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DETERMINATION OF EXPLOSIVE BLAST LOADING EQUIVALENCIES WITH AN EXPLOSIVELY DRIVEN SHOCK TUBE

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Abstract. Recently there has been significant interest in evaluating the potential of many different non-ideal energetic materials to cause blast damage. We present a method intended to quantitatively compare the blast loading generated by different energetic materials through use of an explosively driven shock tube. The test explosive is placed at the closed breech end of the tube and initiated with a booster charge. The resulting shock waves are then contained and focused by the tube walls to form a quasi-one-dimensional blast wave. Pressure transducers along the tube wall measure the blast overpressure versus distance from the source and allow the use of the one-dimensional blast scaling relationship to determine the energy deposited into the blast wave per unit mass of test explosive. These values were measured for C4, ANFO, and two perchlorate explosives. Explosive equivalencies from these values were found to agree with prior theory and experiment.
Keywords: explosive equivalency, non-ideal explosive, blast pressure measurement, heat of detonation
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INTRODUCTION

The blast loading resulting from detonation of a non-ideal or improvised explosive is currently a subject of intense interest to the explosion community. Despite being in use for more than 250 years, the relative damage capabilities of high explosives (HEs) are still not fully understood. Furthermore, most detailed studies to date have been devoted to characterizing ideal explosives, while the blast loading of non-ideal HEs has received much less attention.

While ideal explosives react promptly and have high levels of brisance (the ability to generate strong shock profiles followed by rapid pressure decays), non-ideal and improvised HEs typically exhibit much less energy release and more extended reaction zones. This results in larger failure diameters, lower peak shock pressures, and a slower pressure decay profile behind the shock front.

Due to this insensitivity, many improvised HEs will not detonate without significant boosting. This is because their extended reaction zones are strongly influenced by edge expansion effects, resulting in detonation failure without sufficiently stiff confinement or sufficiently wide charge geometries. It is often preferable to use a confined rate-stick geometry for non-ideal HE tests, which allows for: a large booster to be placed adjacent to the test HE, a metal tube to be used to confine the detonation, and a planar detonation front shape to further minimize wave diffraction.

However, such an asymmetric charge geometry is not particularly conducive to blast loading measurements, which are most commonly measured in an outdoor blast arena. Blast arena testing involves measuring the shock wave overpressure as a function of distance that results from detonation of a test charge in an open area. Blast-scaling theory can then relate the shock-wave overpressure versus distance to the explosion energy. Spherically symmetric charges are essential in order to obtain meaningful measurements in this test geometry. Unfortunately, rate-stick shaped charges result in asymmetrical shock shapes.

In order to experimentally determine the explosive equivalencies of non-ideal and improvised explosives relative to an ideal reference HE, we have detonated HEs in a short-aspect-ratio, rate-stick geometry while confined in a shock tube. This arrangement allows for full detonation of the test HE before the boosted shock can decay to failure, shaping of the resulting blast wave to a planar front, and successful measurement of the explosive output via one-dimensional blast scaling theory. Unlike many earlier and larger-scale explosively driven shock tube studies, the breech section in the current study has been designed to withstand the close-range explosive loading.

EXPERIMENTAL ASSEMBLY

Our shock tube was composed of a 5.1-m-long tube of carbon steel with an inner diameter of 15.2 cm and a 1.27-cm-thick wall. Slip-on flanges were welded on each end. The downstream end of the tube was left open, while the upstream end was sealed with a 3.65-cm-thick blind flange. During testing, a high-strength, 3.18-cm-thick maraging steel breech was inserted into the upstream end of the shock tube, surrounding the high explosive charge. The breech protected the tube wall from the locally high pressures near the detonating charge and its downstream end was open to allow the explosive products to expand downstream into the shock tube. The breech floated on O-rings that served to partially isolate the rest of the tube from the intense high-frequency loading associated with the detonation-induced shock interacting with the breech wall.

Pressure transducer ports S1–S6 were located at the distances of 0.644, 1.644, 2.644, 3.644, 4.644 and 5.042 m from the test charge, respectively. PCB 113A-series piezoelectric transducers were used and each was flush mounted into a polycarbonate plug that was screwed directly into the tube wall. This plug served to further isolate the transducers from any structural noise induced in the tube during testing. The transducers were sampled at 1.25 MHz.

During testing, the charge was loaded into the breech section of the shock tube. Test HEs were boosted with an HMX- or RDX-based PBX that was initiated with an RP-2 detonator. As some of the non-ideal mixtures were tested at diameters below their unconfined failure diameter limit, charges were formed into right cylinders with length-to-diameter ratios less than unity in order to prevent significant wave decay before the charge was consumed.

After detonation, the expansion of the explosive products drove a shock into the tube's atmosphere. The shock wave was initially asymmetrical, but focused into a quasi-planar front through successive wave reflections from the tube walls. Several diameters from the source, the shock front was sufficiently planar to achieve meaningful blast overpressure measurements.

