

Full Paper

Predicting the Peak Pressure from the Curved Surface of Detonating Cylindrical Charges

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Abstract

Trinitrotoluene (TNT) equivalency depends on knowing the relative strength of different explosives compared to TNT. However, most past work has been carried out only using spherical charges, whereas most military ammunition is cylindrical in shape. It is known that in certain directions, cylindrical charges give an enhanced blast close in when compared to that of spherical charges. This paper examines data for cylindrical explosive 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 close into the curved side of a cylindrical charge it is possible to predict the peak pressure using an equation of the form $\text{Peak pressure} = K \times \text{mass}/\text{distance}^3$, where K is an explosive dependent constant; 2695 Pa m³ kg⁻¹ for Composition B, 2498 Pa m³ kg⁻¹ for pentolite and 2565 Pa m³ kg⁻¹ for PE4, for length to diameter ratios of between 2:1 and 10:1. For a scaled distance (distance/mass^{1/3}) of less than 3.5 m kg^{-1/3}, the results are very accurate. This means that, provided data for cylindrical charges of TNT is obtained, a simple method of determining the TNT equivalency of a cylindrical charge, perpendicular to the curved surface is given by TNT equivalence = $K_{\text{explosive}}/K_{\text{TNT}}$. For a more accurate prediction at a scaled distance of greater than 3.5 m kg^{-1/3} a cubic equation of the form $\text{Peak pressure} = K_1 Z^{-3} + K_2 Z^{-2} + K_3 Z^{-1}$ has been found to apply where $Z = \text{distance}/\text{mass}^{1/3}$ and the coefficients K_1 , K_2 and K_3 depend on the explosive type.

Keywords: Cylindrical Charges, Peak Pressure

1 Introduction

TNT equivalency has long been used to determine the relative strength of explosives, by relating a particular property of an explosive to that of TNT. Various properties are used: peak pressure [1] for explosive effects on windows [2] and for demolition charges [3]; positive impulse [1], for explosive loading on buildings [2] and for bombs and shells [3]; strength [4]; energy of explosion [5];

energy density [6]; specific energy [7]; density [5]; detonation velocity [5]; ballistic mortar, plate dent sand crush and Trauzl tests [5].

In each case the TNT equivalency of an explosive is given by relating the given property of the explosive to that of TNT. So for example for peak pressure, TNT equivalency is given by $\text{TNTequivalency}_{\text{Peak pressure}} = \text{Peak pressure explosive}/\text{Peak pressure TNT}$, measured under the same conditions. It cannot be assumed that TNT equivalency is a constant, since TNT equivalency actually varies with distance [8,9]. Also little work has been published which compares the results from the different tests used to determine TNT equivalency 'and in many cases where data are available the comparisons are not always consistent' [10]. This lack of consistency is due to variables such as differences in experimental set up and experimental error.

Moreover most development work for TNT equivalency has been carried out for spherical charges, yet most military charges are more nearly cylindrical. Despite the fact that it has long been known that the blast from a cylindrical charge is different to that from spherical charges, little has been done to examine these differences.

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 such that 0° is 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 the distance from the centre of the charge and M is the mass.

The effect of shape on the measured overpressure was noted as early as 1948 when Stoner and Bleakney [11] measured the excess peak pressure (Π , measured in atmospheres) from spherical, cylindrical and rectangular

charges of pentolite. The peak overpressure was found to be

$$\Pi = \frac{a}{Z_n} + \frac{b}{Z_n^2} + \frac{c}{Z_n^3} \quad (1)$$

where Z_n is the non-dimensional variable $Z_n = R/(\rho\tau)^{1/3}$ where τ is the volume of the charge and ρ is the specific gravity. For $\frac{1}{2}$ lb (0.22 kg) rectangular blocks of TNT, $a = 13.5$, $b = -769.9$ and $c = 36280$; for 8 lb (3.63 kg) blocks of pentolite, $a = 10.49$, $b = -135.5$ and $c = 21070$; for 4 lb (1.81 kg) cylinders of TNT, $a = 11.34$, $b = -185.9$ and $c = 19210$ and for 3.75 lb (1.70 kg) spheres of pentolite, $a = 8.63$, $b = -295.1$ and $c = 7823$. The equations are valid between $18 < Z_n < 110$, with the dependence on charge shape affecting the excess pressure for values of at least $Z_n = 50$.

