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Title: Shock Waves from Hollow Cylinders

Hollow cylindrical charges of PE4 were detonated. The charges had masses of 0.16 to 0.49 kg and a length to diameter ratio of 1/1 to 1/6. The circular hollows were of diameter 0, 0.01, 0.02 and 0.04 m. The charges were detonated from one end. The results showed that provided the correct ratio of charge mass, charge length to diameter ratio and distance are maintained the peak overpressure and impulse remain constant. This means that it is not necessary to know the size of the hole to predict the peak overpressure and impulse in the radial direction. For PE4 the peak pressure, P, is given by $P = -251\,(M(L/D)^{1/3}R^{-3})^2 + 1677\,M(L/D)^{1/3}R^{-3}$ and the impulse, I, by $I = 150\,M^{2/3}\,R^{-1}$. M is the charge mass, L the charge length, D the charge diameter and R the distance from the charge.

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INTRODUCTION

Non spherical explosive charges, such as slabs and cylinders, can produce multiple shock waves [1-3]. Depending on the geometry, in some directions these shock waves can be double the strength of those from spherical charges [4]. To better understand the blast produced by non-spherical explosive charge, research has been carried out to study the shock waves from solid cylindrical charges [1-3,5-9]. The effect of a hollow charge on the blast wave in the axial direction has been studied since the 1880's due to the Munroe effect and the use of shape charges [1]. The work in this paper extends the work on hollow charges to the radial direction, to study the effect of hollow charges on the blast waves outside the charge.

Blast waves from solid cylindrical charges have been studied and equations developed to predict the peak pressure and impulse in the radial [7-9] and axial direction [3].

In the radial direction, for solid cylinders of length, L, to diameter, D, the peak overpressure, P, can be predicted at all distances by the equation, [9]

$$P=\frac{A}{Z`}+\frac{B}{Z`^{2}}+\frac{C}{Z`^{3}} \tag{1}$$

where A, B and C are explosive dependent constants and $Z` = R/(M^{1/3}(L/D)^{1/9})$. R is the distance form the charge and M the mass of the charge.

Close into the charge, when $M(L/D)^{1/3}/R^3 > 0.08$ kg m^{-3}, a simpler equation can be used [9]

$$P=K`\frac{M\left(L/D\right)^{1/3}}{R^{3}}=K`\frac{1}{Z`^{3}} \tag{2}$$

where K` is an explosive dependent constant. For PE4, K` = 1525 m^3 kPa kg^{-1} [9].

The impulse from a solid cylindrical charge has been found to be independent of the length to diameter ratio in the radial direction [9]. The impulse is given by either

$$I=K`_{I}\frac{M^{2/3}}{R} \tag{3}$$

or

$$I=K_{I}\frac{M^{0.5}}{R} \tag{4}$$

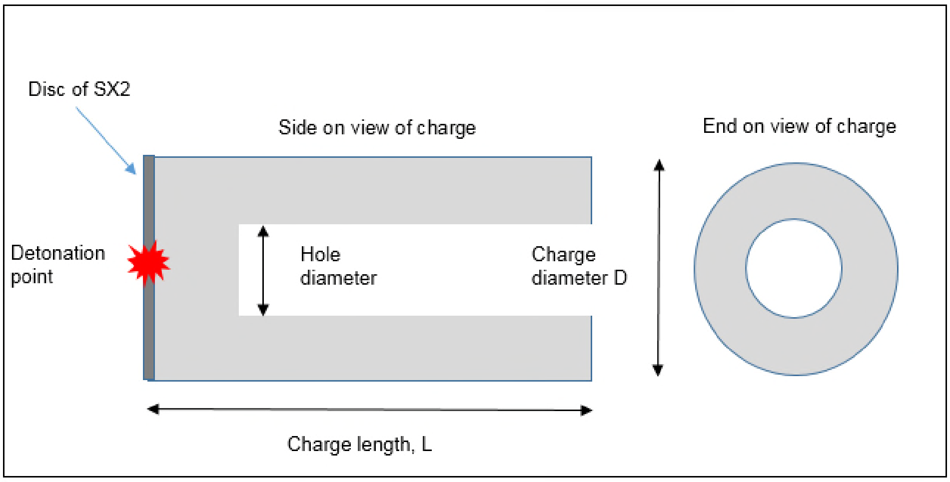

Figure 1. Side and end on view of hollow explosive charge.

