Plate impact experiments on the TATB based explosive PBX 9502 at pressures near the Chapman-Jouguet state

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Abstract. A series of two-stage gus-gun driven plate impact experiments on PBX 9502 (95 wt.% tri-amino-trinitro-benzene, 5 wt.% Kel-F800 plastic binder) was completed in the 28 - 34 GPa pressure range. This is just above the Chapman-Jouguet state of \( \approx 28 \) GPa. The experiments consisted of a thick oxygen free high conductivity copper (OFHC Cu) flyer plate impacting a PBX 9502 sample backed by a Lithium Fluoride (LiF) window. Photonic Doppler Velocimetry (PDV) was used to measure velocity histories (wave profiles) at the PBX 9502/LiF interface. Shock transit times and sample thicknesses were converted to shock velocities, \( U_S \). Particle velocities, \( u_P \), were calculated by way of impedance matching. Lastly, the measured wave profiles were compared with numerical simulations of the experiments using the Wescott-Stewart-Davis reactive-burn model.

1. Introduction
A principal purpose of this research was to measure detonation products Hugoniot points for PBX 9502 at pressures just above the Chapman-Jouguet (CJ) state. The CJ pressure has been reported as 28.0 GPa by Wescott, Stewart, and Davis (WSD) [1], 28.5 GPa by Tang et al. [2], and 28.3 GPa by Menikoff [3]. In the 28 - 40 GPa range, there is considerable scatter in the available data [2, 4]. We believe that this scatter is, in part, due to the limitations of the explosive driven plate impact techniques used to acquire the data. It may be possible to acquire more accurate data using gas-gun driven plate impact techniques.

In addition to the data scatter due to limitations of the explosive driven plate impact technique, there is scatter due to the shock being unsteady. The detonation reaction zone in TATB based explosives is of order 2 - 3 mm [1, 2]. By analogy, if the explosive is impacted at \( \approx \) CJ pressure, the shock velocity will be unsteady for the first 2 - 3 mm after impact. In other words, there will be a transient covering \( \approx 2 - 3 \) mm and 250 - 400 ns, and over this time and distance the wave will be unsteady. Experimentally, the two ways to account for the unsteady wave are to use stepped targets [5] or to perform multiple experiments with the same flyer velocity and different sample thicknesses. In this study, we take the latter approach. Finally, we wanted to acquire wave profiles that could be compared with numerical simulations using reactive burn models [1, 2, 6].
2. Experimental methods

Plate impact experiments to reach overdriven states in PBX 9502 were conducted on the Los Alamos National Laboratory (LANL) two-stage gas gun located at Technical Area 40 [7]. This gun has a launch tube with a 50.8 mm internal diameter. It is capable of launching projectiles with masses ranging from $\approx 90 - 250$ g to velocities ranging from 1.2 - 3.6 km/s.

The configuration for the plate impact experiments is shown in figure 1. Lexan (polycarbonate plastic) projectiles were assembled with an Oxygen Free High Conductivity Copper (OFHC Cu) flyer plate that was nominally 7 mm thick. Projectile velocity was measured using Photonic Doppler Velocimetry (PDV) [8] using a method similar to that described by Jensen et al. [9].

![Schematic of the gas-gun driven plate impact experiments used to study overdriven product Hugoniot states in PBX 9502.](image)

The projectile impacts a target consisting of a PBX 9502 disk backed by a Lithium Fluoride (LiF) window. Impact generates a shock wave that travels through the PBX 9502 into the LiF. PDV is used to measure wave arrival time at the PBX 9502/LiF interface as well as the interface velocity at later time. Impact time is determined when the Cu flyer strikes the two PDV probes that are mounted at the edges of the explosive sample. The probe tips or lenses are nominally flush with the front surface of the PBX 9502 sample. The position of the probe tips relative to the sample surface are accurately measured. A characteristic signal is generated at the time when the flyer impacts a probe tip. (PDV probes were nominally 2.4 mm diameter, 20 mm working distance collimating probes obtained from AC Photonics, Inc., Santa Clara, CA.)