Also in 1948, working with underwater charges Cole pointed out 'that differences in shock wave pressure-time curves around cylindrical depth charges observed at distances of 20 ft (6.10 m) (roughly 15 times the linear dimensions of the charge) are found at distances of 100–500 ft (30.5–152.4 m)' [12, p. 248]. Rice and Ginell [quoted in 13] suggest that a suitable comparison with spherical charges can be made by using a spherical charge of the same weight giving $r_{sph} = (3L_{cyl}/4r_{cyl})^{1/3} r_{cyl}$ where L_{cyl} and r_{cyl} are the length and radius of the charge. They found that the transition from a cylindrical to a spherical case occurred at a standoff distance of approximately half the charge length and that the peak pressure was given by $P(t) \propto (r_{sph}/R)^{0.6}$ for $R < L/2$ and $P(t) \propto (r_{sph}/R)^{1.15}$ for $R > L/2$.

These differences from spherical charges can be significant. 'For non-spherical charges, there are time and directional/orientational effects that can yield multiples to be greater than 2.0', Victor [14]. Unfortunately the paper then continues with the comment 'we shall not dwell on these' though it does quote the JMEM peak pressure for cylinders [15] measured normal to the charge axis namely

$$\frac{P_{cylinder}}{P_{sphere}} = 5.53 \frac{(L/D)^{0.308}}{Z'^{0.998}} + \frac{Z' - L/D}{24.99} \quad (2)$$

where L and D are the cylinder's length and diameter, respectively, and Z' is given in Victor [14] as $Z' = R/(EWF \times W)^{1/3}$ where W is the weight of TNT and EWF is the 'equivalent weight factor' that is the 'ratio of the weight of TNT that will give the same curves to the weight of the explosive of interest'.

In 1978 Phillips [16] looked at data from end initiated cylindrical line charges and warheads and concluded that higher pressures to the sides were obtained than those from a centrally initiated sphere. Ismail and Murray [17] found for 200 and 400 g charges that the far field, where Hopkinson, or 'cubic root' scaling applies, began at 4 m, closer than that the scaling failed.

Plooster [18] carried out extensive tests on bare pentolite charges varying in $L:D$ ratios of 1:4–6:1, of mass 8

and 16 lb (3.63 and 7.26 kg) and spherical charges of 7.8 lb (3.54 kg), measured at 22.5° intervals around the cylinder. The raw data from the free air bursts is presented in his report, from which Plooster concludes that (i) 'The blast waves from cylindrical charges are obviously far from spherical' [18, p. 78], (ii) 'Determination of peak pressures from cylindrical charges is more difficult than from spherical charges, because the pressure-time traces are often more complex' [18, p. 16], (iii) 'Cylindrical charges often generate secondary shock waves which are comparable or even greater in amplitude than the leading shock' [18, p. 17], (iv) 'In all cases the peak charge and impulse close to the charge are largest in the direction of largest presented area' [18, p. 65], (v) 'Pressure is higher at 0° than 180°' [18, p. 65] where in Plooster's experiments 'All charges were initiated at the 180° end of the charge, so that the detonation propagated towards the 0° end', [18, p. 216] and (vi) 'As a general rule, the pressures and impulses at the closer charges exceeded the values for the spherical charges only in the vicinity of the peak values. At more distant gauges they exceed the spherical charge values almost everywhere' [18, p. 78].

Wisotski and Snyder [19] fired bare cylindrical charges of Composition B of nine geometries ($L:D$ varying from 1:4 to 10:1) and mass 1.59–8.16 lb (0.72–3.70 kg) in free air, as well as some spherical charges for comparison. The raw data are presented in their report. They found that there was 'no indication of the blast contours approaching that of a sphere within the scope of pressures measured in this program' [19]. High speed photographic records showed bridge waves and triple points off the corners of the cylinders. From their results they concluded that along the 90° line for peak pressure (i) Cube root scaling applies along the 90° line for 1:1, 2:1 and 3:1 end detonated cylindrical charge [19, p. 14], (ii) peak pressures become higher at a given scale distance as $L:D$ increases up to 6:1 and then drops away [19, p. 14] and (iii) peak pressures from cylindrical charges of $L:D \geq 1:1$ are generally greater than those for spherical charges [19, p. 3].