where $K`_I$ and $K_I$ are explosive dependent constants. Currently there is not enough data to determine which is the correct equation. For PE4, $K`_I$ = 145 kPa ms m $kg^{-2/3}$ and K_I = 170 kPa ms m $kg^{-1/2}$ [7].

This paper extends the work on solid, cylindrical charges to study the effect of a circular hollow in a cylindrical charge on the blast wave in the radial direction.

EXPERIMENTAL WORK

New experiments were carried out to collect data for hollow charges. PE4 explosive (RDX/binder 88/12) was used as it can be hand moulded into different shapes.

The hollow charges were based on a cylindrical shape, with a circular hole along the axis, see Figure 1. The charge shape was obtained using metal moulds. An outer, hollow cylinder was constructed with a base. A central spigot of the correct size for the hole required was then screwed into the base. PE4 was then hand pressed into the volume.

Hole diameters of 0, 1, 2 and 4 cm were used. The hollow charges had masses of 0.18 kg to 0.487 kg, lengths of 0.063 to 0.215 m and L/D ratios of 1/1 to 6/1. A full list of charge sizes is given in the Appendix, Table IV. At least three replications of each charge were detonated. Replicate charges were accurate to within ± 0.003 kg.

Detonation was carried out using 8 star detonators containing 1.4g of PETN. To ensure complete detonation of the charge, a disc of SX2 (an RDX based sheet explosive), weighing 6 g was placed across the charge at the ignition end, Figure 1.

The pressure was measured using Kistler piezoelectric pressure transducers. In the radial direction the gauges were placed between 0.5 and 4 m from the charge. This results in a scaled distance, $Z = R/M^{0.33}$, of 0.8 to 7.8 m $kg^{-1/3}$. The charge and gauges were placed 2 m above the ground to avoid ground reflections reaching the pressure transducers before the positive phase of the blast wave had crossed over the transducers.

TABLE I. CORRELATION COEFFICIENCTS FOR PEAK OVERPRESSURE PLOTTED AGAINST $M^n(L/D)^mR^p$.

$M^n(L/D)^mR^p$	**Correlation coefficient**	
	y = mx	**y=mx²+mx**
M/R^3	0.79	0.87
$M(L/D)^{1/4}/R^3$	0.88	0.97
$M(L/D)^{1/3}/R^3$	0.88	0.97
$M(L/D)^{1/2}/R^3$	0.88	0.96
$M(L/D)^{1/3}/R^2$	0.83	0.88
$M^{1/2}(L/D)^{1/3}/R^3$	0.77	0.87
$M^2(L/D)^{1/3}/R^3$	0.05	0.5

The data collected was then combined with previously published work on solid cylindrical charges [9]. The previous work used the same experimental technique and consisted of charge sizes of 0.1 to 5 kg and a length to diameter ratio, L/D, of 4/1 to 6.5/1. The data in the previous work was collected at scaled distances of Z = 1.05 to 10.9 m $kg^{-1/3}$.

RESULTS AND DISCUSSION

The experimental data from the pressure transducers was examined to obtain the peak overpressure and impulse in the radial direction. The resulting data was then analyzed to determine whether the hole size affected the peak overpressure or impulse.

Peak Overpressure

To determine the dependency of the peak overpressure on the charge's mass and length to dimeter ratio and the distance from the charge, data for the peak overpressure was plotted against values of $M^n(L/D)^mR^p$. In this equation n, m and p are constants. It is assumed that the peak overpressure will be zero when the mass is zero or the distance is infinite and so the line is assumed to pass through the origin. Plots of the data, as in Figure 2, showed that the data might not give a straight line. As a result, the data was compared using both a straight line and a second order polynomial. A least squared fit was used to determine the best correlation coefficient for each line. The results are given in Table I.

