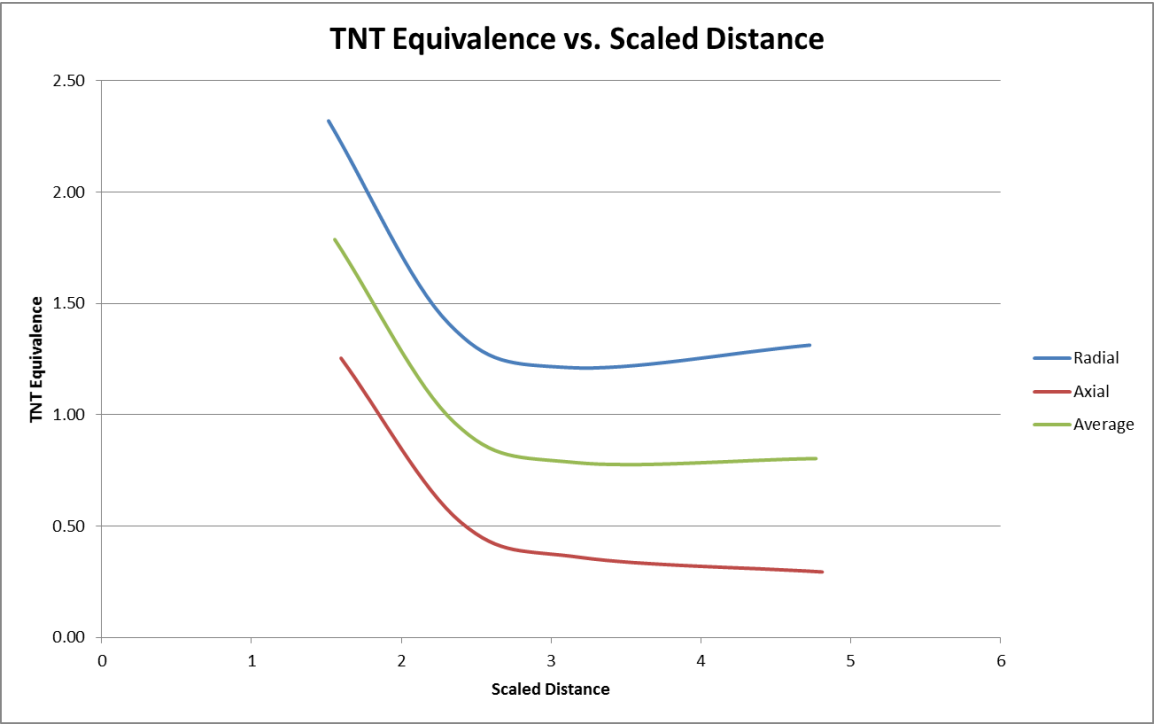
E. Bullseye vs. TNT (for Overpressure) at equal mass



F. Bullseye vs. TNT (for Impulse) at equal mass



G. TNT Equivalence vs. Scaled Distance for Bullseye



9.0 – Additional Data

This section contains complete data sets used in the main body of this thesis.

9.1 – Miscellaneous

9.1.1 Range Set-Up

Approximate Pressure Gauge Locations		
Gauge	Distance	Direction (where appropriate)
1	1m	Radial
2	1.5m	Radial
3	2m	Radial
4	3m	Radial
5	1m	Axial
6	1.5m	Axial
7	2m	Axial
8	3m	Axial

9.1.2 Raw Digital Data Download

A compressed folder containing the pressure time data (viewable in DPlot) for firings 4-17 can be downloaded from the following link: <http://tinyurl.com/oxz22r7>