Working with the data from Wisotski and Snyder, Plooster [20] developed two complicated equations for charges where $L:D$ was greater or less than 1 to predict the peak over pressure at any angle around the charge. Plooster's equation produces a good prediction of the blast, however the equation is explosive dependent and inconvenient to apply as a method of determining TNT equivalency for explosives.

Swisdak [9] presented only smoothed data for cylindrical charges of TNT, which prevents useful exploration of other possible correlations. Based on his data he comments that 'Present data indicate that over the range of scaled distances presented herein, that Hopkinson or cube-root scaling applies to the cylindrical data. Very close to cylindrical charges cube-root scaling is known not to apply, with a transition region of some sort spanning the gap between the two regions'.

Swisdak's cylindrical data ranges in scaled distance from 4 to 22.5 ft/lb^{1/3} (2.7–15 m kg^{-1/3}). For a 1 kg charge

this implies that the cube root scaling applies down to distances of 2.7 m or less, but for a 5 kg charge only to 4.6 m. Given that many storage areas for munitions, such as on board ship, may be of this size or smaller, it is important to understand the blast close in to cylindrical charges in order to accurately predict the risks from accidental explosions.

More recently in 1999, Held [21] studying the momentum transfer and impulse from blast waves from cylindrical charges of Composition B3, noted that 'The transferred radial momentum is very strongly deviating from a spherical detonation wave at near distances'. He also found that 'in the radial direction ... much more momentum is transferred compared to diagonal directions, in which bridge waves are built'.

As the maximum pressure for cylinders ($L:D \geq 1$) as opposed to discs ($L:D < 1$) is in the 90° direction, i.e. perpendicular to the curved surface as shown in Swisdak [9] and the waves in this direction are the simplest, as there are no bridging or precursor waves, this paper will concentrate on the 90° direction. Only free air bursts, to avoid ground effects, are considered.

2 Analysis of Published Data for 90° Angle

An analysis was carried out of the overpressure data of Wisotski and Snyer [19] considering only the data along the 90° line. Plotting the peak pressure against the scaled distance for all $L:D$, Figure 1, shows a general decrease in pressure with scaled distance, but a spread of data around the curve. The data for cylinders ($L:D \geq 2:1$) lie on a single curve, different from that obtained for discs. The following analysis considers only cylindrical charges where $L:D \geq 2:1$.

Comparing the cylindrical data with spherical data, it can be seen that the peak pressure from the spheres is significantly less than that from the cylinders for $R/M^{1/3} \leq 5.0 \text{ m kg}^{-1/3}$, that is 5 m for a 1 kg charge or 8.55 m for a 5 kg charge. At greater distances the two shapes give sim-

ilar peak pressures. If the disc charges are also included then the spheres produce results that lie between those of the disc and long cylindrical charges.

To determine if the peak pressure decreased cubically, the overpressure was plotted against M^n/R^n where n and m were set to 0.33, 1, 2, 3 and 4. The best fit of a straight line forced to go through zero (as far from the charge there should be no overpressure) was for M/R^3 with a correlation coefficient of $r^2 = 0.99$, as shown in Figure 2. The equation

$$P = 2695 \frac{M}{R^3}, \quad r^2 = 0.99 \quad (3)$$

is an equation of the form

$$P = K \frac{M}{R^3} \equiv K \frac{1}{Z^3} \quad (4)$$

where K is a constant that will be explosive dependant. If the same holds true for other explosives it would give a simple method of calculating the peak pressures for each explosive and determining TNT equivalence using $TNT_{\text{explosive}} = K_{\text{explosive}}/K_{\text{TNT}}$.

This equation accurately predicts the peak pressure for Composition B close to the charge at a scaled distance, Z , of less than $3 \text{ m kg}^{-1/3}$, but is not satisfactory at greater distances, Figure 3.