The best data fit was for the fit of a quadratic curve to either $M(L/D)^{1/3}R^{-3}$ or $M(L/D)^{1/4}R^{-3}$. The former, $P = K`\, M(L/D)^{1/3}R^{-3}$, is the same as Equation (2), that is the equation for predicting the peak overpressure in the radial direction for solid cylinders, [9]. Hence that is the equation used in this work. The equation is given by

$$P=251\left(\frac{M(L/D)^{1/3}}{R^3}\right)^2+1677\frac{M(L/D)^{1/3}}{R^3} \qquad (5)$$

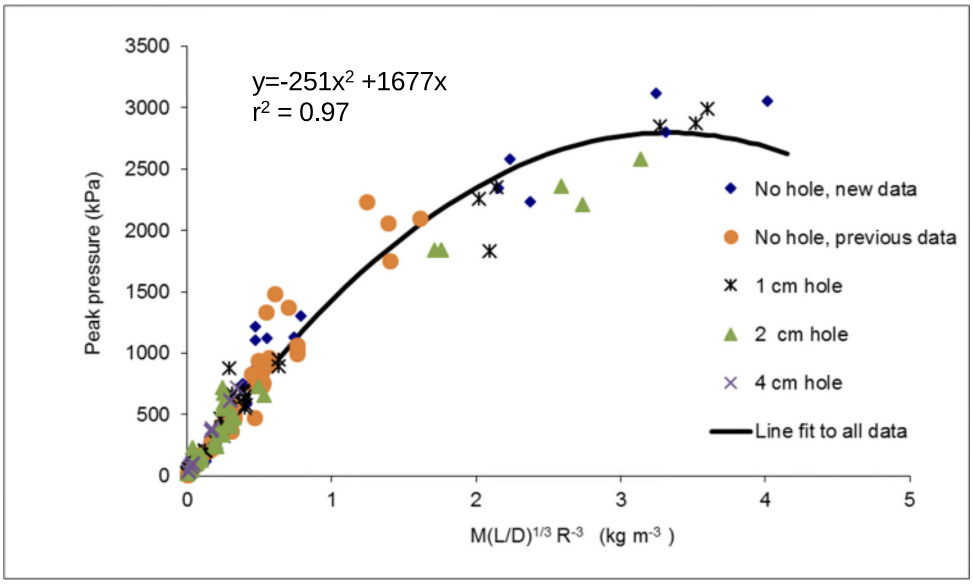

Figure 2. Peak pressure plotted against M $(L/D)^{1/3}$ R^{-3} for all data, r^2 is the correlation coefficient.

The plot of the peak overpressure against $M(L/D)^{1/3}R^{-3}$ is shown in Figure 2. The results show that the new data collected for solid cylinders for this work (solid diamonds in Figure 2) does not appear to be distinguishable from the previous data [9] collected for solid charges (solid circles in Figure 2).

The results show no difference between hollow and solid charges. This means that provided the ratio of $M(L/D)^{1/3}R^{-3}$ is maintained between charges the results show that having a hollow in a charge does not affect the peak overpressure.

Looking at the data in detail shows two parts to the curve. The first part is for $M(L/D)^{1/3}R^{-3} < 1$ kg m^{-3}. A large amount of data has been collected at these distances in the past [9] and added to in the current work. Fitting a straight line to this data gives (see Figure 3)

$$P = 1703 \frac{M(L/D)^{1/3}}{R^3} \qquad r^2 = 0.92 \qquad (6)$$

This equation has a different value of the coefficient K` than for the work previously published. In this work the coefficient is K` = 1703 kPa kg^{-1}. In the previous work K` = 1525 m^3 kPa kg^{-1} [9]. The difference in values is because in the previous work there were only four data points with a value of $M(L/D)^{1/3}R^{-3} > 1$ kgm^{-3} (ringed values in Figure 3). These were included in the straight line data fit that gave the coefficient of 1525 m^3 kPa kg^{-1}.

