Experimental Measurement of TNT Equivalency For Contact Charges

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Abstract

The ability to compare explosives is fundamental. Numerous methods are used and while simple conversion factors are often used, the use of TNT Equivalency (TNTe) is not a simple subject as explosives exhibit very different equivalencies depending on whether the pressure or impulse are being considered as well as other conditions. The scaled distance has been found to have a significant effect on the TNTe but due to the difficulty of taking measurements at very close ranges, no TNTe have been quoted for charges in direct contact (Z=0). This paper describes the use of a ballistic pendulum to measure the impulse from contact charges and presents some surprising results that require a two-stage propulsion, as originally described by Backofen, to be explained.

Key Words: Ballistic Mortar, Explosive, Tamping, measurement of impulse, TNT Equivalency, two-stage propulsion

Introduction

The ability to compare different explosive materials with each other is important. It gives blasters the ability to optimise shots, use cheaper explosives or enhance performance by selecting explosives with different compositions or from different suppliers.

The need to be able to compare different explosives has been fundamental to the understanding of explosives since they were first invented. Tests such as the Trauzl test (1903) which was known to give misleading results with slow-burning explosives such as black powder [1, p. 34], the sand crush test (1910) [2, p. XXI], and the plate dent test (1917) [2, p. XX] all give a method of comparing various explosives. The Ballistic Mortar [3] is a piece of equipment that was used as the primary method of measuring the explosive "strength" defined by Taylor and Morris as the "maximum mechanical work the explosion products are capable of performing", and was commonly used for testing batches of explosives for conformity. It consists of a heavy pendulum mass with a cavity into which a projectile is inserted. A 10g charge of the explosive to be tested is positioned within the mortar and detonated, ejecting the projectile, and causing the pendulum to swing. The angle of the swing is used to calculate the total energy Q. The ballistic mortar was seen as superior to the earlier tests as it gives results in absolute figures. These are then compared against a reference explosive to give a relative strength [4, p. 36]. In the UK the reference explosive was Polar Blasting Gelatine [5, p. 178] and in the US TNT was used to give a 'triton value'[6], which is defined as the number of grams of TNT which will give the same swing to the ballistic mortar as 10g of the explosive under test.

Large-Scale Testing

With the advent of electronic instrumentation, tests could be conducted in which pressure transducers recorded pressure-time histories. Much of the original experimental work for developing the blast tables used today was done in the late 1950s and 1960s [7]. A series of four large TNT detonations were conducted at Suffield Experimental Station in Canada, culminating in a 500 tonne TNT test shot (Operation Snowball [8]). The results from these trials was later developed by Kingery and Bulmash into a more usable form [9] that now forms the basis of blast prediction software such as ConWep [10]. For that reason, the data used for predicting blast is all based on bare, spherical or hemispherical TNT charges that are centrally initiated. As TNT is no longer a commonly used main explosive most modern work requires TNT equivalence (TNTe) to allow the older field data to be used for predictions to be made for other explosives. If the same trials were to be conducted today, another explosive, such as RDX would no-doubt have been selected instead.

A series of trials were conducted in the 1970s and 1980s at the US Army Armament Research and Development Command to use a standardised test to obtain TNT equivalencies for many explosives and propellants [11]–[14]. The standardised test configuration used rays of pressure sensors aligned on two perpendicular axes around charges. Charges ranging from 50lb to 120lb in specific packaging were detonated and recorded at scaled distances ranging from 3.0 - 40 ft/lb1/3 (1.19 – 15.87 m/kg1/3) [10], [15]. Most this data was presented as TNT equivalencies however one report in the series from 1978 refers to equivalent weight factor and used Pentolite (50:50 TNT/PETN) as the standard explosive [16]. This seems to have been short-lived and later reports reverted to TNT equivalency.

This series of trials expressed the TNT equivalency as a percentage for both pressure and impulse at a range of scaled distances. This shows that there are clearly very different TNT equivalencies depending on the configuration of the charge and the scaled distance. RDX, for instance, had equivalencies for pressure ranging from 116% up to 526% and for impulse from 30% up to 258% [11].

While most references generally quote a single set of TNT equivalencies for pressure and impulse for each explosive, the TNT Equivalency trials conducted by the US Army Armament Research and Development Command clearly show that this is overly simplistic, and that any equivalency can only be used within specific scaled distance ranges.

Scaling

In order to normalise data and allow meaningful comparisons to be made between trials, the Hopkinson or "cube-root" scaling is typically used [17] in order to determine the Scaled Distance (Z), Scaled Time (τ) or Scaled Impulse (ζ) [18] which are calculated as:

$$Z = R/E^{1/3} \; or \; R/W^{1/3} \qquad \text{(Equation 1)}$$

$$\tau = t/E^{1/3} \;\; or \;\; t/W^{1/3} \qquad \text{(Equation 2)}$$

$$\zeta = I/E^{1/3} \text{ or } \mathrm{I}/W^{1/3} \qquad \text{(Equation 3)}$$

Where

R = distance, E = energy of the explosive, W = weight of the explosive, t = time, I = Impulse

The scaled distance allows different charge/distance configurations to be compared or scaled down experiments to be done such that the time-pressure histories are comparable. For example, 8,000kg of TNT at 100m has a scaled distance of 5m/kg1/3. If a scaled down charge were to be tested that had 1kg at 5m, the scaled impulse would also be 5m/kg1/3 meaning that the blast characteristics would be the same for both tests.

