Shock initiation sensitivity and Hugoniot-based equation of state of Composition B obtained using \textit{in situ} electromagnetic gauging

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Abstract. A series of gas gun-driven plate impact experiments were performed on vacuum melt-cast Composition B to obtain new Hugoniot states and shock sensitivity (run-distance-to-detonation) information. The Comp B ($\rho_0 = 1.713$ g/cm\textsuperscript{3}) consisted of 59.5\% RDX, 39.5\% TNT, and 1\% wax, with \~{}6.5\% HMX in the RDX. The measured Hugoniot states were found to be consistent with earlier reports, with the compressibility on the shock adiabat softer than that of a 63\% RDX material reported by Marsh.\textsuperscript{[4]} The shock sensitivity was found to be more sensitive (shorter run distance to detonation at a given shock input condition) than earlier reports for Comp B-3 and a lower density (1.68-1.69 g/cm\textsuperscript{3}) Comp B formulation. The reactive flow during the shock-to-detonation transition was marked by heterogeneous, hot spot-driven growth both in and behind the leading shock front.

1. Introduction
Composition B is a widely-used high explosive consisting of an approximately 60:40 ratio of RDX and TNT by weight, and is part of a larger class of melt castable explosives based on TNT. “Comp B” can be prepared by a variety of methods including vacuum melt, open melt or hot pressing, and with or without 1\% wax desensitizer \textsuperscript{[1]}. Despite its prevalence as a military explosive, there are only a few reports of unreacted equation of state (Hugoniot) data or measurements of shock initiation sensitivities of various Comp B formulations \textsuperscript{[2-10]}. Traditional Comp B consists of 59.5\% RDX, 39.5\% TNT, and 1\% wax desensitizer, and is melt-cast either under vacuum melt or open melt conditions to obtain bulk charges with densities of 1.713-1.715 g/cm\textsuperscript{3} or 1.680-1.690 g/cm\textsuperscript{3}, respectively. Historically, high quality melt castings of Composition B often resulted in a “richening” of the formulation with up to 4\% RDX; for example “LASL Comp B” contained 63\% RDX, 36\% TNT, 1\% wax \textsuperscript{[4]}. Composition B-3 is similar to Composition B, but contains no wax densensitizer, and can similarly, be prepared by (vacuum or open) melt casting, or hot pressing.

In the present work, gas gun-driven plate impact experiments were employed to: 1) obtain new unreacted shock (Hugoniot) states, and determine the shock sensitivity (Pop-plot) of vacuum melt Comp B, with comparisons with previous reports, and 2) apply \textit{in situ} electromagnetic gauging to investigate the reactive flow during and subsequent to the shock-to-detonation transition. Photonic
Doppler velocimetry (PDV) was also applied, for the first time, to measure the spatiotemporal characteristics of the detonation profile and chemical reaction zone following turnover to detonation.

2. Experimental

A vacuum melt-cast Composition B billet, 300 mm diameter × 57 mm thick, was machined into 1.7” diameter wedge samples for embedded electromagnetic gauging experiments as described previously. The properties of the Comp B used in this study are summarized in Table 1. The Comp B consisted of nominally 59.5% RDX (58.3 ± 1.1%), 39.5% TNT, and 1% wax by weight. The RDX was contaminated with 5.9% HMX by HPLC/MS, consistent with new Holston lots (6.5% HMX) recently received by LANL. A scanning electron micrograph illustrating the size and morphology of the RDX crystals in the formulation is shown in Figure 1A.

Table 1. Summary of properties of vacuum melt-cast Composition B.

| Property                   | Value                                      |
|----------------------------|--------------------------------------------|
| Formulation (by weight)    | 59.5% RDX                                 |
|                            | 39.5% TNT                                  |
|                            | 1.0% wax                                   |
| HMX % in RDX               | 5.9% a                                     |
| Initial density (g/cm³)    | 1.713 ± 0.004                              |
| Detonation velocity (km/s) | 7.92b                                      |
| Rankine-Hugoniot fit       | c₀ = 2.41 (± 0.27)                         |
|                            | s = 2.30 (± 0.36)                          |

a by HPLC-MS. b Reference [14].

