Measurements of near-field blast effects using kinetic plates

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Abstract. Few tests have been designed to measure the near-field blast impulse of ideal and non-ideal explosives, mostly because of the inherent experimental difficulties due to non-transparent fireballs and thermal effects on gauges. In order to measure blast impulse in the near-field, a new test has been developed by firing spherical charges at 152 mm (6 in) from steel plates and probing acceleration using laser velocimetry. Tests measure the velocity imparted to the steel plate in the 50 - 300 µs timeframe, and are compared with free-field over-pressure measurements at 1.52 m (5 ft) and ms timescales using piezoelectric pencil gauges. Specifically, tests have been performed with C4 to probe the contributions of ideal explosives and charge size effects. Non-ideal aluminized explosive formulations have been studied to explore the role of aluminum in near-field blast effects and far-field pressure, and are compared with formulations using LiF as an inert surrogate replacement for Al. The results are compared with other near-field blast tests and cylinder tests, and the validity of this test is explored with modeling and basic theory.

1. Introduction
Coupling between air blast and structures is an important aspect of modeling explosions. Jones-Wilkins-Lee (JWL) equation of state (EOS) and hydrocode modeling can reasonably predict the generation of air blast by explosives. However, the EOS may not contain sufficient information to predict the performance of all types of explosive material, or whether the blast delivered by non-ideal explosives and propellants may couple more efficiently with nearby structures. In an attempt to understand the differences in blast effects between different explosive charges, this test methodology utilizes laser velocimetry to measure the momentum delivered to test structures. Similar tests in the past utilized a ballistic pendulum [1] or photographic techniques to measure the momentum imparted to structures. However, utilization of these diagnostics restricts the test geometry. The ballistic pendulum test allows for measurement of early blast performance, but may not capture the near-field blast impulse relevant to structures of interest. The purpose of this study is to investigate explosive air-blast effects relevant to rigid structures, allowing for comparison of various explosives with respect to near-field blast performance.

2. Method
These measurements used a 127 × 127 × 12.7 mm steel plate weighing 1584 ± 10 g, loosely placed inside a steel collar to prevent blast waves from passing around the plate within the experimental time scale. The plate and collar are generally placed 152 mm (6 in) from the center of the explosive charge unless stated otherwise. Test geometry was chosen to present a surface facing the explosive charge...
that was within the fireball generated by detonation of the charge. The plate thickness and mass result in velocities fast enough to be measured accurately with the available instrumentation, but slow enough that the plate distortion effects are small.

A picture of a basic test setup is shown in figure 1. The square plate is loosely taped inside the outer collar, and the tolerances are such that the gap between plates is as small as possible without inhibiting plate motion. The strip of tape stabilizes the hardware prior to detonation, but imposes negligible resistance to plate motion. High-speed video demonstrates that the 127 mm plate velocities are slightly faster than those of the collar, as intended.

We observed near-field blast effects with C4, C4/sand, potassium chlorate mixtures with fuels (KC/fuels), and aluminized formulations in order to determine how blast couples to structures with both ideal and non-ideal explosives. All charges were prepared using two hemispherical molds. The KC/fuel explosive charges were formed using a hemispherical mold with a 38.00 mm radius (volume 229.9 cm³), and a liner formed from Silver Shield gloves for chemical compatibility with the fuels. The presence of the liner and shifting of material during setup may result in ±10% variations in volume and density. The booster (a 12.7 mm dia × 12.7 mm long right circular cylinder, PBX 9501 or PBX 9407, 3 g) was placed in the center of the charge, and the RP-1 detonator (HE = 0.625 g) was positioned parallel to the plate. The setup was lined in tape to hold it together and keep the spherical shape. The C4 charges were prepared in foil liners using hemispherical molds with varying diameters, giving a range of sizes from 73.0 g – 453.2 g [2]. The C4 shots with sand additives were prepared in a spherical mold with volume 164.6 cm³. HMX formulations were prepared containing aluminum (HMX-Al) and lithium fluoride (HMX-LiF), an inert surrogate for aluminum, in a similar setup and described in detail previously [3].