The PBX 9502 explosive was manufactured by Holston Army Ammunition Plant, Kingsport TN, and was pressed at LANL. Densities of individual samples were measured by water immersion, and all fell within the range of $1.890 \pm 0.003$ g/cm$^3$. All PBX 9502 was from manufacturers lot HOL86A891-004. This is a “recycled” lot. Further details about this lot of PBX 9502 can be found in reference [10].

Lithium Fluoride (LiF) windows were obtained from Reflex Analytical Corporation, Ridgewood, NJ. The LiF is UV grade, high purity single crystal with the (100) plane oriented along the window thickness. One surface was anti-reflection coated for 1550 nm light (0.25% reflectance at normal incidence) and the other was vapor plated with a specular aluminum mirror. For PDV interface velocity measurements, the window correction factor is $1.2669 \pm 0.0037$ [9].

3. Results

Nine gas-gun experiments were performed in this series. Results are displayed in table 1. The “Shot #" is the unique identifier for the experiment. $u_{flyer}$ is the flyer velocity or projectile velocity at impact time. $u_{flyer}$ was measured using two PDV probes. $\Delta x$ and $\Delta t$ are the PBX 9502 sample thickness and shock transit time respectively. $U_S$ is the “average” shock velocity $\Delta x/\Delta t$. Note that average shock velocities tend to increase with sample thickness; a result of the
unsteady waves. \( u_P \) is the “average” particle velocity calculated by way of impedance matching methods [11] using the measured average \( U_s \), \( u_{flyer} \), and the EOS of the copper flyer \((\rho_0 = 8.924 \pm 0.010 \text{ g/cm}^3, C_0 = 3.90 \pm 0.05 \text{ km/s}, S = 1.51) \) [12]. Calculation of the “combined” shock velocity and particle velocity will be described in a later section.

### Table 1. Summary data for near CJ plate impact experiments. \( u_P \) was calculated by impedance matching to the Cu flyer.

| Shot #   | \( u_{flyer} \) (km/s) | \( \Delta x \) (mm) | \( \Delta t \) (\( \mu \)s) | \( U_S \) (km/s) | \( u_P \) (km/s) |
|----------|------------------------|----------------------|-----------------------------|------------------|-----------------|
| 2s-680   | 2.594 ± 0.004          | 6.006 ± 0.007        | 0.813 ± 0.012               | 7.39 ± 0.11      | 1.963 ± 0.008   |
| 2s-700   | 2.575 ± 0.005          | 9.001 ± 0.016        | 1.202 ± 0.012               | 7.49 ± 0.08      | 1.942 ± 0.007   |
| 2s-681   | 2.569 ± 0.005          | 12.021 ± 0.017       | 1.597 ± 0.012               | 7.53 ± 0.06      | 1.935 ± 0.007   |
| Combined | 2.579 ± 0.012          |                      |                             | 7.67 ± 0.17      | 1.935 ± 0.014   |
| 2s-701   | 2.790 ± 0.003          | 6.009 ± 0.007        | 0.804 ± 0.012               | 7.48 ± 0.11      | 2.112 ± 0.008   |
| 2s-702   | 2.800 ± 0.002          | 9.006 ± 0.008        | 1.202 ± 0.012               | 7.49 ± 0.08      | 2.119 ± 0.007   |
| 2s-675   | 2.802 ± 0.003          | 12.006 ± 0.009       | 1.568 ± 0.012               | 7.66 ± 0.06      | 2.111 ± 0.006   |
| Combined | 2.797 ± 0.006          |                      |                             | 7.84 ± 0.17      | 2.096 ± 0.012   |
| 2s-674   | 3.008 ± 0.010          | 6.014 ± 0.013        | 0.796 ± 0.012               | 7.56 ± 0.12      | 2.280 ± 0.011   |
| 2s-633   | 3.018 ± 0.005          | 9.011 ± 0.008        | 1.184 ± 0.013               | 7.61 ± 0.08      | 2.285 ± 0.008   |
| 2s-634   | 3.011 ± 0.005          | 12.017 ± 0.009       | 1.564 ± 0.013               | 7.69 ± 0.06      | 2.274 ± 0.007   |
| Combined | 3.012 ± 0.008          |                      |                             | 7.81 ± 0.18      | 2.267 ± 0.014   |

Figure 2 shows wave profiles from 3 experiments with nominal impact velocity 2.6 km/s. Wave profiles are the velocity of the PBX 9502/LiF interface vs. the time after impact. All the profiles feature a von-Neumann spike with peak particle velocity \( \approx 2.3 \text{ km/s} \). Following the VN spike, the particle velocity drops to a plateau over the course of several hundred ns. The plateau indicates that the detonation is “supported” by the thick copper flyer. The VN spike and subsequent particle velocity drop indicate that the PBX 9502 is not turned instantly into products.

