

Full Paper

Predicting the Impulse from the Curved Surface of Detonating Cylindrical Charges

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Abstract

TNT (Trinitrotoluene) equivalency depends on knowing the relative strength of different explosives compared to TNT. However, the current values for TNT equivalency mostly depend on work on spherical charges, whereas most military ammunition is cylindrical in shape. Cylindrical charges are known to give an enhanced blast close in when compared to that of spherical charges. A previous paper looked at predicting the peak pressure perpendicular to the curved side of a cylinder. This paper examines impulse data for the curved surface of cylindrical charges from the literature for Composition B and Pentolite and then describes experimental work carried out on cylindrical PE4 charges. Analysis of the free air experimental and literature data shows that it is possible to predict the impulse using a linear relationship, though it is not possible to decide on the best fit based on the current data. The fits for both $I = K_1 M^{0.5}/R$ and $I = K'_1 M^{2/3}/R$ give very similar correlation coefficients, where M is the charge mass and R the distance from the charge and K_1 and K'_1 are constants characteristic of the explosive. Values of K_1 and K'_1 have been fitted to literature and current experimental data for Composition B, Pentolite and PE4. Whichever of these two relationships is used, it should be possible to develop a method of determining TNT equivalency for the curved surface of cylindrical charges by using $\text{TNT equivalency} = K_1 \text{ explosive} / K_1 \text{ TNT}$, provided that data for TNT cylinders is obtained.

Keywords: Cylindrical Charges, Impulse, TNT Equivalency

1 Introduction

TNT equivalency has long been used to determine the relative strength of explosives, Knock and Davies [1], for example in safety cases. It does this by determining how all explosives behave in terms of TNT, by relating the property of an explosive to that of TNT. However, the data used is mainly based on spherical charges, or tests such as the ballistics mortar or Trauzl tests that have not been calibrated to free air bursts, Cooper [2]. Yet most military

charges are more cylindrical in shape and despite the fact that it has been known since at least 1948, Stoner and Bleakney [3] that detonating cylindrical charges results in different blast fields to spherical charges, little has been done to study the effect. Previous work by the authors studying the blast from the curved side of a cylinder [1] has shown that it is possible to predict the peak pressure from a cylindrical charge in this direction. However, when examining the effects of explosions in terms of explosive loading on buildings, the parameter of concern is the blast's impulse, Enstock et al. [4]. For this the TNT equivalency is given by $\text{TNT equivalency}_{\text{impulse}} = \text{Impulse}_{\text{HE}} / \text{Impulse}_{\text{TNT}}$.

A review of TNT equivalency and the peak pressure for cylindrical charges [1] showed that there has only been a limited amount of work on the peak pressure around cylindrical charges. There is even less for impulse, with some authors who studied peak pressure, Stoner and Bleakney [3], not considering impulse at all.

A variety of definitions are used in papers and reports on this subject area. For consistency in this report the following definitions will be used. The orientation to the cylinder is defined as 0° being at the end of the cylinder from which initiation takes place, 90° is perpendicular to the curved side of the cylinder and 180° is from the far end of the cylinder to the initiation point. The scaled distance, Z is defined by $Z = R/M^{1/3}$ where R is distance from the centre of the charge and M is the mass of the charge. Scaled impulse, I_s , is defined in terms of the impulse, I , by $I_s = I/M^{1/3}$.

Extensive tests have previously been reported on bare Pentolite charges by Plooster [5]. Cylindrical charges varying in length to diameter ratios, L/D ratios, of 1:4–6:1 and having a mass of 3.63 or 7.26 kg and spherical charges of 3.54 kg were used. Measurements of pressure were taken at 22.5° intervals around the cylinder, from 0°

to 180°, with the distance from the charges varying from 2.1 to 9.4 m. The raw data from the free air bursts is presented in the report. From the data Plooster [5, pp. 65, 78] concludes that for impulse from cylindrical charges (i) blast waves are 'far from spherical', (ii) the impulse close to the charge was 'largest in the direction of largest presented area', (iii) the impulse was 'higher at 0° than 180°' and (iv) the '... impulse at the closer gauges exceed the values of spherical charges only in the vicinity of the peak values. At the more distant gauges, on the other hand, they exceed the spherical charge values almost everywhere.'

