Shock initiation experiments with ignition and growth modeling on low density HMX

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Abstract Shock initiation experiments on low density (~1.2 and ~1.6 g/cm³) HMX were performed to obtain in-situ pressure gauge data, characterize the run-distance-to-detonation behavior, and provide a basis for Ignition and Growth reactive flow modeling. A 101 mm diameter gas gun was utilized to initiate the explosive charges with manganin piezoresistive pressure gauge packages placed between packed layers (~1.2 g/cm³) or sample disks pressed to low density (~1.6 g/cm³). The measured shock sensitivity of the ~1.2 g/cm³ HMX was similar to that previously measured by Sheffield et al. and the ~1.6 g/cm³ HMX was measured to be much less shock sensitive. Ignition and Growth model parameters were utilized that yielded good agreement with the experimental data at both initial densities.

1. Introduction
Increase in shock sensitivity at low density is a concern for safety scenarios as a result of the higher hazard present. To investigate these low density scenarios, a series of Shock Initiation experiments were performed using pour density and low density pressings of HMX with 2 different densities: lightly tamped (hand packed into rings) HMX (~1.2 g/cc / ~65% TMD) and pressed to low density (~1.6 g/cc / ~86% TMD, 50 mm diameter). These experiments with Class 1 HMX were done in a similar fashion to other experiments performed on HMX based [1] and Triaminotrinitrobenzene (TATB) based [2] explosive formulations. Earlier work by Sheffield [3] has been performed on low density HMX and will be compared to the results provided. This paper will detail the procedures used for the testing, present the run-distance-to-detonation data in the form of a “Pop-plot” with comparisons to other data, discuss the gauge records for the experiments with comparisons to the associated Ignition and Growth modeling results, and outline future work.

2. Experimental Procedure
The shock initiation experiments were performed using the 101 mm diameter propellant driven gas gun at LLNL. Figure 1 shows a schematic of the experimental setup used in the testing. The projectile consisted of a multi-component Mod II sabot with a 6061 Aluminum (Al) flyer on the impact surface. As seen in figure 1 the target includes a 6061 aluminum buffer plate on the front of the explosive and backed by a Teflon disk. The explosive consisted of thin disks as shown (nominally 50 mm diameter by 3, 5, or 10 mm thick) of explosive material with the gauge packages inserted in between for the low density pressings as shown in figure 1 or Teflon rings (90 mm outer diameter and 70 mm inner diameter in thicknesses of 3,4,5,7, and 10 mm thick) that are hand packed with the Class 1 HMX powder for the lowest density experiments. The assembly of the hand packed powder into rings was...
performed by stacking each ring of desired thickness and hand packing each layer before adding a gauge package and the next ring until the assembly was complete. The Class 1 HMX was measured to have a mean particle size of $52 \pm 5.2 \, \mu m$ with an appreciable range of particles from approximately 1 to 220 $\mu m$.

Manganin piezoresistive foil pressure gauges (nominally 25 $\mu m$ thick) were placed within the explosive sample and were “armored” with sheets of Teflon insulation (nominally 125 $\mu m$ thick) on each side of the gauge. Manganin is a copper-manganese alloy that changes electrical resistance with pressure (i.e. piezoresistive). Other researchers have used electromagnetic velocity gauges with similar results [4] except the particle velocity is measured instead of the pressure. From figure 1, lead zirconium titanate piezoelectric crystal pins were used to measure the projectile velocity and tilt (planarity of impact). During the experiment, oscilloscopes measure the gauge voltage traces over time that are converted to pressure traces over time by using the hysteresis corrected calibration curve published elsewhere [5,6]. Stretching of foil gauges is a concern, since as the gauge stretches it causes a resistance change in the foil that appears as a fictitious pressure increase. This stretching usually occurs later in time when the two-dimensional effects reach the gauge locations. From the data of the shock arrival times of the gauge locations, a plot of distance vs. time (“x-t plot”) is constructed with the slope of the plotted lines yielding the shock velocities with two lines apparent, a line for the un-reacted state as it reacts and a line representing the detonation velocity. The intersection of these two lines is taken as the “run-distance-to-detonation,” which is then plotted on the “Pop-plot” [7] showing the run-distance-to-detonation as a function of the input pressure in log-log space.

![Figure 1. Schematic of one of the configurations used in the testing with a 101 mm diameter gun showing the sabot impacting a 50 mm diameter target built with target disks with gauge packages in between. The other configuration used rings of Teflon that were hand packed with HMX powder between gauge packages.](image)

**3. Ignition and Growth Reactive Flow Modeling**

Since not all possible scenarios involving condensed phase High Explosive (HE) shock initiation and detonation can be tested experimentally, hydrodynamic computer reactive flow models are developed and implemented in one-, two-, and three-dimensional codes to predict the effects of shock initiation and detonation in complex geometries. The Ignition and Growth reactive flow model of shock initiation and detonation [8] has been used to understand many shock initiation and detonation studies of solid explosives and propellants in several codes. The model uses two Jones-Wilkins-Lee (JWL) equations of state, one for the unreacted explosive and one for reaction products, in the temperature dependent form:

\[
p = A e^{-R_Y} + B e^{-R_Y} + \omega C_v T / V
\]

where $p$ is pressure, $V$ is relative volume, $T$ is temperature, $\omega$ is the Gruneisen coefficient, $C_v$ is the
average heat capacity, and $A$, $B$, $R_1$ and $R_2$ are constants. The reaction rate equation is:

$$\frac{dF}{dt} = I_1 - F \rho / \rho_0 - 1 - a(x < F < F_{\text{Fig max}}) + G_1 1 - F \rho \gamma + G_2 (1 - F)^{\gamma} \rho \gamma$$

where $F$ is the fraction reacted, $t$ is time in $\mu$s, $\rho$ is the current density, $\rho_0$ is the initial density, $p$ is pressure in Mbars, and $I$, $G_1$, $G_2$, $a$, $b$, $c$, $d$, $e$, $g$, $x$, $y$, and $z$ are constants.