The current work includes far more data when $M(L/D)^{1/3}R^{-3} > 1$ kg m^{-3} and seems to demonstrate that when $M(L/D)^{1/3}R^{-3} > 1$ kg m^{-3} the rate of change in peak overpressure with distance is different to when $M(L/D)^{1/3}R^{-3} < 1$ kg m^{-3}.

For the data for $M(L/D)^{1/3}R^{-3} > 1$ kg m^{-3} a straight line can also be fitted giving the equation

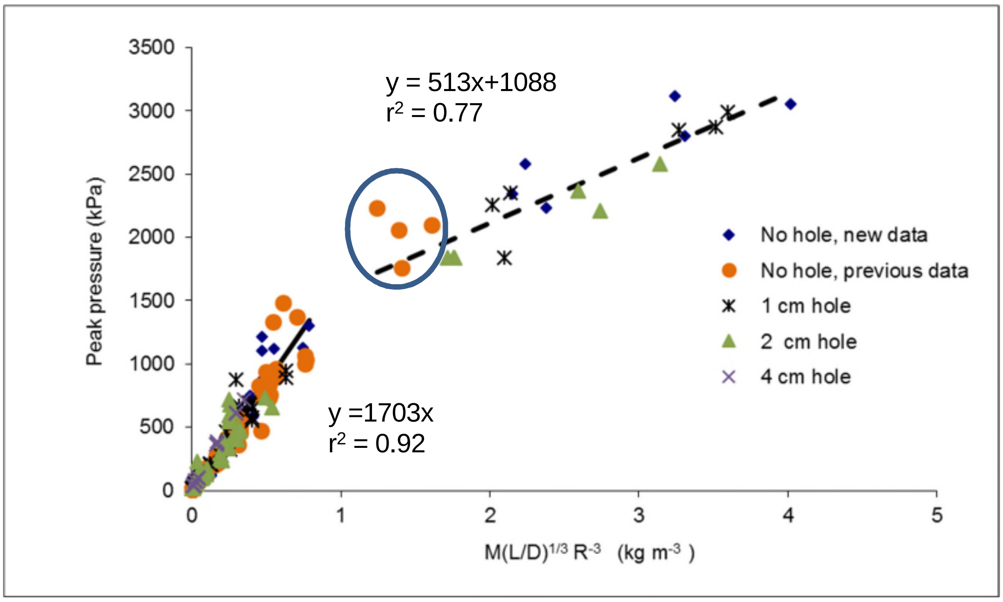

Figure 3. Peak pressure plotted against M $(L/D)^{1/3}$ R^{-3}, r^2 is the correlation coefficient. Points in the circle are data points which in previous work [9] was combined with the data M $(L/D)^{1/3}$ $R^{-3} < 1$ to give a straight line fit.

$$P=513\frac{M(L/D)^{1/3}}{R^3}+1088 \qquad r^2=0.77 \qquad (7)$$

The split of the data into two suggests that as the shock wave moves away from the charge it is altering. It is not possible to tell from either the pressure transducer data or the high speed camera data what is happening. The data for when the peak overpressure is greater than 1500 kPa has a scaled distance of Z = 0.71 to 1.1 m $kg^{-1/3}$. For when the peak overpressure is less than 1500 kPa the scaled distance Z is always greater than 1.27 m $kg^{-1/3}$. This suggests that the effect may not depend on the length to diameter ratio, however there is not enough data to confirm this.

Impulse

Data for the impulse was plotted against values of $M^n(L/D)^mR^p$, where n, m and p are constants The results were compared using a straight line, least squared fit to the data, Table II. It is assumed that the impulse will be zero when the mass is zero or the distance is infinite. Hence the straight line fit is assumed to pass through the origin.