It has long been suggested that at sufficient distance from a non-spherical charge, the blast 'heals' to that of a spherical charge, where the peak pressure varies as $R/M^{1/3}$. Plotting peak pressure against $M/R^{1/3}$ for Composition B gives a curve for which the best fit, assuming that a long way from the charge the overpressure is zero, is an equation, of a form similar to that used by Stoner and Bleakney [11], given by

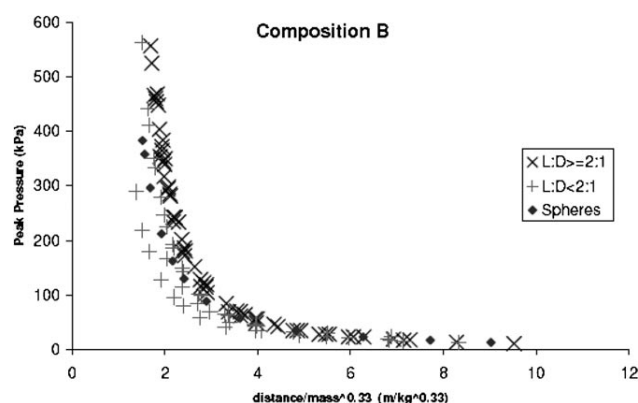


Figure 1. Peak overpressure at 90° to charge axis against scaled distance for Composition B. Data from Wisotski and Snyer [19].

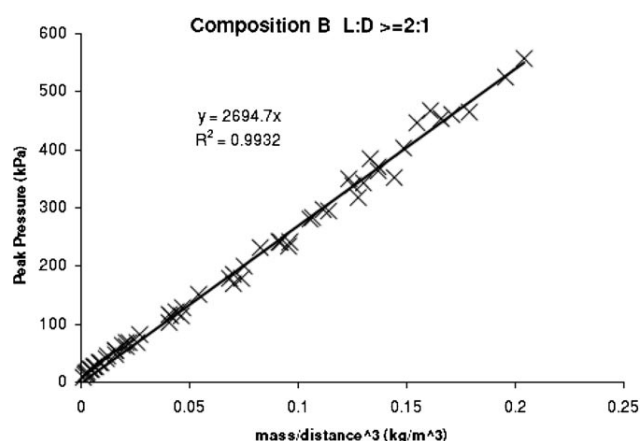


Figure 2. Peak pressure at 90° to charge axis against mass/distance³ for cylindrical charges of Composition B for $L:D \geq 2:1$. Data from Wisotski and Snyer [19].

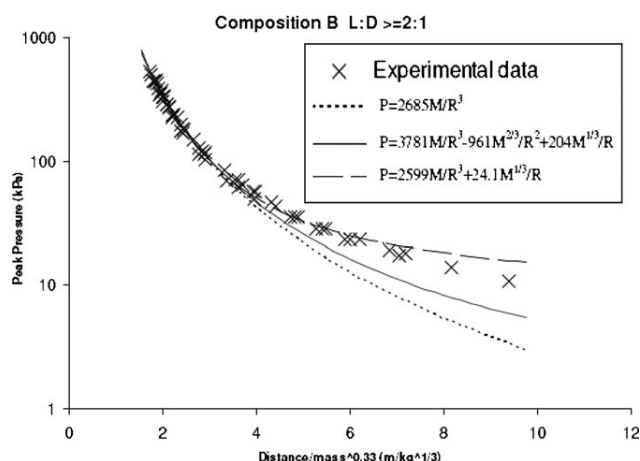


Figure 3. Prediction of overpressure at 90° to charge axis against scale distance for cylindrical Composition B charges, compared to experimental data from Wisotski and Snyer [19]. Vertical axis altered to a log scale to show differences at low peak pressures.

$$P = 3781 \frac{M}{R^3} - 961 \frac{M^{2/3}}{R^2} + 204 \frac{M^{1/3}}{R} \quad (5)$$

$$\equiv 3781 \frac{1}{Z^3} - 961 \frac{1}{Z^2} + 204 \frac{1}{Z}, \quad r^2 = 0.99$$

The first term is of the same form as Eq. (4) and the final term relates to that used to predict the peak pressure for spherical charges. The middle term must therefore represent in some manner the transition between the near and far field.