Work by Wisotski and Snyer [6] on bare cylindrical charges of Composition B used nine geometries (L/D varying from 1:4 to 10:1) and masses of 0.72–3.70 kg in free air, as well as some firings of spherical charges for comparison. The raw data is presented in the report. Wisotski and Snyer found that there was 'no indication of the blast contours' approaching that of a sphere within the scope of pressures measured in this program'. High speed photographic records showed bridge waves and triple points off the corners of the cylinders. From their results, Wisotski and Snyer concluded that (i) for their measurement techniques the variability in the data for impulse was higher than for peak pressure and needed to be treated with caution, (ii) impulse values obtained from the sides of charges with small L/D ratios did not show the same relative decrease in peak pressure relative to the results obtained from charges with large L/D ratios and (iii) along the 90° line the impulse values for cylindrical charges are generally higher than for spherical charges for $L/D \geq 1:1$.

Work has been carried out on cylindrical charges of TNT by Swisdak [7], but only smoothed data is presented in his report, which prevents useful exploration of other possible correlations.

In conclusion of this paper of the available literature data on the impulse from cylindrical charges, what data there is agrees with the conclusion that the blast behaviour from cylindrical charges differs to that from spherical charges. Given that most military ammunition is based on a cylindrical shape, in order to be able to produce safety cases for the storage of munitions it is essential to understand the impulse from cylindrical charges. As a starting point of the required investigation, this paper will both review existing experimental data and report new data on the impulse from the curved side of a cylinder, i.e. along

the 90° line, where the waves are the simplest as there are no bridging or precursor waves. Only free air bursts, that avoid ground effects, are considered.

2 Analysis of Published Data for 90° Angle

Considering only the data at 90° to the cylinder, the authors reanalysed the published data for cylindrical charges for Composition B, from Wisotski and Snyer [6] and for Pentolite, from Plooster [5]. The aim was to show if a relationship could be determined between the impulse, I , the charge mass, M , and the distance from the centre of charge, R . Correlation coefficients were obtained for plots of impulse against $\text{mass}^n/\text{distance}^m$ where n and m are constants of value +0.333, +0.5, +1, +2 and +3. Key correlations are presented in Table 1.

Earlier work by the authors [1] showed a good correlation between measured pressure and the parameter M/R^3 . However Composition B data from Wisotski and Snyer [6] (averaged over a given mass and L/D ratio) shows no correlation between impulse and M/R^3 . For impulse, see Table 1, for $M^{0.5}/R$ a correlation coefficient of $r^2=0.86$ was obtained. For scaled impulse against scaled distance the correlation is not as good, $r^2=0.84$. However, for a linear fit going through the origin, plotting $I/M^{1/3}$ against $M^{1/3}/R$ is equivalent to plotting I against $M^{2/3}/R$, except that the coefficient will have different units. For I against $M^{2/3}/R$ the correlation coefficient is marginally lower ($r^2=0.858$ compares with 0.860 for $M^{0.5}/R$) but is also $r^2=0.86$ to two decimal places, which is statistically indistinguishable from the correlation for impulse against $M^{0.5}/R$.

The authors then looked selectively at the data for $L/D \geq 2:1$, as earlier work by the authors [1] showed a difference for the results for peak pressure between the data for $L/D \geq 2:1$ and data for $L/D < 2:1$. For impulse, if only the data for $L/D \geq 2:1$ is considered, then the best correlation was again for $M^{0.5}/R$ but the results were practically identical to those for $M^{2/3}/R$, both giving a correlation of $r^2=0.89$ to two significant figures. Comparing the plots of impulse against $M^{0.5}/R$ for all the data and for data for $L/D \geq 2:1$, Figures 1 and 2, respectively, unlike with peak pressure there is only a slight decrease in correlation when both discs and cylinders are studied together.

Plotting the data for spherical charges for Composition B from Wisotski and Snyer [6] on the same plot as the cylindrical data for $L/D \geq 2:1$ with the x axis set to $M^{0.5}/R$,

Table 1. Correlation coefficients for all Composition B data (from Wisotski and Snyer [6]) and for Pentolite data (from Plooster [5]).