Near-Field, Mid-Field and Far Field Tests

It is known that TNTe varies depending on several factors, including the scaled distance. To compensate for this, some researchers separate tests into either near-field or far-field. While the authors have not found any defined ranges they appear to consider near-field to be scaled distances between 0.2 and 3m/kg1/3 and far-field to be greater than 3m/kg1/3 [19], [20]. Interestingly, Kingery and Bulmash present data from 1kg charges from distances ranging from approximately 0.05m to 40m [9]. When the scaled distance is plotted against incident pressure there are two inflection points, one at $Z = 0.4$ and another at approximately $Z=4$ (Fig. 1). The authors propose that this be used as the basis for defining the thresholds for near-field and far-field measurements and the introduction of the mid-field which would lie between $Z > 0.4$ and $Z<4$.

The US DOD classification procedures have three ranges for Scaled distance when considering peak pressure, 0.2-2.9, 2.9-23.8 and 23.8-198.5 m/kg1/3 and four when considering Impulse, 0.2-0.96, 0.96-2.38, 2.38-33.7 and 33.7-158.7 m/kg1/3 [21, Tbls. 6–1]. There is no explanation given within the text for these ranges.

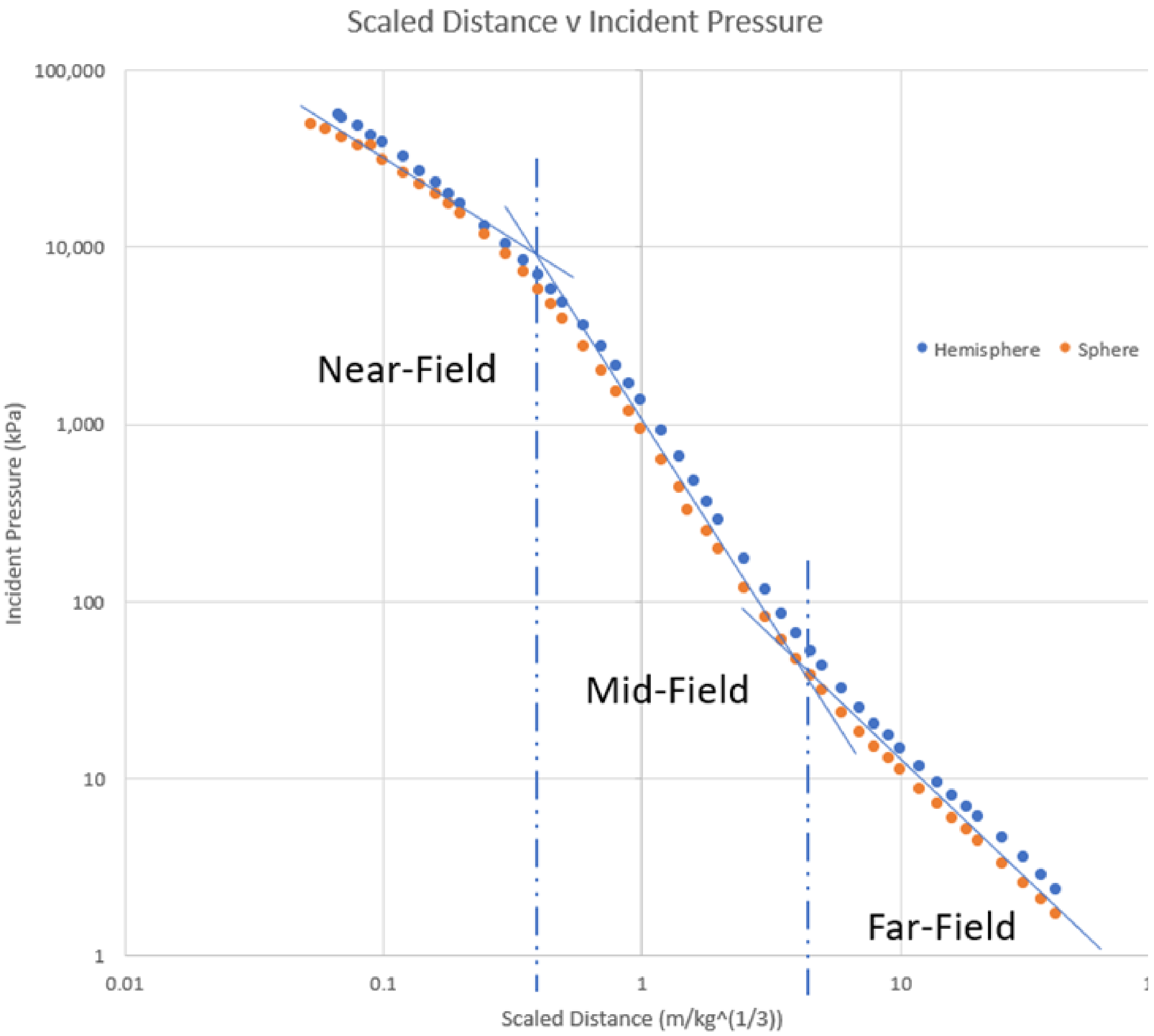


Fig. 1. Kingery & Bulmash data for 1kg Spherical TNT charge [9, Tbls. 1 & 3] with author's best-fit lines illustrating the three distinct regimes for incident pressure