As the meaning of the middle term was unclear a second curve was fitted to the data, in which the middle term was set to zero; this gave

$$P = 2599 \frac{M}{R^3} + 24.1 \frac{M^{1/3}}{R} \equiv 2599 \frac{1}{Z^3} + 24.1 \frac{1}{Z}, \quad r^2 = 0.99 \quad (6)$$

Now the coefficient of the first term is of a similar magnitude to the term in Eq. (3), representing the near field pressure and the second term represents the far field pressure where the blast field ‘heals’ to that of a sphere. All three equations have similar coefficients of correlation and so it may not be worth the extra computation required by Eqs. (5) and (6).

These equations give good predictions of the peak pressures, close to the charge, as shown in Figure 3, but at a sufficient distance the best prediction is given by Eq. (5), with Eq. (6) giving a better fit than the simplest equation, Eq. (3). Looking at only the results close to the charge, it can be seen that all the predictive equations closely match the experimental data up to a scaled distance of +3.4 m kg^{-1/3}, but at scaled distances greater than +3.5 m kg^{-1/3} begin to diverge from the experimental results. The cubic equation overpredicts the pressure and the other

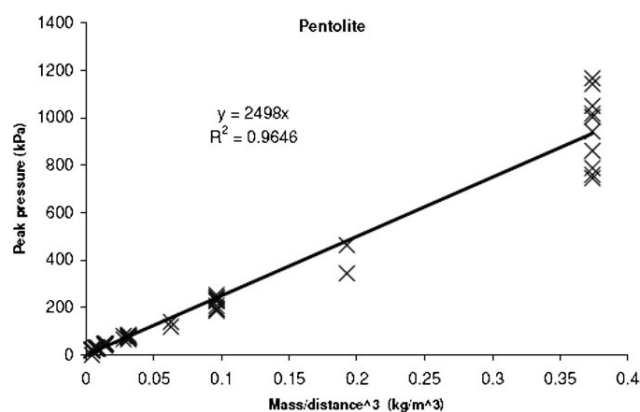


Figure 4. Prediction of over pressure at 90° to charge axis against mass/distance³ for cylindrical charges of pentolite. Data from Plooster [18].

equations underpredict it. This means that at a scaled distance of less than +3.5 m kg^{-1/3} a simple equation of the form of Eq. (4) can be used, but further out a more complex equation is needed.

Calculating the equivalent spherical radius for a spherical charge of the same mass using the equation given by Rice and Ginell [quoted in 13] and then plotting the peak pressure against r_{sph}^n / R^m where n and m were set to +0.33, +1, +2, +3 and +4 gives the best fit for when peak overpressure is plotted against r_{sph} / R^2 with $r^2 = +0.90$, a lower correlation than those obtained earlier.

The fitting of curves to plots of peak overpressure against M^m / r_{cyl}^n where r_{cyl} is the radius of the cylinder, did not provide correlations as good as those already given, the best being $P = 55506 R_{\text{cyl}} / R^2$ with $r^2 = +0.76$.

Plotting the peak pressure at 90° from Plooster's data [17] for pentolite charges ($L:D$ ratios 1:4–6:1, mass 8 and 16 lb, 3.63 and 7.26 kg), against M/R^n gives the best fit for $n = +3$, Figure 4.

This is an equation of the same form as for Composition B, Eq. (4), with for pentolite,

$$P = 2498 \frac{M}{R^3}, \quad r^2 = +0.96 \quad (7)$$

Applying an equation of the form of Eq. (5), for peak pressure against $M/R^{1/3}$ gives

$$P = 3933 \frac{1}{Z^3} - 1410 \frac{1}{Z^2} + 285 \frac{1}{Z}, \quad r^2 = 0.97 \quad (8)$$

which is only a slightly better fit. For an equation without the second term of Eq. (8), the fit is

$$P = 2534 \frac{1}{Z^3} - 16 \frac{1}{Z}, \quad r^2 = 0.97 \quad (9)$$

As with Wisotski and Snyer's data for Composition B the first term of this equation has a coefficient of a similar order of magnitude to that for Eq. (7). Now however