Figure 3 shows sample thickness, \( \Delta x \), plotted as a function of the shock transit time, \( \Delta t \). In this figure, the “combined” shock velocity is the slope of the line; \( U_S = 7.67 \pm 0.17 \text{ km/s} \). Note that the combined shock velocity calculated in this way is higher than the “average” shock velocity through a single sample.

#### 3.1. Uncertainty analysis

Uncertainties listed in table 1 were calculated as follows. Uncertainty in \( u_{flyer} \) is the standard deviation in the PDV measured projectile velocity over the \( \approx 1 \text{ \( \mu \)s} \) prior to impact. Uncertainty in \( u_{flyer} \) is a measured quantity.

Uncertainty in PBX 9502 sample thickness, \( \Delta x \), includes (1) the spread (not the standard deviation) in the measured thickness (2) the calculated glue layer thickness (3) the uncertainty in thickness due to not controlling the temperature. A linear coefficient of thermal expansion of 60 \( \mu \text{m/m-K} \) is used with an assumed temperature uncertainty of 10K. The total thickness uncertainty from not controlling the temperature is 0.6 \( \mu \text{m/mm} \). Uncertainty in \( \Delta x \) is a measured quantity.

Uncertainty in shock transit time, \( \Delta t \), includes (1) uncertainty in the height of the PDV probes relative to the surface of the explosive. This is assumed to be 10 \( \mu \text{m} \), the worst we have ever measured. Note that this position or distance uncertainty is divided by \( u_{flyer} \) to result in a time uncertainty. (2) uncertainty in the time when PDV probe is impacted \( \approx 1 \text{ ns} \) (3) uncertainty in time when the shock wave breaks out at the LiF window \( \approx 1 \text{ ns} \).
Lastly, there is uncertainty in $\Delta t$ caused by the flyer plate bow. In hindsight, we ought to have measured this. Flyer plate bow can cause significant differences in the edge to center plate impact time. For example, Mitchell and Nellis [13], using projectiles launched up to 7.5 km/s, reported flyer plate bows as large as 20 ns. If measured, flyer plate bow can be corrected for. Unfortunately, we did not measure bow and so cannot correct for it and must consider it as an uncertainty. How much uncertainty in $\Delta t$ is caused by flyer plate bow? We chose to use $\pm$ 12 ns because this value was a little greater than the largest time residual in the thickness vs. shock transit time fits (e.g. figure 3). We think 12 ns is a reasonable value, because it is the same order of magnitude as the 20 ns measured by Mitchell and Nellis. However, because we are launching to lower velocities, 3 km/s vs. 7.5 km/s, it is also reasonable to use 12 ns vs. 20 ns. Even so, the 12 ns uncertainty due to flyer plate bow controls the size of the total uncertainty in $\Delta t$.

Projectile to target impact tilt was measured and accounted for in the $\Delta t$ measurements. Typical tilt for this type of experiment is $\approx$ 3 mrads.

Uncertainty in $U_S$ for each shot was calculated using the uncertainties in $\Delta x$ and $\Delta t$ using Monte-Carlo methods. Likewise, Monte-Carlo methods were used to propagate and aggregate uncertainties into the calculated $u_P$. Note that uncertainties in $u_P$ are much smaller than uncertainties in $U_S$. This is because uncertainties in $u_P$ depend mostly on uncertainties in $u_{flyer}$ which are quite small.

3.2. Overdriven products Hugoniot

Figure 4 plots the “combined” Hugoniot points together with data from the literature [2, 4, 5] and the products Hugoniot developed by Wescott, Stewart, & Davis [1]. Given the scatter in the data sets and the error bars for our data, the WSD products Hugoniot is adequate.