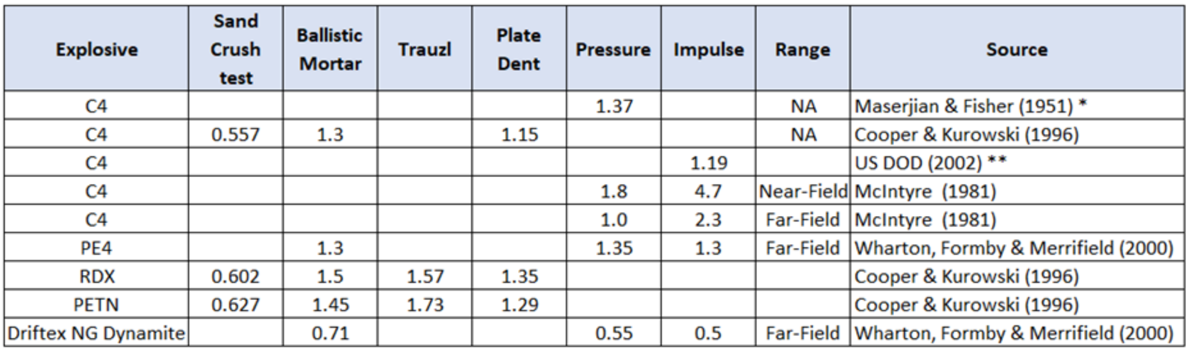
To use this data with different explosives the TNT Equivalence (TNTe) is required for each explosive being used. There are several methods of deriving the equivalency, both theoretical and experimental [10] which will be discussed in further detail later, but it is important to recognise that the TNTe varies depending on what factor is being compared, for example the explosive strength or power, overpressure or impulse. It is also known that the TNTe is not constant with scaled distance and can vary significantly, in particular in the near-field and mid-field ranges [10], [15].

The authors are interested in the impulse from charges in direct contact with a target where Z=0 and the event is within the fireball. A literature search found nothing on tests with these conditions.

Locking describes some of the main theoretical methods used to determine the TNTe [22] and no further discussion will be made in this paper. Theoretical methods include using the Power Index (PI) which uses the heat of detonation and the volume of gas produced, hydrodynamic work calculations which use the Chapman-Jouguet Detonation Pressure and the explosive density, and the Heat of Detonation (Q) which simply compares the heat of detonation between the test explosive and TNT.

Clearly, there is no single and highly accurate way to determine TNTe for explosives [23]. Cooper stated that "TNT Equivalence" has little practical meaning in respect to most of the tests which are used to define it. For applications where our interest is in understanding and quantifying the effects of explosives which apply to shattering and/or producing plastic deformation of an adjacent material, the CJ pressure of the explosive is the precise property which is applicable" [24]. The TNT equivalence is also known to change with scaled distance, impulse and pressure [22] and the TNT equivalencies of explosives have been found to vary significantly for Pressure (TNTe P) and Impulse (TNTe I) [10].

Table 1. Sample TNTe factors from various published sources



Explosive	Sand Crush test	Ballistic Mortar	Trauzl	Plate Dent	Pressure	Impulse	Range	Source
C4					1.37		NA	Maserjian & Fisher (1951) *
C4	0.557	1.3		1.15			NA	Cooper & Kurowski (1996)
C4						1.19		US DOD (2002) **
C4					1.8	4.7	Near-Field	McIntyre (1981)
C4					1.0	2.3	Far-Field	McIntyre (1981)
PE4		1.3			1.35	1.3	Far-Field	Wharton, Formby & Merrifield (2000)
RDX	0.602	1.5	1.57	1.35				Cooper & Kurowski (1996)
PETN	0.627	1.45	1.73	1.29				Cooper & Kurowski (1996)
Driftex NG Dynamite		0.71			0.55	0.5	Far-Field	Wharton, Formby & Merrifield (2000)

* [25] **[25]

Despite these limitations, TNTe is the simplest and most common way to allow some comparisons to be made between charges using different explosives [20]. Table 1 has a selection of TNTe factors for C4 and Dynamite from various sources.

TNTe for Contact Charges

The authors' primary interest is in the use of explosive charges that can be used in explosive demolition and explosive method of entry (breaching) for displacing cut sections of structures and stripping concrete or creating access ports in walls [26]–[28]. These types of charge are generally in direct contact with the target so a knowledge of TNTe for different explosives when the scaled distance is zero is required. For these applications, the impulse is the most useful explosive characteristic, and this is known to have the most deviation as the scaled distance reduces (fig. 2). There is no simple way to directly measure the impulse or pressure at Z=0 using pressure sensors as they would be destroyed before they could measure any readings. For this reason, using a ballistic pendulum is the only viable method. The only reference found for this is for testing done by Baum et al in the former Soviet Union in the 1960 in which a ballistic pendulum seems to have been constructed with a long horizontal bar as the pendulum mass. Explosive charges were placed against one end of the bar to cause it to swing in order to determine the impulse of force [5, p. 177].