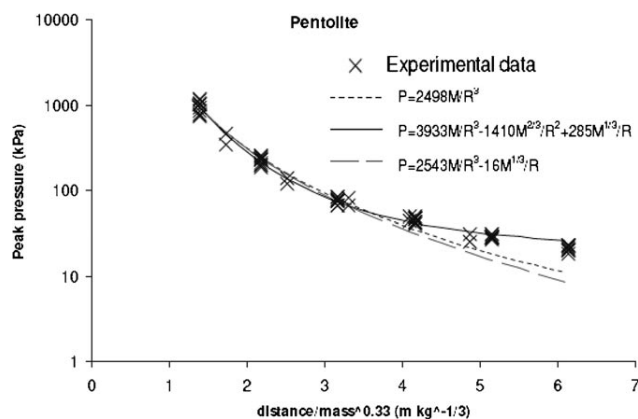


Figure 5. Prediction of over pressure at 90° to charge axis mass/distance³ for cylindrical charges of pentolite. Experimental data from Plooster [18]. Note vertical scale is a log scale.

the term in $M^{1/3}/R$ has a negative sign, which is physically difficult to understand. Also the equation has a correlation coefficient almost indistinguishable from Eq. (7).

Plotting the predicted curves against the experimental data for pentolite, Figure 5, shows that all three equations give an accurate prediction of the peak overpressure for a scaled distance of $3.3 \text{ m kg}^{-1/3}$ or less and so only the simplest equation, Eq. (7), is needed to predict the results, but above $3.0 \text{ m kg}^{-1/3}$, Eq. (8) is most accurate.

3 Experimental Work

To determine if these curve fits were applicable to another explosive, a series of PE4 (RDX/binder 88/12) charges of $L:D$ ratio 4:1 and 6:1 and mass 0.4, 1.0, 3.0 and 5.0 kg were fired by the authors. The charges were made by hand compaction into cylindrical moulds lined with cardboard from which the very lightly cased charges could be removed without distortion. Ease of handling restricted the $L:D$ of such charges to about 2:1, so longer charges were produced by butting two or more charges firmly together, supporting the join by wrapping it with an extra layer of cardboard and running a slim wooden batten along the length for suspension from the firing post.

The charges were end initiated using commercial 8 star detonators that contain approximately 1 g of PETN.

The experiments were carried out at Cranfield University's Ordnance Testing and Evaluation Centre. Each charge was suspended horizontally from a gantry 3 m above a level concrete pad, Figure 6 and the blast wave was measured side-on using Kistler pressure gauges level with the charge at 0, 45, 90, 135 and 180° to the charge, Figure 7. In the 90° direction gauges were placed at 1, 2, 3, 5 and 8 m from the charge for the 0.4 and 1 kg charges and at 2, 4, 5, 8 and 15 m for the 3 and 5 kg charges, Figure 7. The temperature, wind strength and humidity were recorded at the time of each firing.

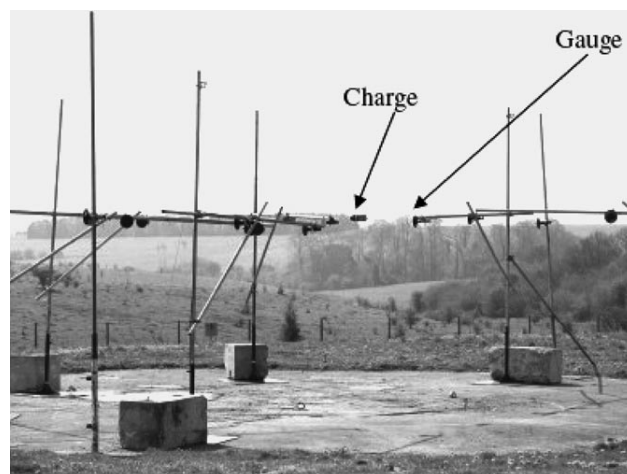


Figure 6. Experimental setup for air burst of cylindrical charge of PE4.

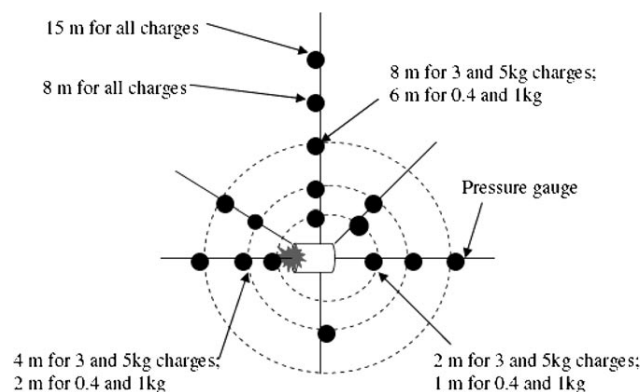


Figure 7. Gauge position for air burst of cylindrical charge of PE4. Gauges on a given circle are the same distance from the centre of the charge.