The best correlation coefficient was for $I = K`_I M^{2/3}/R$ with a correlation coefficient of $r^2 = 0.86$. When the length to diameter ratio, L/D, is included the correlation coefficient does not change, suggesting that the impulse is independent of the length to diameter ratio.

TABLE II. CORRELATION COEFFICIENCTS FOR IMPULSE PLOTTED AGAINST $M^n(L/D)^mR^p$.

$M^n(L/D)^mR^p$	**Correlation coefficient**
$M^{0.5}/R$	0.8
$M^{2/3}/R$	0.86
$M^{0.75}/R$	0.77
M/R	0.28
$M^{2/3}(L/D)^{1/3}/R$	0.77
$M^{2/3}(L/D)^{1/8}/R$	0.85

The results for $I = K`_I\ M^{2/3}/R$ are plotted in Figure 4. As with the peak overpressure it is not possible to distinguish between data collected for this work for solid charges and previous data for solid charges [9]. It is also not possible to distinguish between the results for hollow and solid charges. For the hollow and solid data presented in this paper, $K`_I$ = 150 kPa ms m $kg^{-2/3}$. This is very close to the published data for solid charges, which is $K`_I$ = 145 kPa ms m $kg^{-2/3}$ [7].

Hence the results show that the impulse is independent of the length to diameter, L/D ratio. Also the impulse is independent of hole size, provided the correct ratio of mass and distance is maintained, namely $M^{2/3}/R$.

As for the peak pressure, there appears to be two possible regions to the impulse data. Far out from the charge, when $M^{2/3}R^{-1} < 0.6$ kPa ms m $kg^{-2/3}$, then the data shows a steady decrease in impulse with distance. Note that the value of $M^{2/3}R^{-1} < 0.6$ kPa ms m $kg^{-2/3}$ is an estimate as there is not enough data to define the value.

Excepting the four values greater than I = 150 kPa ms, then closer into the charge, $M^{2/3}R^{-1} > 0.6$ kPa ms m $kg^{-2/3}$ the impulse appears to be constant.