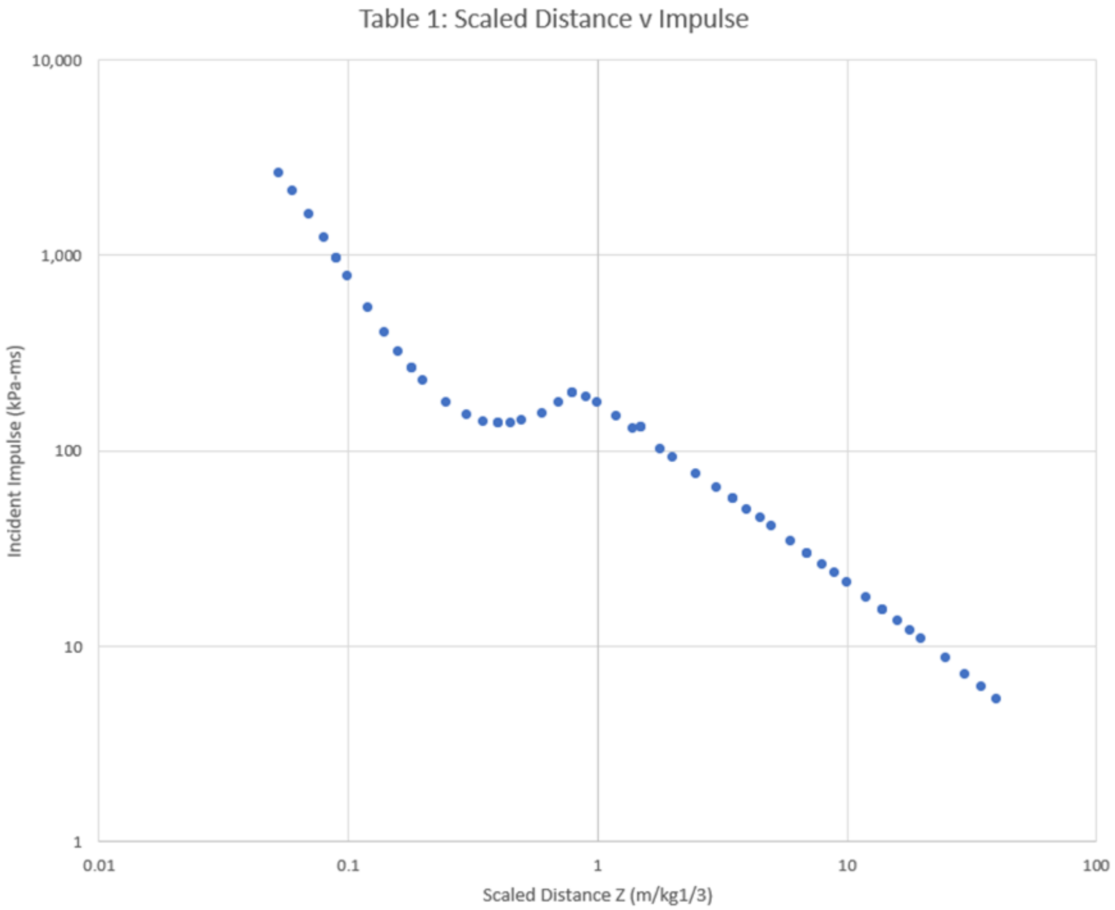


Fig. 2. Kingery & Bulmash data for 1kg Spherical TNT charge [9, Tbl. 1] showing a major discontinuity that appears common with impulse

Experimental Methods

Instrumentation

The authors have previously presented work on a modular ballistic pendulum (MBP) with interchangeable masses for measuring impulse produced by charges placed in direct contact with the pendulum mass [29]. The pendulum has previously been used to measure the impulse from explosive charges both with a stand-off (Z = 0.7) and for contact charges (Z = 0). The system offers a simple method of measuring the impulse and comparing different charges.

It is reasoned that the same system could be used in much the same way that the original ballistic mortar to compare the relative performance of different explosives in terms of impulse.

Unlike the ballistic mortar, the ballistic pendulum does not have a firing chamber for containing the explosive and there is no projectile to be ejected. Charges are directly fixed to the anvil on the pendulum and the gas products allowed to vent directly into the atmosphere while imparting impulse into the pendulum, causing it to swing.

The angle of swing is recorded on video and the impulse calculated using:

$$J = m\sqrt{2gr\,(1 - \cos\theta)}$$

(Equation 4)

Where J is Impulse, m is mass of pendulum (kg), g is gravity, r is the length of the pendulum arm and θ is the angle of rotation.