4 Experimental Results

In this paper only the results along the 90° line (perpendicular to the curved surface of the cylinder) are discussed.

Most firings gave a typical pressure–time trace. Close to the charge the results from repeated firings varied considerably, by as much as 50 % in some cases, as shown in Figure 8, whereas at greater distance the measurements were very consistent. There are several possible reasons for this. It is possible that variations in the consistency of the charges result in local changes in blast, that 'heal' as the blast wave moves further out. Alternatively, there may be errors in the measurement of the blast as it is possible that the booms on which the gauges were placed moved as the blast came through.

Figure 8 shows no significant difference between the pressure readings for 6:1 and 4:1 charges.

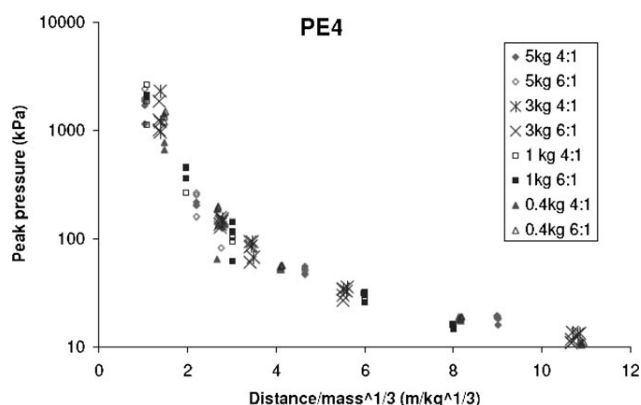


Figure 8. Prediction of overpressure at 90° to charge axis against scale distance for cylindrical PE4 charges. Note the vertical scale is a log scale.

Plotting the average pressure readings for each type of charge, the best fit occurs for peak pressure plotted against M/R^3 . The correlation, $r^2 = 0.95$, is not as good as that for Composition B, perhaps reflecting the variability of the experimental data. From Figure 9 the value of the coefficient is

$$P = 2565 \frac{M}{R^3}, \quad r^2 = 0.9187 \quad (10)$$

Applying an equation of the form of Eq. (5) for peak pressure against $M/R^{1/3}$, as shown in Figure 10, gives a fit of

$$P = -1981 \frac{1}{Z^3} + 5218 \frac{1}{Z^2} - 1065 \frac{1}{Z}, \quad r^2 = 0.9557. \quad (11)$$

Physically this equation is not realistic as it becomes negative for large distances as shown in Figure 11. Refitting the above equation, without the second term, as in Eq. (6), gives

$$P = 2127 \frac{1}{Z^3} + 305 \frac{1}{Z}, \quad r^2 = 0.9324 \quad (12)$$

Using these three equations to predict the actual peak overpressure, Figure 11, Eq. (12) gives the best fit far from the charge, $Z > 4 \text{ m kg}^{-1/3}$ and close in, $Z < 3 \text{ m kg}^{-1/3}$, the best fit is given by Eq. (10).

5 Conclusion

An analysis of published data for cylindrical charges of Composition B and pentolite has been carried out for peak pressure perpendicular to the curved side of a cylindrical charge. To this has been added new experimental data obtained by the authors for PE4 cylindrical charges. A comparison of literature data for spherical and cylindrical charges of Composition B confirmed the difference

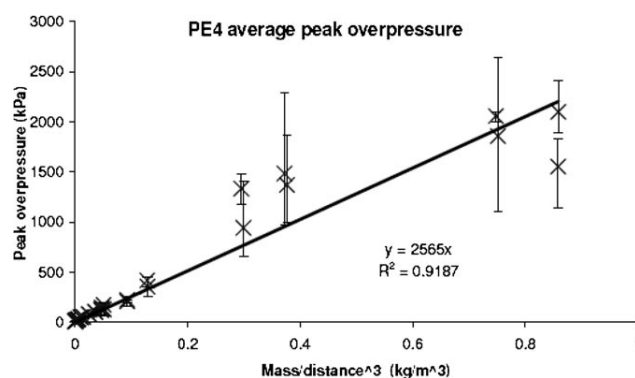


Figure 9. Prediction of average peak overpressure at 90° to charge axis mass/distance³ for cylindrical charges of PE4.