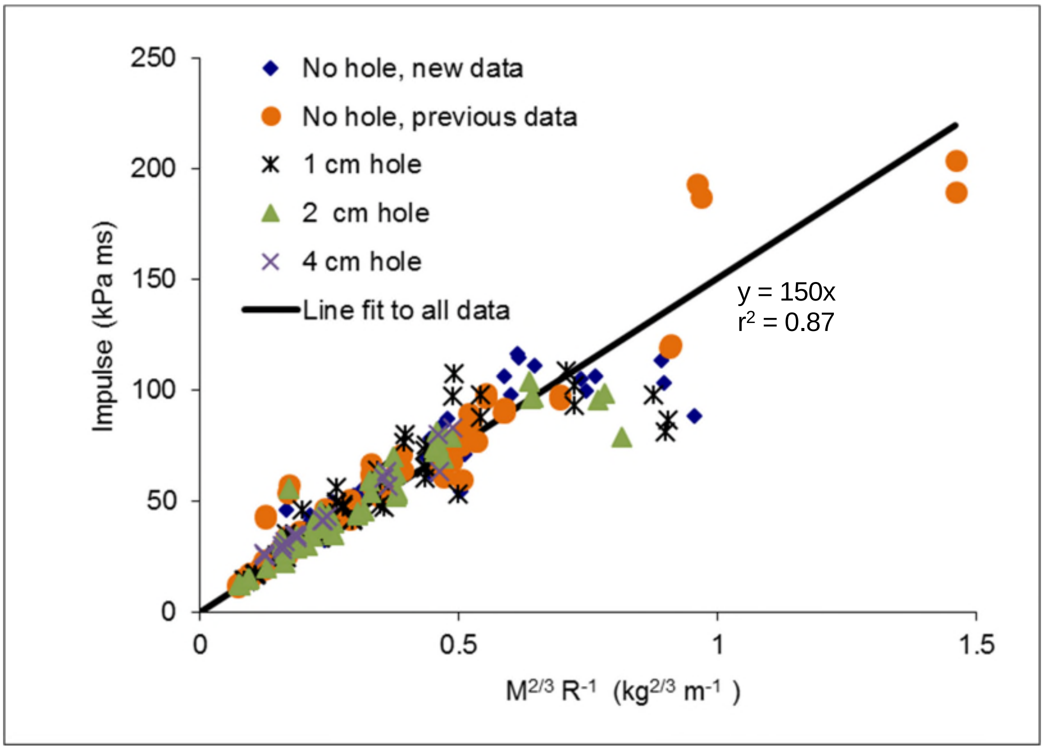

Figure 4. Impulse plotted against $M^{2/3}/R$.

TABLE III. CORRELATION COEFFICIENCTS FOR IMPULSE PLOTTED AGAINST $M^n(L/D)^mR^p$ FOR DATA WHERE $M(L/D)^{1/3}R^{-3} > 1$ kg m^{-3}.

$M^n(L/D)^mR^p$	**Correlation coefficient**
$M^{0.5}/R$	0.85
$M^{2/3}/R$	0.91
$M^{2/3}(L/D)^{1/6}/R$	0.86
$M^{2/3}(L/D)^{1/4}/R$	0.89

This split in data is different to that for the pressure. Using the split of the data for peak overpressure, then for when $M(L/D)^{1/3}R^{-3} >1$ kg m^{-3} the plot for impulse against $M^{2/3}/R$ is as in Figure 5. Fitting straight lines through the origin for impulse against $M^n(L/D)^mR^p$ showed, Table III, that the best fit for the data was for $M^{2/3}/R$. This equation is the same form as for impulse of solid charges in past work [7]. However, the removal of data points when $M(L/D)^{1/3}R^{-3} >1$ kg m^{-3} has resulted in a different value for the explosive dependent coefficient. It is now 173 kPa ms m $kg^{-2/3}$ [7] compares to 145 kPa ms m $kg^{-2/3}$ for all the solid charges [7].

For when $M(L/D)^{1/3}R^{-3} >1$ kg m^{-3}, there is not enough data to determine how the impulse depends on the explosive mass, length to diameter ratio and distance from the charge (see Figure 6.)

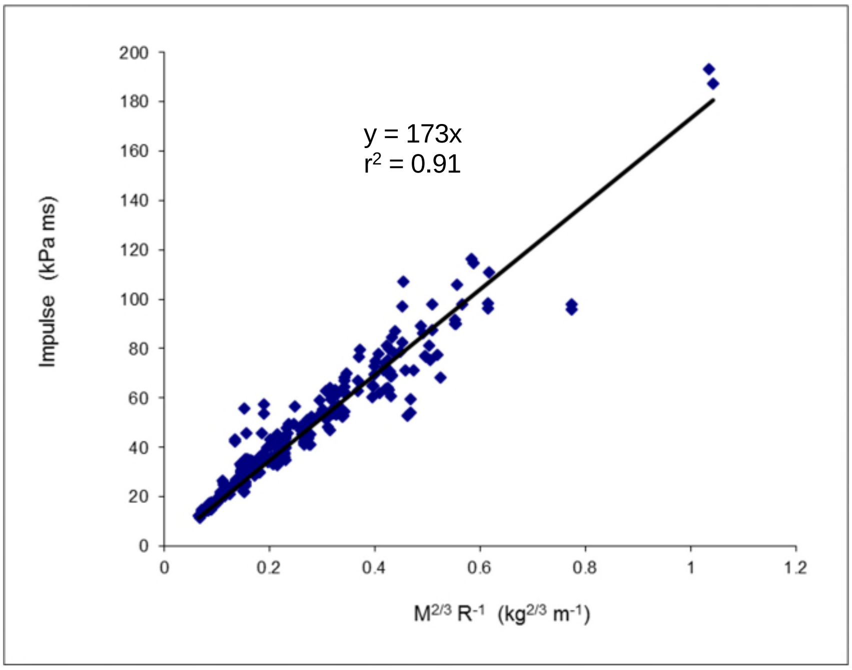

Figure 5. Impulse against $M^{2/3}/R$ for when $M(L/D)^{1/3}R^{-3} > 1$ kg m^{-3}.