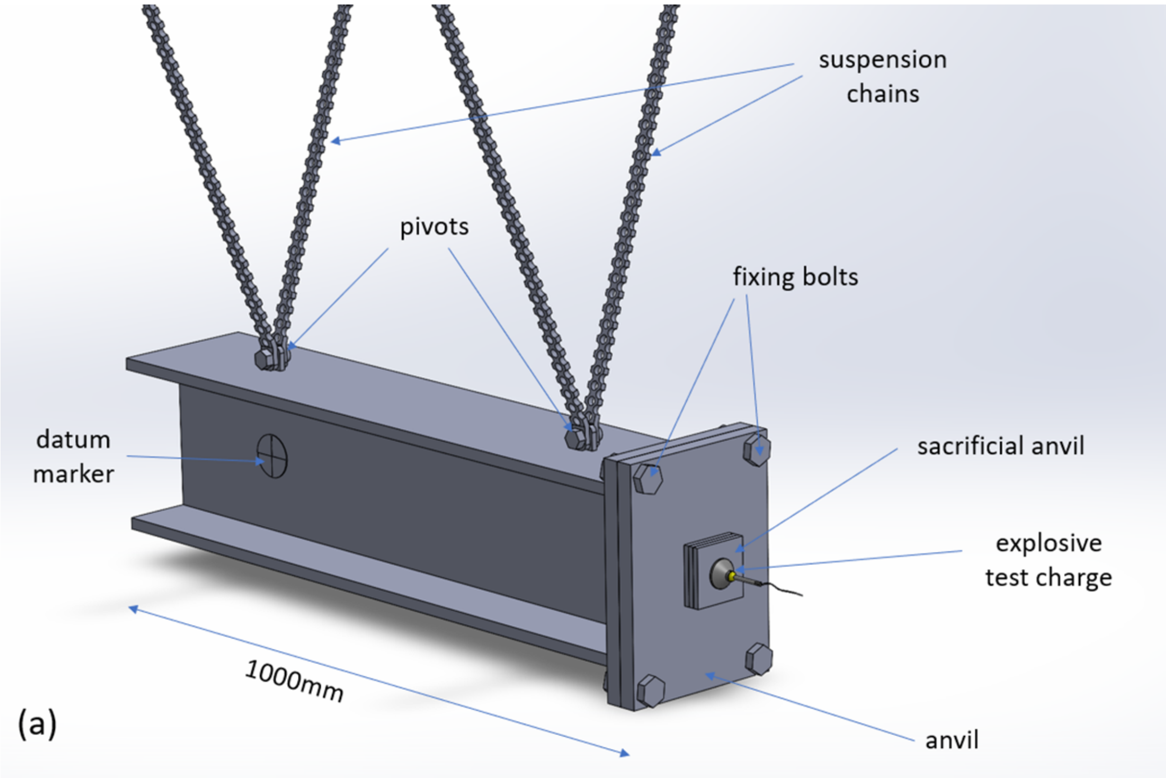


Fig. 3. (a) The 86kg pendulum mass has replaceable anvils and each charge has one or more sacrificial steel anvil plates to protect the pendulum mass from damage (b) The MBP frame and light mass being swung by a 30g charge of plastic explosive. “Tracker” software allows accurate measurement of the angle of rotation from recorded video.

Materials

Tests were carried out with charges ranging from 10g to 70g for a range of explosives which were fixed directly to small sacrificial anvils designed to transmit the force into the pendulum mass while preventing damage to the mass. It was reasoned that as the traditional ballistic mortar is used with 10g charges, this magnitude of charge could be used if a light pendulum mass were selected and conducting a series of firings in which the explosive increases would be a substitute for increasing the scaled distance.

The explosives tested were cast TNT (poured-clear-coarse) [30], Poladyn [31] and PE4 which is RDX-based [32].

Plastic moulds or charge containers were 3D printed to make the cast charges and the more plastic explosives were shaped by hand and not fired in a container. Various charge shapes were tested (short cylinders, hemispheres, and cones of different angles.

(a)

(b)

(c)

(d)

Fig. 4. Examples of different test shapes and explosives. (a) Hand-rolled Poladyn hemispheres, (b) Poladyn charge fixed to pendulum mass, (c) 3D printed conical moulds used for casting TNT charges and forming mouldable explosives, (d) cast TNT after removal from mould. Later tests kept the charge in the mould which was considered to be a consumable.

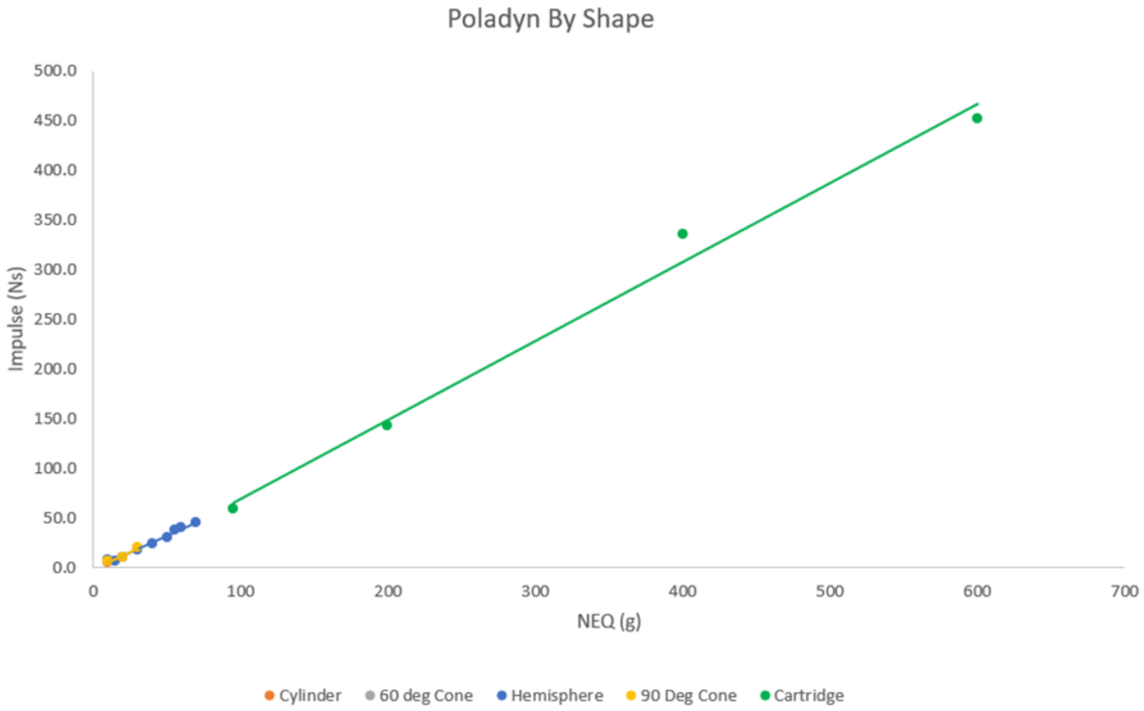


Fig. 5. Comparison of results with different charge shapes Poladyn show that the charge shape has relatively little effect on the impulse measured

When impulse was plotted against NEQ for different charge shapes, analysis of the data showed that the shape appears to have little effect on the impulse measured (Fig.5).