4. Direct numerical simulations using the WSD reactive burn model

Figures 5, 6, and 7 show direct numerical simulations of shots 2s-680, 2s-701, and 2s-674 using the WSD reactive burn model. This model includes the reactant EOS, product EOS, and WSD reaction rates, [1] These shots used nominally 6 mm thick samples and had nominal impact velocities of 2.6, 2.8, and 3.0 km/s.

The numerical methods used for the WSD simulations was a 2nd order total variation
Figure 4. Hugoniot data for PBX 9502 products. Origin of the data is shown beside the symbol in the legend. The solid black line is the product Hugoniot of Wescott, Stewart, and Davis [1].

Figure 5. Wave profile from shot 2s-680 (green line) compared with WSD simulation (thin black line).

Figure 6. Wave profile from shot 2s-701 (blue line) compared with WSD simulation (thin black line).

Figure 7. Wave profile from shot 2s-674 (red line) compared with WSD simulation (thin black line).

diminishing Lagrangian method in conjunction with a linearized Riemann Solver that allows for arbitrary equations of state. The method is outlined in reference [14]. The initial Lagrangian grid spacing was 10 μm. The equation of state for Cu is that given by Anderson [12]: \( \rho_0 = 8.924 \text{ g/cm}^3, C_0 = 3.90 \text{ km/s}, S = 1.51, \Gamma_0 = 2.0, \rho \Gamma = \text{constant} \). The equation of state for LiF is from LASL Shock Hugoniot Data [15]: \( \rho_0 = 2.638 \text{ g/cm}^3, C_0 = 5.15 \text{ km/s}, S = 1.35, \Gamma_0 = 1.5, \rho \Gamma = \text{constant} \).

Compared to the experimental data, all simulations have slightly early wave arrival times. This could be due to \( U_S \) in the model being slightly too high or to reaction rates in the model that are slightly too high. Compared to the measured chemical reaction zone, the simulated reaction zone is short. This indicates a model reaction rate that is too high. Simulated quasi-steady plateau particle velocities, from 1.5 - 2.0 μs, are 1 - 2 % lower than experiment. All of these differences are within experimental error.

The biggest difference between experiment and the WSD numerical simulations is in the arrival time of the small step in \( \mu_P \) seen at \( \approx 2 \mu s \). This step originates when the initial shock interacts with the LiF window. A small amplitude shock is reflected back toward the Cu flyer and subsequently back to the LiF. Because the wave is low amplitude, the arrival time is closely tied to the sound speed in the detonation products. Compared to the experiment, the simulated
wave arrives late in all three cases. This indicates the WSD products EOS has a sound speed that is too low.

Wescott, Stewart, and Davis did not calibrate their products EOS to the sound speed data of Tang et al. [2]. This is likely the cause of the difference between experiment and simulation. It may be useful to try simulations with reactive burn models (eg. reference [6]) that calibrated to sound speed data.

5. Conclusions
Using gas-gun driven plate-impact techniques, we have measured $U_S$, $u_P$ Hugoniot points and interface velocity wave profiles in PBX 9502 shocked to 28 - 34 GPa. This is very near the CJ pressure of $\approx 28$ GPa. Uncertainties in $U_S$ and $u_P$ are of $O(2.3\%)$ and $O(0.7\%)$ respectively. Future experiments wishing to reduce these uncertainties might adopt a “top-hat” configuration, similar to that used by Green et al. [5]. In this configuration, it is possible to account for impactor bow, the largest source of uncertainty in these experiments, and also account for the initial unsteadiness of the shock waves, probably the largest source of uncertainty in the experiments of Tang et al. [2]. It should also be possible to measure interface velocity wave profiles.

Numerical simulations using the Wescott, Stewart, Davis reactive burn model [1] reproduced measured shock arrival times and measured interface velocities to within 1 - 2%. However, the calculated sound speeds in the products are too low.

Acknowledgements
Special thanks to Adam Pacheco and Larry Vaughn for operating the two-stage gas-gun.

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