Sample pressure traces are shown in Fig. 1 for 25.1 g of C4 boosted by 2.6 g of PBX 9407. At position S2, the shock front is still steepening and a lower maximum pressure is recorded than at S3, where the front is more defined. After S3, the maximum shock overpressure decreases with increasing distance. Multiple reflections are apparent behind the lead shock, some of which are artifacts of structural ringing of the shock tube.

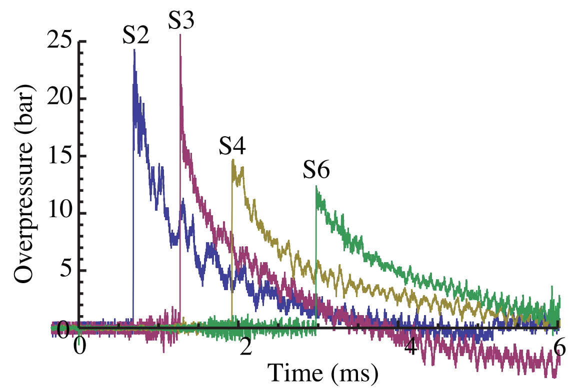

FIGURE 1. Pressure traces for a C4 test.

BLAST SCALING THEORY

The development of blast scaling theory dates back to the early 1940's when G.I. Taylor [1, 2] and L.I. Sedov [3] both independently developed self-similar solutions to predict the conditions behind a blast wave expanding from an intense explosion.

Concisely, the theory assumes that the propagation of a strong blast wave relies on only four independent variables: E, the source energy; ρ_0, the ambient atmospheric density; r, the distance of the shock front from the source (the only length scale in the problem); and t, the time from energy release. From these parameters, the self-similar group η_ν can be formed

$$\eta_\nu = \frac{r}{\left(\frac{E}{\rho_0}\right)^{1/(2-\nu)} t^{(2/2-\nu)}} \tag{1}$$

where the geometry index ν is 1, 2, and 3 for planar, cylindrical, and spherical blast waves, respectively. The source energy accordingly has dimensions of $\frac{Energy}{Area}$, $\frac{Energy}{Length}$, or simply $\frac{Energy}{1}$. Note that initial pressure of the atmosphere P_0 is neglected, which is an acceptable approximation for strong shock waves.

Proceeding in the planar geometry represented by the shock tube ($\nu = 1$ and $E = E_0/A$), the shock velocity versus distance is

$$u = \frac{2}{3}\sqrt{\frac{\alpha E_0/A}{\rho_0}}\frac{1}{\sqrt{r}} \tag{2}$$

where A is the cross-sectional area of the tube and E_0 is the total energy release. Parameter α is close to unity and varies with the ratio of specific heats γ and the geometry index ν [3].

To obtain the overpressure $[P]$ across the shock, the strong shock and perfect gas relations can be combined with Eq. 2.

$$[P] = \frac{2}{\gamma+1}\left(\frac{4}{9}\frac{\alpha E_0}{A}\frac{1}{r}\right) \tag{3}$$

Thus, the energy release for a given explosion in the shock tube can be found by fitting Eq. 3 to the peak-shock-overpressure-versus-distance data, varying only E_0. Subtraction of the known booster energy then yields the energy associated with the test explosive. Dividing this energy by the explosive mass gives the heat of detonation ΔH_{det}.

Applying this methodology to the C4 traces in Fig. 1 with a least-squares fit gives a ΔH_{det} of 5.01 kJ/g. This agrees well with energy release values from C4 cylinder tests (5.36 kJ/g) [4] and the thermochemical-equilibrium code Cheetah (4.87 kJ/g) as shown in Fig. 2.

All experimental data from the current study is shown on a plot of nondimensional overpressure $\frac{[P]}{P_0}$ versus nondimensional distance $\frac{rP_0}{(E_0/A)}$ in Fig. 3. Good agreement is seen with with blast-scaling theory (Eq. 3) except close to the source, where experimental pressures are somewhat lower. This is a commonly observed phenomenon for chemical explosives, which have a finite (CJ) pressure at their source as well as a non-negligible size, requiring distance for shock-steepening to occur. Blast scaling theory assumes a point source with infinite pressure.

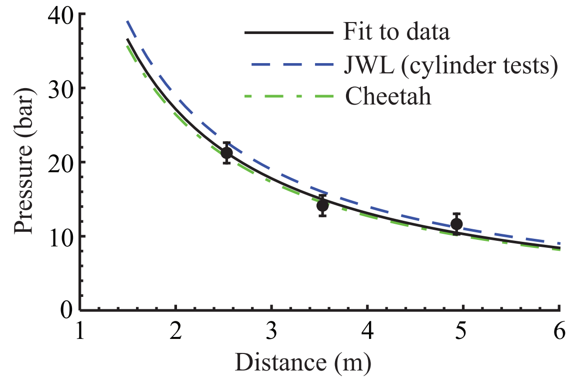

FIGURE 2. Maximum experimental overpressure from traces S3, S4, and S6 in Fig. 1 compared to theoretical estimates and fits.