Hemispheres were found to be good for mouldable explosives as a ball of explosive could simply be squashed onto the anvil to form a hemisphere, however cast explosives require a mould for casting into. In this case it was felt easier to design conical moulds for any given NEQ by assuming an explosive density of 1.6. The final shape selected was therefore a 90-degree cone.

It had been assumed that making 10g TNT charges would be simple and that they would initiate easily given that they have historically been used in the ballistic mortar. In fact, it was found that getting small cast TNT charges to initiate is rather difficult.

Various initiation conditions were used, all with a No. 8* electric detonator and a small PETN-based explosive booster. It was eventually found that a 20g charge with a 2g booster was capable of detonating, but not with 100% reliability. No literature was found to describe cast TNT charges of this size and with larger charges it is known that loose TNT is easier to detonate. Cook wrote that fine-grained loose TNT (density 0.8) could be initiated with knotted detcord whereas cast TNT required a tetryl booster was required [4, p. 54].

For this reason, despite several test shots being attempted, only four data points were obtained for 10g and 20g loads. All other charges either deflagrated or failed to initiate completely.

Tests were conducted using charges of three different explosives. These were cast TNT, Poladyn, and PE4. The smallest pendulum mass, weighing 86.2kg, was used. Charges were attached to single-use steel plates 10mm thick and 100mm square which were damaged by the blast of the more brisant charges.

Results and Discussion

Data Analysis

Test shots were filmed at 4K Resolution on a digital camera positioned 5 from the test equipment. The video was then analysed using software called Tracker [33] which allowed a protractor to be overlayed on the image to measure the angle of swing. This was then used in Equation 4 to derive the impulse from each charge.

Test Results

Table 2. Test Firing Data

Test No.	Explosive	NEQ g	Impulse Ns
1-1	TNT-C Cylinder	10	4.5
1-2	TNT-C Cylinder	10	5.3
1-3	TNT-C Cylinder	10	4.5
1-4	TNT-C 90 deg cone w. 2g booster	10	4.9
1-5	TNT-C 90 deg cone w. 2g booster	20	8.1
1-6	TNT-C 90 deg cone w. 2g booster	30	7.0
2-1	Poladyn Cart	94.9	58.7
2-2	Poladyn Cart	200	142.5
2-3	Poladyn Cart	400	335.2
2-4	Poladyn Cart	600	452.2
2-5	Poladyn Cylinder	10	6.5
2-6	Poladyn Cylinder	10	6.1
2-7	Poladyn Cylinder	10	4.9
2-8	Poladyn Hemisphere	10	8.1
2-9	Poladyn Hemisphere	20	10.8
2-10	Poladyn Hemisphere	30	17.8
2-11	Poladyn Hemisphere	40	23.7
2-12	Poladyn Hemisphere	50	30.7
2-13	Poladyn Hemisphere	60	40.4
2-14	Poladyn Hemisphere	15	7.0
2-15	Poladyn Hemisphere	55	38.2
2-16	Poladyn Hemisphere	70	44.7
2-17	Poladyn Hemisphere	30	18.9
2-18	Poladyn 60 deg cone	20	9.7
2-19	Poladyn 90 deg cone	10	5.9
2-20	Poladyn 90 deg cone	20	10.8
2-21	Poladyn 90 deg cone	30	19.9
3-1	PE4 Cylinder	10	20.3
3-2	PE4 Cylinder	10	18.7
3-3	PE4 90 deg cone	10	16.7