Microsecond-duration, sustained shock waves were introduced into Comp B samples by gas gun-driven plate impact using a 50 mm bore launch tube two-stage light gas gun, described previously [11-13], to obtain projectile velocities of up to 2,034 km/s. The principal diagnostic in the experiments was electromagnetic gauging [13], which allows for measurement of particle velocity wave profiles at up to 10 Lagrangian positions in the sample, including at the impact interface. Figure 1B shows a photograph of an assembled Comp B target showing a stirrup gauge on the impact face, and embedded gauge at a 30° angle in-material.

Figure 1. (A) Scanning electron micrograph of melt cast Comp B following a toluene-etch to remove the TNT. The RDX crystals have particle sizes from ~25 - 250 µm. (B) Photograph of assembled target, showing the stirrup gauge on the impact face, and embedded gauge at a 30° angle in-material.
A Lexan projectile fitted with a Kel-F 81 polymer impactor was impacted into the Comp B targets at velocities ranging from 1.321-2.034 km/s using the LANL two stage light gas gun [12]. A single experiment was performed using a z-cut sapphire impactor launched by a 72 mm bore single stage light gas gun [15]. The error in measured projectile velocity is ~0.1%, and is reported for each experiment in table 2.

3. Results and Discussion
A total of six plate impact experiments were performed on Comp B, with shock input stresses ranging from 1.0 to 8.4 GPa. In all of the two-stage experiments, Comp B shock initiated to detonation, and features of the reactive flow along the shock-to-detonation transition were measured in situ. Comp B initiates via a heterogeneous initiation mechanism derived from hot spot-driven reactive growth, as evidenced by an increase in particle velocity, both in and behind the shock front, similar to heterogeneous plastic-bonded explosives [11]. In contrast to explosives based on HMX, TATB, and TNT studied by these authors, electrical noise was measured on the embedded gauges up to a condition near the turnover to detonation, which is believed to be due to piezoelectric effects in RDX. Example particle velocity wave profiles from shot 2s-685 are shown in figure 3A. The response of the right shock tracker is shown in figure 3B, which illustrates the disappearance of electrical noise near the turnover to detonation. In shot 2s-685, Comp B was shocked to 6.6 GPa, and turnover to detonation is observed between gauges 5 and 6, or \( t^* = 1.03 \pm 0.07 \) µs and \( x^* = 4.8 \pm 0.1 \) mm.
Figure 3. A) Response of the stirrup gauge and 9 embedded particle velocity trackers in shot 2s-685, with a shock input stress of 6.6 GPa. Turnover to detonation is observed between gauges 5 and 6 or $t_D = 1.03 \pm 0.07$ $\mu$s and $x_D = 4.8 \pm 0.1$ mm. B) Example of the response of the right shock tracker in the same experiment.

Table 2. Summary of unreacted Hugoniot states, and run-distance/time-to-detonation for vacuum melt-cast Comp B as a function of shock input stress (GPa). Also included are the early-time detonation velocities measured in the experiments. *Detonation velocities are the average values measured using 3 shock tracker elements in each experiment, except for shot 2s-710 which was obtained using the center shock tracker.

| Shot #  | Projectile velocity (km/s) | Initial particle velocity (mm/µs) | Initial shock velocity (mm/µs) | Shock input stress (GPa) | $x_D$ (mm) | $t_D$ (µs) | Meas. detonation velocity (km/s) |
|---------|-----------------------------|----------------------------------|--------------------------------|---------------------------|------------|------------|-------------------------------|
| 2s-683  | 2.034 ± 0.001               | 1.005 ± 0.008                    | 4.86 ± 0.01                    | 8.4 ± 0.1                 | 3.3 ± 0.2 | 0.67 ± 0.02 | 7.556 ± 0.045                |
| 2s-685  | 1.704 ± 0.001               | 0.835 ± 0.015                    | 4.58 ± 0.02                    | 6.6 ± 0.1                 | 4.8 ± 0.1 | 1.03 ± 0.07 | 7.990 ± 0.010                |
| 2s-708  | 1.871 ± 0.006               | 0.939 ± 0.020                    | 4.50 ± 0.03                    | 7.2 ± 0.1                 | 3.9 ± 0.1 | 0.80 ± 0.02 | 7.737 ± 0.068                |
| 2s-709  | 1.553 ± 0.002               | 0.785 ± 0.020                    | 4.09 ± 0.03                    | 5.5 ± 0.1                 | 5.7 ± 0.2 | 1.29 ± 0.02 | 8.134 ± 0.034                |
| 2s-710  | 1.321 ± 0.001               | 0.679 ± 0.015                    | 3.69 ± 0.03                    | 4.3 ± 0.1                 | 8.4 ± 0.1 | 2.08 ± 0.05 | 7.993 ± 0.013*               |
| 1s-1563 | 0.235 ± 0.001               | 0.029 ± 0.002                    | 3.19 ± 0.02                    | 2.98 ± 0.01               | 0.16 (HEL) | 1.04       | N/A                           |