Variable	Correlation Coefficient			
	Composition B (All Data)	Composition B ($L/D \geq 2:1$)	Pentolite (All Data)	Pentolite ($L/D \geq 2:1$)
M/R	0.67	0.78	0.79	0.84
M/R^3	None	None	0.03	0.38
$M^{1/2}/R$	0.86	0.89	0.82	0.89
$M^{1/3}/R$	0.78	0.86	0.81	0.88
$I/M^{1/3}$ vs. $M^{1/3}/R$	0.84	0.89	0.82	0.88
$M^{2/3}/R$	0.86	0.89	0.82	0.89

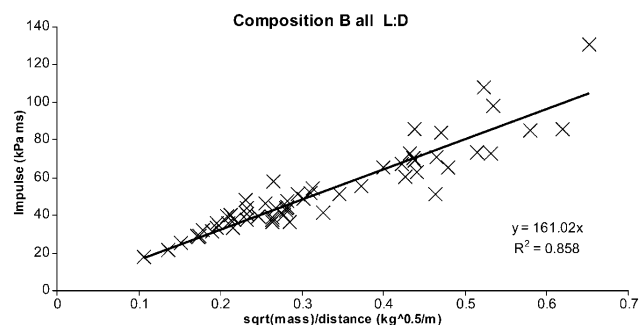


Figure 1. Impulse against $\text{mass}^{0.5}/\text{distance}$ for all Composition B data from Wisotski and Snyder [6].

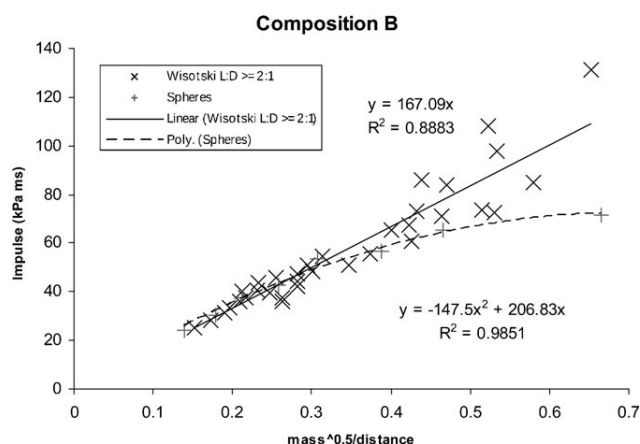


Figure 2. Impulse against $\text{mass}^{0.5}/\text{distance}$ for Composition B data from Wisotski and Snyder [6] for $L/D \geq 2:1$.

Figure 2, shows that the spherical data does not give a linear fit (a straight line fit gives a correlation coefficient of $r^2=0.65$). There is less scatter in the spherical data than the cylindrical data, but whilst the cylindrical data is taken from several experiments of different charge mass and L/D ratio, the spherical data is from a single configuration. Far from the charge the spherical data gives similar values to the cylindrical data, close in the impulse is far lower than that from the cylindrical charges. A similar result is seen if scaled impulse is plotted against $M^{1/3}/R$, Figure 3, with the spherical data again requiring a quadratic fit.

Using the data for Pentolite from Plooster [5] the best correlation for $L/D \geq 2:1$, is for $M^{0.5}/R$ ($r^2=0.89$, see Table 1 and Figure 4) or for $M^{2/3}/R$ ($r^2=0.89$). However, those for M/R ($r^2=0.84$), $M^{1/3}/R$ ($r^2=0.88$) and for scaled distance ($r^2=0.88$) are almost as good and based on one set of data only it is not possible to determine which is the most appropriate. All of these low correlations are due in part to the wide range of values closest to the charge, Figures 4 and 5. Looking in Figure 5 at the scaled impulse plotted against scaled distance, then as with Composition B, the correlation is slightly worse than that for impulse against $M^{0.5}/R$, but not enough to be significant. If all ratios of L/D are analysed for Pentolite then