3-4	PE4 90 deg cone	20	38.2
3-5	PE4 90 deg cone	30	51.1

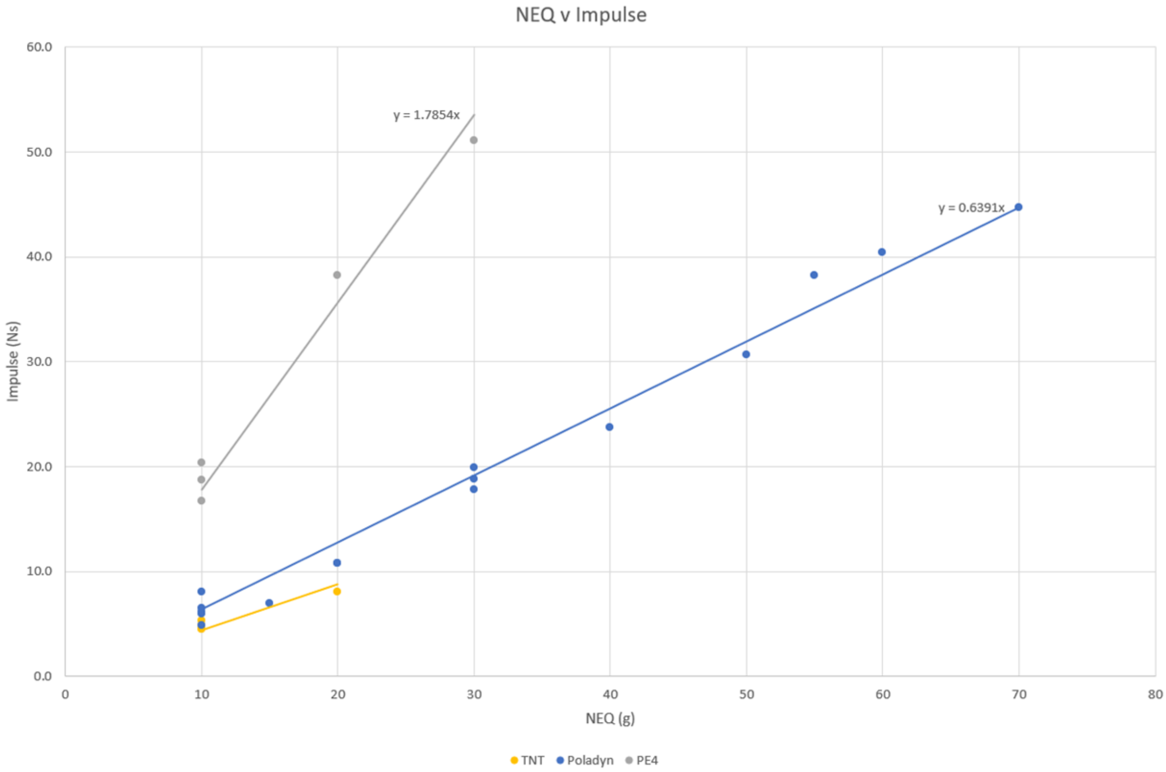
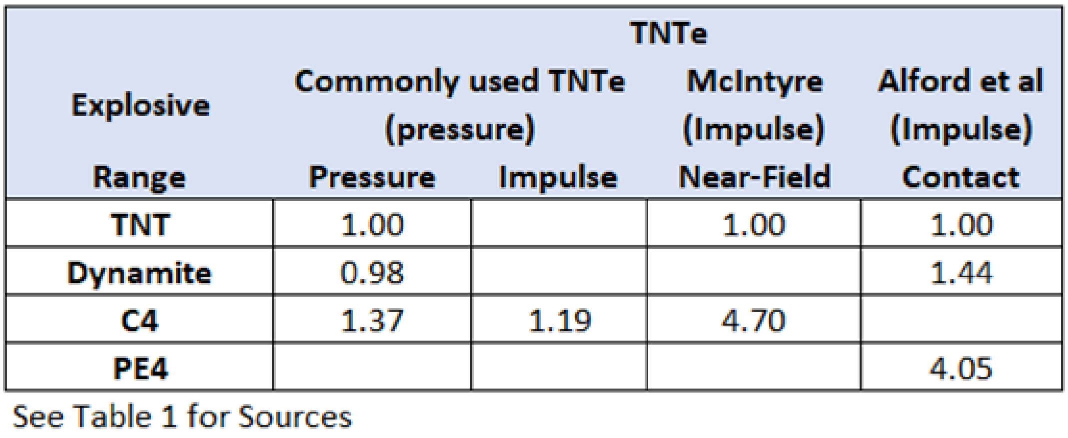


Fig. 6. Impulse plotted against NEQ for the three explosives tested. All trendlines are set to intercept the origin.

Table 3. *Summary of key TNT Equivalency for different explosives*



Explosive	TNTe			
	Commonly used TNTe (pressure)		McIntyre (Impulse)	Alford et al (Impulse)
Range	Pressure	Impulse	Near-Field	Contact
TNT	1.00		1.00	1.00
Dynamite	0.98			1.44
C4	1.37	1.19	4.70	
PE4				4.05

See Table 1 for Sources

Discussion

Two questions arise from the results (Table 2). The first is whether the TNTe for PE4 of 4.05 is realistic given that the most quoted figure, taken from CONWEP, is 1.37 for pressure and 1.19 for impulse [34]. The second question is why there is such a large difference between the TNTe of Poladyn and PE4 given that they are normally expected to be in the ranges of 0.98 - 1.19 respectively [35].

The TNTe figures obtained for the three explosives in Table 3 appear, at first glance, anomalous as PE4 is highly comparable to C4 [36], [37] whereas the tests gave a TNTe of 4.05 which is 3,7 times higher. The confirmation shots done with PENO gave comparable results to those from PE4.

Given that the results were based on a range of charge sizes and the data shows highly linear relationships, it should be assumed that these results are correct and that an explanation for the variation is required.