3.1. Unreacted Hugoniot

The unreacted Hugoniot data, table 2, are plotted in the pressure-particle velocity ($P-u_p$) plane in figure 5A, along with experimental data reported by Marsh [4] and Lemar [3], and linear Rankine-Hugoniot relationships ($U_s = c_0 + su_p$) by Coleburn and Liddiard [2], and Urtiew et al. [7-8]. A linear Rankine-Hugoniot fit to the new Hugoniot data in the $U_s-u_p$ plane to 8.4 GPa is $U_s = 2.41 (\pm 0.27) + 2.30 (\pm 0.36)u_p$. As seen in the figure, there is qualitative agreement of the new unreacted Hugoniot states with those reported by references 2 and 7, but softer behavior than in Ref. 4 due to a lesser RDX content in the material studied here. An increase in scatter in the experimental data is observed as the input shock pressure is increased into the initiation regime, consistent with other explosives. In a
single experiment (1s-1563), a quasi-elastic limit was measured, \( u_{p,el} = 0.029 \text{ mm/\( \mu \)s}, U_{s,el} = 3.185 \text{ mm/\( \mu \)s}, P_{HEL} = 0.16 \text{ GPa}, \) and a low pressure Hugoniot state below \( u_p = 0.5 \text{ mm/\( \mu \)s}.

3.2. Initiation mechanism and Pop-plot

Comp B initiates via a heterogeneous initiation mechanism in which there is a continual increase in the shock and particle velocities in the front leading to detonation. There are marked similarities between Comp B, and plastic-bonded explosives, such as PBX 9501, in which the peak particle velocity associated with reactive burn lags the initial shock wave in space and time [11]. Also notable is the large increase in particle velocity from the unreacted shock input condition to the von Neumann condition at the front of the detonation wave. Following turnover, the detonation is nearly steady, similar to other heterogeneous explosives, and the measured detonation velocities are reasonably consistent with the reported steady detonation velocity \( D_s = 7.92 \text{ km/s} \) [15].

From the embedded gauge records, the run distance and time to detonation were determined to < 5%. The Pop-plot for vacuum melt Comp B is overlaid with that of Comp B-3 from Ramsay [5-9], and Urtiew [7-8] for a lower density formulation in figure 4B. The vacuum-melt Comp B was found to be more sensitive than previous reports, with the run distance being shorter by >5 mm at some input conditions. The detonation profile, measured at the PMMA window, showed a peak interface particle velocity \( u_p \sim 3.7 \text{ km/s}, \) with a fast (~ 10-15 ns) and slow (~ 200 ns) component, figure 5. Further analysis of the unreacted and product equations of state are on-going to estimate the chemical reaction zone length for Comp B.

![Figure 4](image)

Figure 4. A) Unreacted Hugoniot loci obtained for vacuum melt Comp B, overlaid with data and/or fits from previous works, and the linear Rankine-Hugoniot fit to the Hugoniot loci in the pressure-particle velocity plane. B) Pop-plot for vacuum melt Comp B shown with reported Pop-plots for a lower density formulation (Urtiew) and for Comp B-3 from Ramsay.

4. Conclusions

A series of shock initiation experiments have been performed on vacuum melt Composition B with an initial density of 1.713 g/cm\(^3\). From multiple in situ embedded electromagnetic gauges, new unreacted Hugoniot and run-distance (time)-to-detonation data are presented. Comp B initiates by a hot spot-driven “heterogeneous” initiation mechanism, with reactive growth close both in and behind shock front. The shock sensitivity of the vacuum melt formulation is greater than that reported by Ramsay (Comp B-3) [5-9] and Urtiew et al. [7-8]. Future work will compare the shock sensitivity and chemical reaction zone of vacuum melt Comp B with pressed Comp B-3 and related formulations.
Figure 5. Photonic Doppler velocimetry spectrogram of the particle velocity wave profile recorded at the Comp B-PMMA windowed interface, 23.00 mm from the impact face in shot 2s-709.

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