9.2 – Stage 1

9.2.1 Fragment Data

	Fragment Mass (g)		
	Firing 1	Firing 2	Firing 3
End Cap	142.2	137.4	1000.9
	843.3	841.16	5.1
	6	2.54	7.6
	7.6	4	9.7
	14.6	4.3	17.8
	18.1	5.2	18.6
	24.8	6.3	21.2
	28.7	7.8	25
	29.5	9.1	25.5
	40.6	9.7	31.4
	41.3	11.2	55.6
	41.7	11.5	115.8
	48.1	12.5	138.1
	51.9	13.1	162.2
	55.5	15	167.2
	68.7	18.1	173.6
	98.9	18.7	
		19.34	
		19.9	
		22	
		22.8	
		23.3	
		24.5	
		26.1	
		28.8	
		29.7	
		31.6	
		32.9	
		34.7	
		37.5	
		44.8	
		44.9	
		45.9	
		49.7	
		50.9	
		69.1	
		74.3	

9.3 – Stage 2

9.3.1 100g PE4, 10g Propellant

Gauge	Arrival Time (ms)	Pressure (Pa)	Distance (m)	Impulse (Pa.ms)
1	0.908	235548	0.938	35417.08
2	1.939	93247.52	1.438	29607.06
3	3.136	49375.47	1.938	20856.55
4	5.73	26013.45	2.938	14387.15
5	0.941	174994.2	0.987	31692.82
6	2.028	72423.69	1.487	26793.02
7	3.257	50262.4	1.987	20914.75
8	5.862	26483.98	2.987	13758.55

9.3.2 100g PE4, 20g Propellant

Gauge	Arrival Time (ms)	Pressure (Pa)	Distance (m)	Impulse (Pa.ms)
1	0.838	261698.5	0.942	37038.38
2	1.839	96813.67	1.442	30609.38
3	3.032	51552.54	1.942	22016.64
4	5.627	26770.12	2.942	17598.8
5	0.89	181250.6	0.987	36284.41
6	1.931	93710.86	1.487	29875.48
7	3.136	54204.32	1.987	23921.2
8	5.701	27083.5	2.987	16333.28

9.3.3 100g PE4, 30g Propellant

Gauge	Arrival Time (ms)	Pressure (Pa)	Distance (m)	Impulse (Pa.ms)
1	0.834	238281.8	0.94	39517.16
2	1.807	111297.4	1.44	32164.18
3	2.97	60034.74	1.94	22664.78
4	5.526	29380.94	2.94	14303.51
5	0.912	228320.4	0.988	37533.89
6	1.934	95910.51	1.488	30794.63
7	3.128	51635	1.988	23646.56
8	5.699	29259.08	2.988	16131.88

9.3.4 100g PE4, 40g Propellant

Gauge	Arrival Time (ms)	Pressure (Pa)	Distance (m)	Impulse (Pa.ms)
1	0.779	273406.8	0.937	38717.51
2	1.763	107238.3	1.437	33175.22
3	2.941	60551.42	1.937	23760.12
4	5.496	30412.63	2.937	16136.3
5	0.863	261972.1	0.989	39117.54
6	1.878	92831	1.489	30473.1
7	3.085	50166.81	1.989	23642.69
8	5.647	28418.51	2.989	17097.29

9.3.5 100g PE4, 50g Propellant

Gauge	Arrival Time (ms)	Pressure (Pa)	Distance (m)	Impulse (Pa.ms)
1	0.804	272302.3	0.94	41052.29
2	1.771	111205.1	1.44	34221.76
3	2.925	61886.19	1.94	24783.04
4	5.477	28601.9	2.94	17649.22
5	0.863	282631.7	0.987	41754.09
6	1.839	99605.94	1.487	33700.65
7	3.026	52491.44	1.987	27980.8
8	5.58	31039.1	2.987	18485.4

9.3.6 100g PE4, 100g Propellant

Gauge	Arrival Time (ms)	Pressure (Pa)	Distance (m)	Impulse (Pa.ms)
1	0.741	358458.2	0.938	50331.16
2	1.644	144600.7	1.438	43795.41
3	2.743	78635.31	1.938	30489.02
4	5.234	37613.44	2.938	27266.14
5	0.729	302013.3	0.987	44787.32
6	1.717	117555.1	1.487	37706.52
7	2.866	63992.22	1.987	32959.12
8	5.348	36354.44	2.987	21544.65