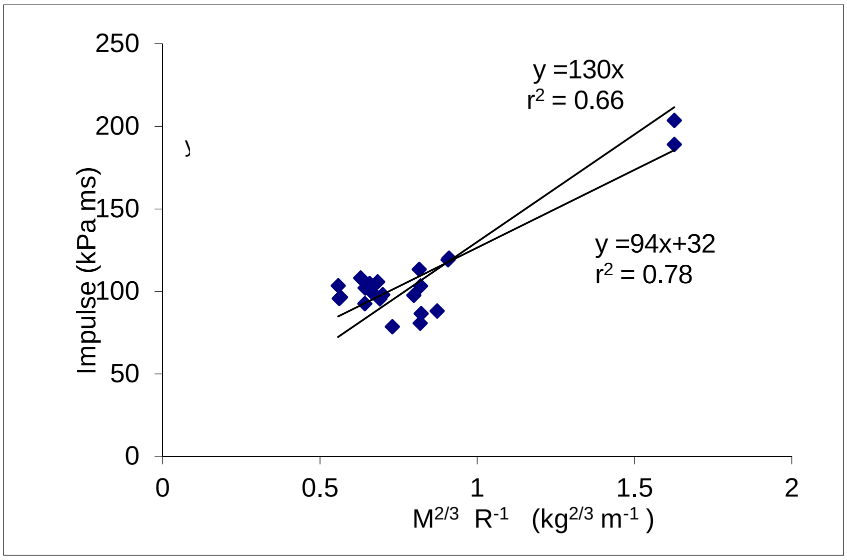

Figure 6. Impulse against $M^{2/3}/R$ for when $M(L/D)^{1/3}R^{-3} < 1$ kg m^{-3}.

CONCLUSIONS

Experiments were carried out to measure the blast in the radial direction from hollow, cylindrical charges of PE4. The results showed that for PE4, the peak pressure for all hole sizes and solid charges can be predicted using a single equation, namely $P = -251\,(M(L/D)^{1/3}R^{-3})^2 + 1677\,M(L/D)^{1/3}R^{-3}$. That means that provided that the ratio of $M(L/D)^{1/3}R^{-3}$ is maintained the same peak pressure will be observed. Hence the size of the hole inside the charge does not matter.

The impulse for PE4 can be predicted using $I = 150\,M^{2/3}R^{-1}$. So the impulse will be the same provided the ratio of $M^{2/3}R^{-1}$ is maintained. As with the peak over pressure the hole size does not affect the results.

Hence by altering the relative size and mass of a charge it could be possible to place ammunition parts such as the electronic systems inside the explosive charge and not affect the blast in the radial direction

The results in the paper include measurements that are far closer to the charge than those previously reported in [3,7,8,9]. Both impulse and peak overpressure showed a different rate of change of decay with distance, as the value of $M(L/D)^{1/3}R^{-3}$ decreased to less than 1. Further work will be needed to explain why.

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APPENDIX

Table IV. CHARGE SIZES

Mass (kg)	Diameter (mm)	Length (mm)	L/D	Hole diameter (mm)
0.282	39	156	4/1	0
0.420	36	215	6/1	0
0.261	39	156	4/1	10
0.380	36	215	6/1	10
0.207	39	156	4/1	20
0.308	36	215	6/1	20
0.18	40	100	2.5/1	0
0.169	40	100	2.5/1	10
0.137	40	100	2.5/1	20
0.251	40	140	3.5/1	0
0.234	40	140	3.5/1	10
0.189	40	140	3.5/1	20
0.324	63	63	1/1	0
0.316	63	63	1/1	10
0.301	63	63	1/1	20
0.201	63	63	1/1	40
0.487	63	94.5	1.5/1	0
0.302	63	94.5	1.5/1	40