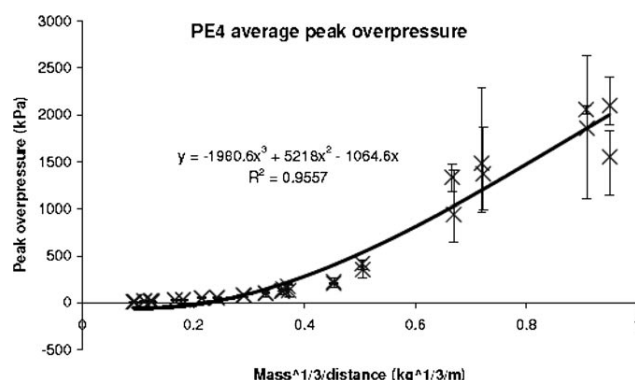


Figure 10. Prediction of average peak overpressure at 90° to charge axis $M^{1/3}/R$ for cylindrical charges of PE4.

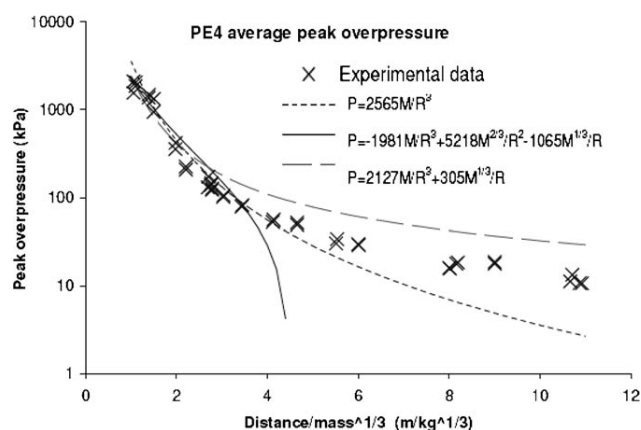


Figure 11. Predictive equations for PE4 peak overpressure at 90° to charge axis, compared to authors' mean data plots. Note log scale on vertical scale. (Note: above distance/mass^{1/3} = 4, the cubic equation gives negative values).

between the blast and peak pressure produced by the different shaped charges.

Close in ($Z \leq +3.5 \text{ m kg}^{-1/3}$, that is 6 m for a 5 kg charge) to a cylindrical charge of 10:1 $\geq L:D \geq 2:1$ the

peak overpressure perpendicular to the curved surface may be predicted by the equation $P = K M/R^3$. For Composition B, $K = 2695 \text{ Pa m}^3 \text{ kg}^{-1}$, for pentolite, $K = 2498 \text{ Pa m}^3 \text{ kg}^{-1}$ and for PE4, $K = 2565 \text{ Pa m}^3 \text{ kg}^{-1}$. This means that, given data for cylindrical charges of TNT, a simple method of determining the TNT equivalency of cylindrical charges in this direction (the direction with the greatest blast) is $\text{TNTequivalence} = K_{\text{explosive}}/K_{\text{TNT}}$. However, close into the charge the data for PE4 are highly variable and further tests are needed to validate the results.

For a more accurate prediction at a scaled distance of greater than +3.5 an equation of the form $P = +K_1 Z^{-3} + K_2 Z^{-2} + K_3 Z^{-1}$ gives a better fit to the data, where the coefficients K_1 , K_2 and K_3 depend on the explosive type. The first term gives the peak pressure close in and the third term is of the same form as that for a spherical charge representing the blast wave once it has travelled far enough to 'heal' to a spherical wave. The middle term (which is negative for Composition B and pentolite) may represent the transition between the two phases. Further work will need to be carried out to develop our equation for PE4 as it gives negative peak pressures at larger distances from the charge.

Acknowledgments

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