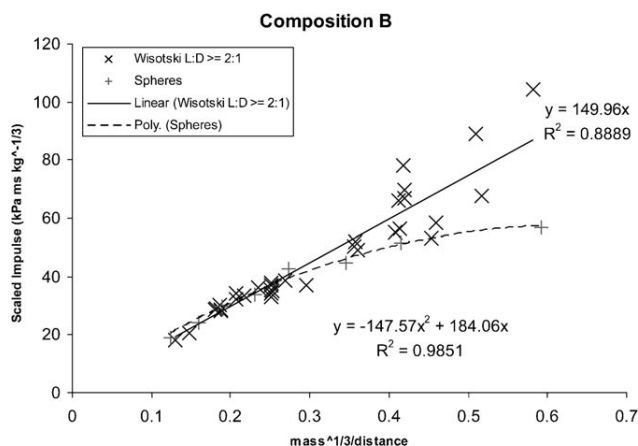


Figure 3. Scaled impulse against $\text{mass}^{1/3}/\text{distance}$ for all Composition B data from Wisotski and Snyder [6].

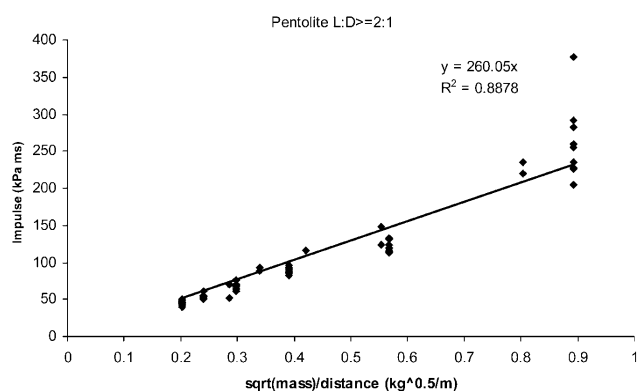


Figure 4. Impulse against $\text{mass}^{0.5}/\text{distance}$ for pentolite $L/D \geq 2:1$ data from Plooster [5].

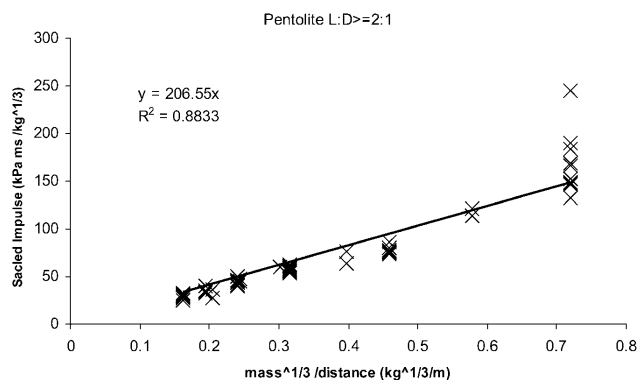


Figure 5. Scaled Impulse against $\text{mass}^{1/3}/\text{distance}$ for pentolite $L/D \geq 2:1$ data from Plooster [5].

the correlation is significantly worse with the best correlation being for $M^{0.5}/R$ with $r^2=0.82$, or for $M^{2/3}/R$ with $r^2=0.82$.

Based on the literature data of Wisotski and Snyder [5] and Plooster [6], it appears that there is a slight difference in the impulse between discs ($L/D < 2:1$) and cylin-

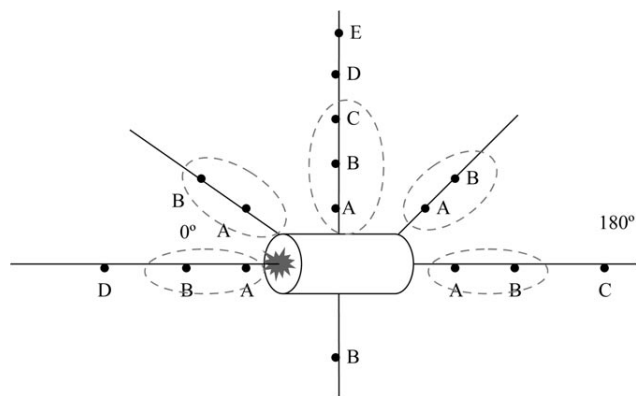


Figure 6. Gauge layout. Gauges in the same oval are mounted on the same boom. Gauge distances for the 1 and 0.4 kg trials are; A is at 1 m, B is at 2 m, C is at 3 m, D is at 5 m and E is at 8 m. For the 3 and 5 kg trials A is at 2 m, B is at 4 m, C is at 5 m, D is at 8 m and E is at 15 m.

ders ($L/D \geq 2:1$) for Pentolite but not for Composition B. The exact dependency of impulse, particularly on mass, is difficult to extract from the data, as fits to $M^{1/2}/R$ and $M^{2/3}/R$ give very similar correlations.