The primary diagnostic employed during the test series was Photonic Doppler Velocimetry (PDV), a laser interferometric technique that utilizes 1550 nm infrared laser light to measure the plate velocity during the first ~400 µs of motion. Four PDV probes were mounted in an aluminum plate in a nominal 76 × 76 mm square array. The laser probes were mounted opposite the explosive charge at a distance of 100 – 150 mm from the plate, and aligned perpendicular to the plate surface using a mirror. PCB Piezotronics pencil pressure gauges were fielded at a distance of 1.52 m (5 ft) from the charge center; these utilize side-facing piezoelectric elements to measure the overpressure profile. Videos were taken of the shots using a Vision Research Phantom Miro eX4 digital camera, with ~8200 frames/s.

Figure 1. Test setup; the spherical charge is 152 mm from the dark gray plate on the left, and the PDV probes (dashed red lines) are located on the right-hand side of the plate/collar, imbedded in the lighter gray plate.

3. Results
Duplicate tests were conducted with three different KC/fuel mixtures, held in a Silver Shield glove material. Video frames for one representative shot are shown in figure 2. The PDV probe data were processed using a Fourier transform spectrogram. Each resulting curve was fit to an empirical, exponential function modified with oscillatory terms, which was used in analysis of every shot for consistency (figure 3). The plate velocity traces show some oscillation structure that corresponds to mechanical vibrations of the plate. The asymptote of each fit was taken as the maximum plate velocity for that probe. The probe velocities for each plate were combined, decomposing into their separate linear and rotational velocity components, in order to obtain the final linear velocity for each experiment. For each test, uncertainties in the plate speed are calculated from the standard deviation of the four probe velocities after accounting for position and plate tilt. The plate speeds reported are therefore determined from the steady-state velocities of the plate, which are generally reached ≥ 230 µs after detonation. An average of
the probe velocities was taken after they reached steady-state values, and these average values generally gave plate velocities within 0.5 m/s of the linear velocity fits described above. All KC/fuel shots gave plate velocities within 1 m/s of each other; the average and standard deviation of all KC/fuel shots are shown in table 1. The same fitting procedure was used for charges of C4 [2], C4 with added sand, and HMX mixtures [3] (table 1). The peak pressures were taken at 1.52 m for each shot, and are shown in table 1 (the large range of KC/fuel values is due to non-ideal effects).

Figure 2. Assembly for a KC/fuel shot. Pictures were taken using a Phantom Miro eX4 camera (one frame every ~ 122 µs). The fireball is visibly flattened on the right side by the large collar holding the plate.

Figure 3. (a) Four probe velocities are collected in each KC/fuel shot. (b) Plate velocities are calculated from velocimetry techniques (PDV), using a fitting procedure at the asymptote of the fit.

4. Discussion

4.1 Summary of data
The C4 shots were performed with a variety of charge masses in the same test assembly (table 1). For these data, all parameters were the same (ie. charge center standoff of 152 mm). As shown in figure 4, the resulting plate velocity scales linearly with charge mass (which includes the mass of the detonator and booster). To test how an inert substance distributed throughout an explosive will affect the impulse, sand was mixed with charges of C4 (20% sand by mass). The average charge mass (without sand) of 198.4 g corresponds to an average plate velocity of 21.7 m/s. Using a charge mass of 198.4 g (202.0 g including detonator/booster mass) in the linear regression line shown in figure 4, we obtain a calculated plate velocity of 20.8 m/s. The charge containing sand is therefore 4.3% higher than the calculated charge mass containing no sand, showing that even an inert additive can increase the impulse imparted to the plate. These results have been verified by modeling, and are discussed in a separate report by Neuscamman, et al [4].

In order to probe the non-ideal effects of aluminum in HMX formulations, HMX-Al and HMX-LiF charges were placed in the same test configuration, but with additional tests conducted with a standoff distance of 254 mm (10 in) between the center of the charge and the plate. At the standard 152 mm test configuration, the average plate velocity for the HMX-Al shots is 22% higher than the
average plate velocity for HMX-LiF [3]. At 254 mm, the average HMX-Al plate velocity is 31% higher than HMX-LiF, indicating that the increased distance between the charge and the plate may allow post-detonation burning and other late-time reactions to increase plate velocity.