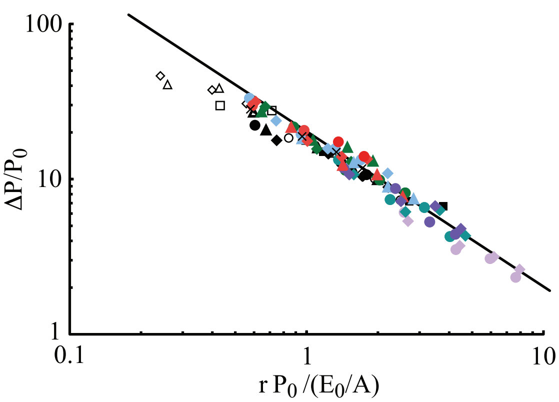

FIGURE 3. A comparison of theory (line) to experiment (symbols) on a plot of nondimensional peak overpressure versus distance. Symbols denote 24 separate tests with varying masses of explosives C4, ANFO, $KClO_4$+$C_{12}H_{22}O_{11}$, $NaClO_4$+$C_{12}H_{22}O_{11}$, PBX 9404, PBX 9407, and PBX 9501.

RESULTS

The results of four explosive mixtures are reported: Composition C4, $KClO_4$ + $C_{12}H_{22}O_{11}$ (potassium perchlorate and sucrose), $NaClO_4$ + $C_{12}H_{22}O_{11}$ (sodium perchlorate and sucrose), and ANFO (am-

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monium nitrate and fuel oil). The perchlorate mixtures were both stoichometrically balanced with sucrose. ANFO mixtures contained 10 wt. % No. 2 diesel fuel.

The C4 charges were boosted with a PBX 9407 booster with a diameter of 12.7 mm and a length of 12.7 mm. All other explosives were boosted with either a PBX 9501 or PBX 9407 booster with a diameter of 38.1 mm and a length of 3.2 mm. Test charge quantities range from 5 to 50 g. The explosive assemblies were only confined by a single layer of 20-lb copy paper and masking tape.

The measured energy release as a function of test explosive mass is shown in Fig. 4 for the $NaClO_4$ explosive. Booster systems were also tested separately

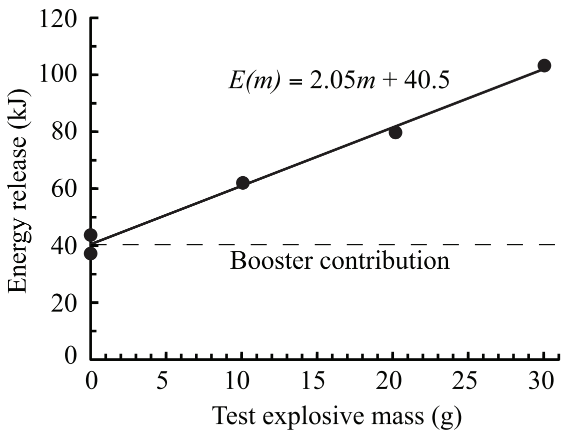

FIGURE 4. Energy values for the $NaClO_4$ mixture.

in order to measure their energy output. A line fitted to each explosive dataset yields the energy of the booster system in the y-intercept and the heat of detonation in the slope. Values determined from this method are shown in Table 1.

TABLE 1. Heat of detonation and equivalency values.

Mixture	$\Delta H_{det} (kJ/g)$	η_{C4}	η_{LLNL}	$\eta_{Cheetah}$
ANFO	2.49	0.50	0.60	0.42
C4	5.01	1.00	1.00	1.00
$KClO_4$	2.41	0.48	0.54	0.40
$NaClO_4$	2.05	0.41	N/A	0.44

Table 1 also contains equivalency data from several sources relative to C4. Equivalency values based on the experimentally determined heat of detonation values from this study are shown in the η_{C4} column. The adjacent column, η_{LLNL}, contains equivalency values determined from other explosive overpressure measurements [4]. Finally, equivalencies as calculated from Cheetah are listed in the $\eta_{Cheetah}$ column. The equivalency data for this study agree with the η_{LLNL} and $\eta_{Cheetah}$ data to within 20%, which we find remarkable given the substantial differences between the two reference sets. This indicates that our method of equivalency determination is consistent with other existing experimental and theoretical methods.

CONCLUSIONS

Explosive equivalencies were determined for a range of ideal and non-ideal explosives. This was done by measuring the shock overpressure versus distance that resulted from detonation of a small test charge located at the driver end of a shock tube. One-dimensional blast scaling theory was then used to determine energy release from the overpressure-distance values. The data obtained agrees well with values from previous experiments and theory.

We feel that this technique is particularly noteworthy because it allows for equivalency and heat of detonation characterization in a rapid and cost-effective manner, with small quantities of explosive. With both ends sealed, this explosively driven shock tube can easily be located in any laboratory environment.

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