3 Experimental Part

To obtain further experimental results to help determine the dependency of impulse on distance and mass, experiments were carried out using PE4 [1]. The experiments consisted of firing hand pressed charges of PE4 (RDX/binder 88/12) of L/D 4:1 and 6:1 and weights 0.4, 1, 3 and 5 kg. Gauges were placed at 1–15 m from the charge at angles of 0°, 45°, 90°, 135°, 180°, see Figure 6.

4 Results

In this report only the results for impulse along the 90° line, that is perpendicular to the curved surface of the cylinder, are discussed. Results for pressure along the 90° line are discussed in Ref. [1] and those at other angles, where the pressure wave is more complex, will be discussed in later papers.

Looking in Figure 6 at all the 90° data, including firings of both 4:1 and 6:1 cylinders, the repeatability between experiments increases with scaled distance, see Figure 7. Far from the charge the repeatability is very good, close in there are large variations in impulse of up to 60%. This is the same problem as occurred with the results for peak pressure [1] and may be due to the hand packing of the charges. The exceptions are two firings (points marked on graph) where a second peak occurs before the peak pressure decreases to zero making it difficult to determine the impulse.

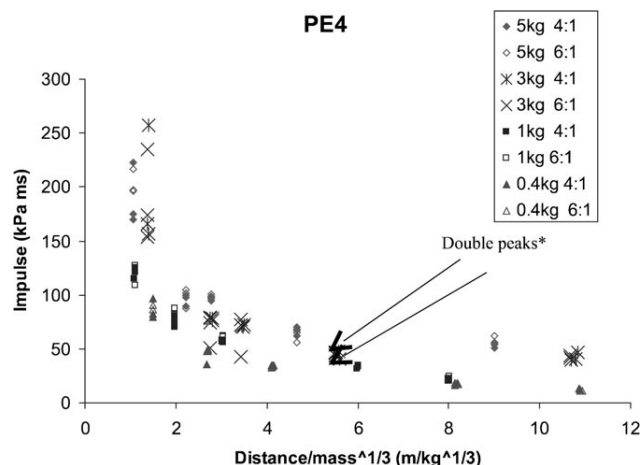


Figure 7. Impulse against scaled distance for all charges for PE4. *The points marked have a second peak before the pressure returns to zero, making it difficult to determine the impulse.

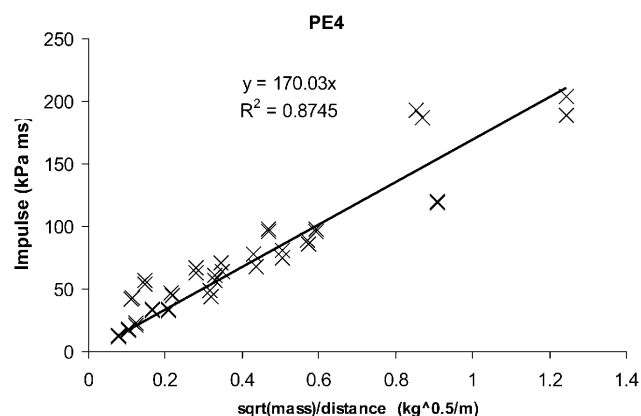


Figure 8. Impulse against $M^{0.5}/R$ for PE4.

In general the results appear to fit a single curve, see Figure 7, of the form $y = ax^{-b}$. Comparing 4:1 and 6:1 L/D ratios the results cannot be separated.

The average impulse data for PE4 were plotted against M^n/R^m , where n and m are constants of value 0.333, 0.5, 1, 2 and 3. The best correlations found as shown in Table 2 were for $M^{0.5}/R$ with a correlation coefficient of $r^2 = 0.87$ as shown in Figure 8 and for $M^{2/3}/R$ with again $r^2 = 0.87$ as shown in Figure 9. This is the same result as for Composition B and Pentolite. However, unlike with Composition B and Pentolite the correlation for $M^{1/3}/R$ was significantly lower ($r^2 = 0.74$).