9.3.7 100g PE4, 0g Propellant

Gauge	Arrival Time (ms)	Pressure (Pa)	Distance (m)	Impulse (Pa.ms)
1	0.868	213981.4	0.941	35412.06
2	1.895	94138.34	1.441	29299.43
3	3.088	52069.22	1.941	20531.64
4	5.669	26664.84	2.941	15487.66
5	0.961	160484.5	0.987	32251.2
6	2.04	77661.62	1.487	25523
7	3.264	50744.15	1.987	21347.5
8	5.857	25479.63	2.987	13596.08

9.4 – Stage 3

Accurate arrival time and impulse data is not available for the majority of small arms firings due to noise.

9.4.1 250g Bullseye (firing 4)

Gauge	Arrival Time (ms)	Pressure (Pa)	Distance (m)	Impulse (Pa.ms)
1	0.598	664136.8	0.932	60983
2	1.258	175032.2	1.432	53703.99
3	2.378	86318.27	1.932	27522.91
4	4.734	44102.33	2.932	28007.82
5	0.545	302412.7	0.998	43801.17
6	1.511	91326.98	1.498	37364.26
7	2.723	38891.61	1.998	37982.54
8	5.391	19064.14	2.998	26713.69

9.4.2 250g Bullseye (firing 5)

Gauge	Arrival Time (ms)	Pressure (Pa)	Distance (m)	Impulse (Pa.ms)
1	0.642	728794.4	0.942	58163.13
2	1.391	204005.9	1.442	49225.03
3	2.477	84940.45	1.942	34629.53
4	4.838	39765	2.942	24248.19
5	0.548	373123.8	0.99	53943.56
6	1.487	86927.67	1.49	35642.52
7	2.692	35710.54	1.99	34151.39
8	5.396	18025.79	2.99	24325.32

9.4.3 250g Bullseye (firing 6)

Gauge	Arrival Time (ms)	Pressure (Pa)	Distance (m)	Impulse (Pa.ms)
1	0.766	273014	0.954	51714.34
2	1.43	166297.4	1.454	52279.36
3	2.45	87093.3	1.954	33454.56
4	4.872	37827.94	2.954	23605.31
5	0.529	488987.9	0.996	50039.41
6	1.28	69110.45	1.496	28202.32
7	2.574	38279.87	1.996	36152.68
8	5.298	15405.21	2.996	25103.11

9.4.4 250g Lil' Gun

Gauge	Distance (m)	Pressure (Pa)
1	0.947	0
2	1.447	21131.68
3	1.947	11652.27
4	2.947	7774.559
5	0.997	27208.89
6	1.497	16882.36
7	1.997	12357.22
8	2.997	6866.675

9.4.5 250g BL-C(2)

Gauge	Distance (m)	Pressure (Pa)
1	0.943	15727.39
2	1.443	8465.472
3	1.943	5515.34
4	2.943	3145.316
5	0.99	9536.659
6	1.49	5872.648
7	1.99	4072.657
8	2.99	2339.638

9.4.6 250g H335

Gauge	Distance (m)	Pressure (Pa)
1	0.947	9503.766
2	1.447	5680.203
3	1.947	3455.233
4	2.947	2421.409
5	0.985	10592.33
6	1.485	5971.758
7	1.985	4621.597
8	2.985	2392.518

9.4.7 250g H322

Gauge	Distance (m)	Pressure (Pa)
1	0.942	29361.32
2	1.442	11047.39
3	1.942	8092.86
4	2.942	4770.791
5	0.987	20276.04
6	1.487	12793.17
7	1.987	9937.306
8	2.987	5085.18

BACK COVER