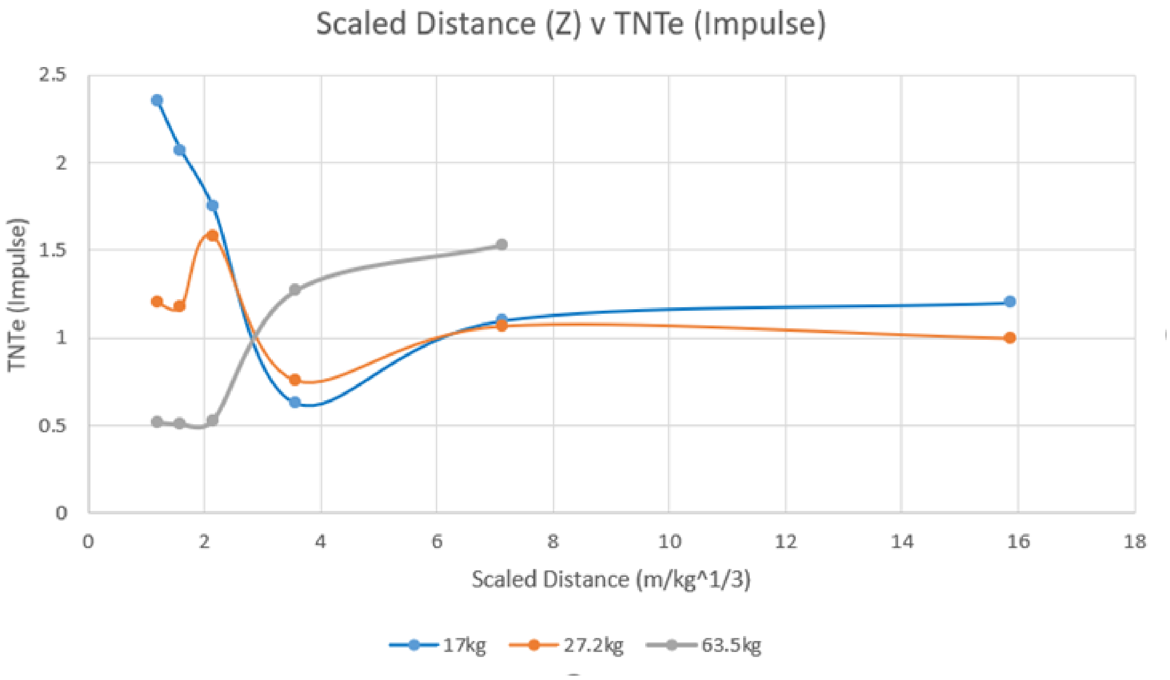


Fig. 7. Plotting McIntyre’s TNTe (Impulse) for C4 and this trial’s comparable figure, one can see that the two smaller NEQ charges from McIntyre show a sudden increase as Z reduces. Extrapolating back to the Y axis, they would meet the axis close to the Z=0 figure **[13, Tbls. 2–4], [38]**.

When the work by McIntyre is considered, in which it was found that the TNTe varied significantly depending on the range of scaled distance [38] the large TNTe factor is not unrealistic. This is illustrated in Fig. 7 in which McIntyre’s data for C4 is plotted. As the scaled distance in McIntyre’s data reduces, the TNTe increases rapidly and could be extrapolated to be heading towards the Z=0 figure of 4.05 which was found in the current tests. This corresponds to the observation by Huntington-Thresher and Cullis that at a scaled distance of 0.5, the values for scaled impulse predicted by the cAst-Euler hydrocode were 4.5 times the CONWEP value [39].

The second question, why were Poladyn impulses so much lower than those for PE4 when the TNTe was much closer to that which would normally be expected, initially requires an appraisal of whether the results are due to an experimental error.

It is possible that the small charges, initiated with a No. 8* electric detonator, did not propagate to full, high-velocity detonation, resulting in far lower than expected impulses. It should be possible to overcome this by increasing the charge sizes. Unfortunately, no successful tests were conducted with larger TNT charges than 20g, however Poladyn tests were successfully conducted with a range of charge sizes from 10g up to 70g. As these results showed a very linear progression, it seems unlikely that the results were due to incomplete or partial detonation.

When considering Fig. 6, the most striking factor is that the explosives with the large TNTe both have high velocities of detonation and are therefore highly brisant explosives compared with TNT and Poladyn which are both grouped together (Table 2).

Alternative Reference Explosive

Given the difficulty found in initiating small cast TNT charges it would be worth considering using an alternative reference explosive for future work.

Ideally any selected explosive should be capable of being reliably initiated with a standard detonator in small quantities, be readily available or readily made in a laboratory and should be capable of being formed into different shapes.

Such an explosive should be either a pure explosive material or a simple mixture which can be produced rather than a commercial or proprietary composition. Two obvious contenders are Composition B (RDX-TNT 60:40) and Pentolite (TNT-PETN 50:50). The former is a military composition that was used as a main fill for munitions but tends to need a booster. It has also largely been replaced by more modern compositions. Pentolite is widely used in commercial blasting boosters and is therefore readily available. It can be melted and cast as easily as TNT and in inexpensive. Most importantly, it can be readily made from the constituents in a laboratory making it suitable as a universal replacement for TNT, at least for smaller-scale testing.

There is a precedent for the use of Pentolite as the reference explosive. Goodman and Giglio-Tos conducted a series of trials as part of McIntyre’s work in 1978 in which they used Pentolite in place of TNT [16]. This attempt to switch clearly failed as subsequent work in the series reverted to TNT.

Two-Stage Theory

Backofen has proposed a two-stage detonation driven model which potentially explains the large difference in the impulse from low and high brisant explosives [40]. The model proposed separates the propulsion into two stages in which the initial motion is caused by a brisant shock-dominated process that requires intimate contact with the target to transfer the shock effectively. The second stage is a gas-dynamic process in which the gas products and blast from the charge pushes. This theory would certainly account for the observed phenomena.

It is proposed that when charges are in direct contact with a target (Z=0) the first brisant-stage plays a significant part in the propulsive effect of the charge that is lost as soon as the explosive is decoupled from the target.

Conclusions

Using the ballistic pendulum as a method of measuring the impulse from charges at Z=0 has been demonstrated to work well and this allows comparisons to be made between different explosives.

Small (10g) TNT charges are not easy to reliably detonate making it particularly inappropriate for use as the standard explosive. An alternative explosive should be considered as the benchmark.

The two-stage propulsion theory from Backofen in which the initial propulsion is provided by a brisant shock appears to fir the evidence well as highly brisant, RDX-based explosives gave a significantly higher Impulse (and TNTe) than a lower-brisant dynamite.

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