The observed plate velocities for the non-ideal KC/fuel explosives can be compared to those for C4, as a standard, more ideal explosive. Due to the similarity in mass, the 253.2 g C4 shot can be used as a direct comparison to the KC/fuel data shown in table 1. The plate velocity of 25.97 m/s in the C4 test is 41% higher than the average value of 18.4 m/s for all of the KC/fuels, and the C4 overpressure at 1.52 m is 51% higher than the upper limit observed in the KC/fuel shots. In general, KC/fuel mixtures have cylinder test velocities of ~1 – 2 mm/µs [5,6], only ~25% as fast as C4 (8.06 mm/µs [7]). In the conditions of the kinetic plate test, the performance of the KC/fuel mixtures relative to C4 is much higher than in cylinder tests, which shows the importance of this test in characterizing non-ideal explosive behavior.

![Figure 4. C4 mass plotted vs plate velocity results in a linear trend.](image)

Table 1. Plate tests conducted on KC/fuel formulations, C4, and aluminized formulations.

| Material            | Charge Mass (g) | Density (g/cm³) | Plate Velocity (m/s) | Uncertainty (m/s) | Peak Pressure at 1.52 m (psi) |
|---------------------|----------------|-----------------|----------------------|------------------|------------------------------|
| Comp C4             | 73.0           | 1.6             | 8.81                 | 0.08             | 11.0                         |
| Comp C4             | 116.2          | 1.6             | 11.65                | 0.19             | 15.2                         |
| Comp C4             | 117.2          | 1.6             | 12.20                | 0.05             | 15.0                         |
| Comp C4             | 127.5          | 1.6             | 12.83                | 0.01             | 14.4                         |
| Comp C4             | 128.2          | 1.6             | 14.94                | 0.15             | 13.4                         |
| Comp C4             | 170.6          | 1.6             | 17.70                | 0.02             | 17.9                         |
| Comp C4             | 174.5          | 1.6             | 18.26                | 0.14             | 18.6                         |
| Comp C4             | 253.2          | 1.6             | 25.97                | 0.22             | 21.0                         |
| Comp C4             | 356.8          | 1.6             | 35.20                | 0.04             | 31.4                         |
| Comp C4             | 453.2          | 1.6             | 45.72                | 0.05             | 34.7                         |
| C4/ 20% sand        | 252.7 (199.3)  | 1.51            | 22.25                | 1.01             | 14.9                         |
| C4/ 20% sand        | 250.6 (197.6)  | 1.50            | 21.07                | 0.02             | 15.5                         |
| KC/fuel Average     | 251.4 (247.8)  | 1.08d           | 18.4                 | 1.1              | 8.9 – 13.9                   |
| HMX-Al (6)          | 179.2 (176.0)  | 1.72            | 19.32                | 0.29             | 19.3                         |
| HMX-LiF (6)         | 179.0 (175.8)  | 1.72            | 15.83                | 0.11             | 14.3                         |
| HMX-Al (10)         | 180.8 (177.6)  | 1.73            | 9.34                 | 0.18             | 19.6                         |
| HMX-LiF (10)        | 180.1 (176.9)  | 1.73            | 7.12                 | 0.08             | 13.9                         |

a Total charge mass, includes inert additives and HE mass in detonator (0.625 g) and booster (2.6 – 3 g).
b Standard deviation of the four probe velocities after accounting for position and plate spin. For KC/fuels and HMX mixtures, multiple tests were performed, and the displayed value is the standard deviation of the average of all plate velocities. c Mass of HE in charge (not including detonator, booster, and inert additives). d The density was estimated using the volume of the mold (229.9 cm³) that shaped the charges. Variations of ±10% are expected due to the liner and the setup process after the charge was removed from the mold. e Ref. 3.
4.2 Analysis of plate velocity traces
We observe in all cases that the plate velocity varies exponentially with time to within experimental scatter. This behavior can be related, through Newton’s law, to the overpressure history acting upon the plate. We will show that the observed plate velocity histories are consistent with the following simple expression for the overpressure, $\Delta P$:

$$\Delta P[t] = P_0 e^{-\frac{t}{\tau}},$$

where $P_0$ is the reflected shock pressure at the plate face, $t$ is time, and $\tau$ is a time constant characterizing the pulse width. Starting with equation 1, we can demonstrate that this expression is consistent with the behavior seen in figure 5. Substituting into Newton’s law, and solving for $v$ gives:

$$v[t] = \frac{P_0 A \tau}{m_p} \left( 1 - e^{-\frac{t}{\tau}} \right),$$

which is the desired result that captures the essence of the observed experimental behavior. The specific impulse is the total impulse divided by the plate mass, $I_{sp} = \frac{I}{m_p}$. Thus, equation 2 can be written as equation 3, where $I_{sp} = v_\infty$, the asymptotic plate speed.

$$v[t] = I_{sp} \left( 1 - e^{-\frac{t}{\tau}} \right)$$

Figure 5 shows fits of equation 3 to the HMX-Al and HMX-LiF data collected at a 152 mm standoff. Here, $I_{sp}$ and $\tau$ are free fitting parameters, but ones with obvious physical significance. As expected, the HMX-Al behaves more energetically than HMX-LiF due to the burn contribution of the aluminum. For both HMX-Al and HMX-LiF, the plate reaches its asymptotic speed in about 100 $\mu$s, or 2 mm travel, which is about 1/6th of the plate thickness. The plate has reached terminal velocity before it has even left the starting gate, meaning that our assumption that the plate is moved solely by overpressure is correct. We are not measuring in a regime where viscous drag has any effect.

4.3 Plate velocity vs charge mass
Figure 4 shows that C4 plate velocity scales linearly with charge mass. Relating the energy of the charge to the energy of the plate is complex because only a portion of the charge’s available energy is transferred into rigid body motion of the plate (figure 6). Several factors influence this process. For example, the charge is not a point source so that standoff from the surface of the charge to the center of the plate actually varies. Charges with larger masses at a given density will have their closest surface nearer to the plate. In the regime for this experiment, the energy and momentum of the transfer medium (i.e., air) are important. To probe these factors further, consider the simplest possible energy balance, as shown in equation 4:
\[
\frac{1}{2} m_m v_\infty^2 = \eta \left( \frac{A}{4 \pi r^2} \right) E_0.
\]

The terms in parentheses specify the area fraction associated with the plate, compared to a sphere of radius \( r \). This quantity is proportional to the solid angle subtended by the plate. The total energy \( E_0 \) is the specific energy \( e_0 \) (a material property) times the HE mass \( m_e \). Only the energy directed toward the plate can contribute to its motion, so \( E_0 \) will be attenuated by this factor. Moreover, not all of the energy nominally directed toward the plate goes into pushing the plate, and this is accounted for by an unknown factor \( \eta \). If \( \eta \) were constant, then \( v_\infty \) would be proportional to the square root of \( m_e \), in disagreement with experimental observation. In order to obtain the observed linear trend, \( \eta \) itself must be proportional to the charge mass, which is consistent with the previous observations that for a given charge density, more massive charges have (1) greater cross-sectional area parallel to the plate, and (2) closest edges nearer to the plate. The numerical simulations do capture the observed linear dependence of \( v_\infty \) upon \( m_e \) [4], supporting that the trend is due to simple geometric factors. The considered numerical models are quite simple and do not capture nuances (certainly not of non-ideal HE burn or after burn in the product cloud), which strongly suggests that the cause(s) are relatively generic.

5. Conclusions
Air blast equivalence has been measured within the near field for multiple charge masses of C4, along with several non-ideal explosive formulations. Measurements were taken using laser velocimetry and free-field pressure gauges, and pressure profiles were taken at 1.52 m from the charge. Data was collected on a variety of ideal and non-ideal explosives, varying charge mass as well as distance between the charge and the plate. The data have been analyzed to explore the role of non-ideal explosives in blast effects, and discuss the validity of the test.

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