5 Conclusion

The analysis in this paper shows that it is possible to predict the impulse perpendicular to the curved side of a cylinder charge using a linear fit to a simple function of charge mass and stand-off distance. However, it is diffi-

Table 2. Correlation coefficients for the authors' PE4 impulse data.

Variable	M/R	M/R^2	M/R^3	$M/R^{0.5}$	$M^{1/2}/R$	$M^{1/3}/R$	M^2/R	$I/M^{1/3}$ vs. $M^{1/3}/R$	$M^{2/3}/R$
Correlation Coefficient	0.65	0.30	None	0.52	0.87	0.74	None	0.87	0.87

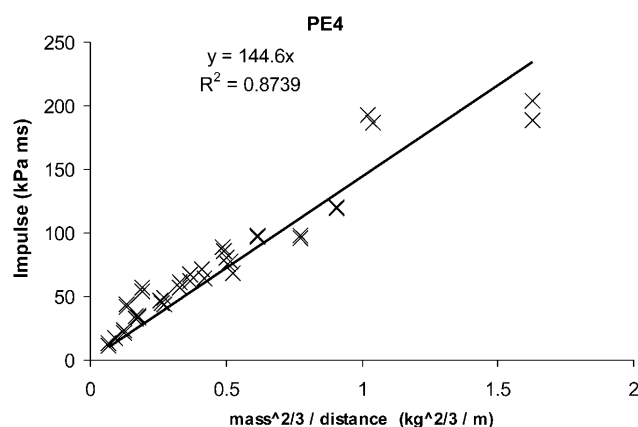


Figure 9. Impulse against $M^{2/3}/R$ for PE4.

cult to determine from the data available which function gives the best fit. For the case when the length is at least twice the diameter ($L/D \geq 2:1$) then the overall best fit appears to be for either $I = K_1 M^{0.5}/R$ or $I = K'_1 M^{2/3}/R$, where for Composition B $K_1 = 167 \text{ MPa m s kg}^{-0.5}$, for Pentolite $K_1 = 260 \text{ MPa m s kg}^{-0.5}$ and for PE4 $K_1 = 170 \text{ MPa m s kg}^{-0.5}$ and for Composition B $K'_1 = 149 \text{ MPa m s kg}^{-2/3}$, for Pentolite $K'_1 = 206 \text{ MPa m s kg}^{-2/3}$ and for PE4 $K'_1 = 145 \text{ MPa m s kg}^{-2/3}$.

For peak pressure the authors [1] found that there is a marked difference in the results between discs and cylinders, $L/D < 2$ and $L/D > 2$, respectively, however this difference is not seen for impulse.

If all L/D data for Composition B from Wisotski and Snyder [6] and Pentolite from Plooster [5] is used then an equation of the form $I = K'_1 M^{2/3}/R$ gives marginally better results than the equation $I = K_1 M^{0.5}/R$, but the differences are not statistically significant. Values for the coefficient K'_1 are $145 \text{ MPa m s kg}^{-2/3}$ for Composition B and $182 \text{ MPa m s kg}^{-2/3}$ for Pentolite and for the coefficient K_1 are $161 \text{ MPa m s kg}^{-0.5}$ for Composition B and $230 \text{ MPa m s kg}^{-0.5}$ for Pentolite.

By obtaining values for K using whichever relationship provides the best fit, it should be possible to develop a

method of determining the TNT equivalency for cylindrical charges by using $\text{TNT equivalency} = K_{I \text{ explosive}}/K_{I \text{ TNT}}$ provided that that values for K_I for TNT cylinders can be obtained. The only published data the authors could find for TNT cylinders was a single firing by Swisdak [7], however the presented data are the results of curve fitting.

The analysis in this paper only covers the impulse from a curved side of a cylindrical charge, further work will be needed to predict the impulse from the ends and corners of a cylindrical charge, where the blast wave is more complex, including double peaks and reflected waves as outlined in Wisotski and Snyder [6].

Acknowledgments

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