The exact details of each gas gun experiment were modeled in LS-DYNA [9] using 50 zones per mm in the explosive and the Teflon coated manganin gauges. The thin manganin element is placed at the center of a 0.3 mm thick Teflon gauge package. The calculated pressure history in the eighth of the 15 zones in each gauge package is compared to the measured pressure history. The equations of state for the inert materials (aluminum and Teflon) [10] used in these experiments are the same as previous work [1,2]. The Ignition and Growth parameters for porous HMX were similar to that detailed in earlier work on HMX [1] with some minor changes. For the 1.24 g/cc experiments, the density was updated, the $A$ and $B$ values of the unreacted equations of state were changed to $A=1000$ Mbar, $B=-0.033177$ Mbar and the $F_{\text{fig max}}$ was adjusted to 0.30. For the 1.64 g/cc experiments, the density was updated, the $A$ and $B$ values of the unreacted equations of state were changed to $A=4198$ Mbar, $B=-0.043033$ Mbar and the $F_{\text{fig max}}$ was adjusted to 0.10. The values of $A$ and $B$ are influenced by the lower sound velocities and the $F_{\text{fig max}}$ adjustment results in igniting more reaction near the shock front to reflect the higher number of hot spots with the decrease in density. The goal of the fitting was to reasonably match the run distances without simulating unrealistic pressures. For future work, a better approach may be to formulate a more complete description of the unreacted porous material for a best fit to the experimental data.

4. Results and Discussion
A summary of the experiments discussed here is provided in table 1 below. A nominal average density of each assembly is provided in the table below with the hand packed powder being ~1.24 g/cc (~65% TMD) and the low density pressed disks of ~1.64 g/cc (~86% TMD). Figure 2 shows the Pop-plot of the material compared to other materials. The Class 1 HMX data shows an increase in shock sensitivity with a decrease in density and reasonable agreement to the experiments in the earlier work by Sheffield [4] at ~65% density. The ~86% dense points fall between the ~65% dense points and the full density line. Due to the porous nature of the material with gauge records not being as clean as full density material, the error bars on the plot are large as a result. For reference, a line (on the log-log plot) was added to the data to provide a generalized fit for the eye to follow in this region. The lines for LX-10 at ~98% density and PBX9404 at ~98% and ~92% density are shown for reference.

| Shot | Velocity | Sabot | Flyer Plate | Impact Plate | Input Pressure | Run to Det |
|------|----------|-------|-------------|--------------|----------------|------------|
| 4788 | 577 m/s  | Mod II| 6061 Al     | 6061 Al      | 1.3 GPa        | 4 mm       |
| 4789 | 351 m/s  | Mod II| 6061 Al     | 6061 Al      | 0.8 GPa        | 6 mm       |
| 4790 | 545 m/s  | Mod II| Teflon      | 6061 Al      | 0.4 GPa        | 8.6 mm     |

Pressed disks to low density, ~1.64 g/cc, ~86% TMD

| Shot | Velocity | Sabot | Flyer Plate | Impact Plate | Input Pressure | Run to Det |
|------|----------|-------|-------------|--------------|----------------|------------|
| 4793 | 690 m/s  | Mod II| 6061 Al     | 6061 Al      | 2.8 GPa        | 4.2 mm     |
| 4794 | 392 m/s  | Mod II| 6061 Al     | 6061 Al      | 1.3 GPa        | 8.3 mm     |

The in-situ gauge records are compared with the ignition and growth modeling simulations in figures 3 (experiments 4788 and 4789 at 65% TMD) and 4 (experiments 4793 and 4794 at 86% TMD). In comparing the records in figure 3, it can be seen that the general shape is reproduced, but the shock
timing is not reproduced well. Some gauge stretching and failures is seen at later time due to the low density of the material, but this can be expected as a result of the powder crushing up in the process. For the comparison of the records in figure 4, a better overall fit than figure 3 is seen with some slight variations in timing being evident.

**Figure 2.** The Pop-plot showing the ~65% and ~86% dense class 1 HMX experiments with comparisons to other HMX work at varying densities.
Figure 3. Comparisons of the lowest velocity (experiment 4788 on left) and highest velocity (experiment 4789 on right) experiments in table 1 performed at ~65% TMD with the ignition and growth modelling results on top and the experimental gauge records on the bottom.

Figure 4. Comparisons of the experiments performed at ~86% TMD (experiment 4793 on left and 4794 on right) from table 1 with the ignition and growth modelling results on top and the experimental gauge records on the bottom.

5. Summary and Future Work
A set of experiments was performed using Class 1 HMX explosive at 2 different densities (~65% and ~86% TMD). Modeling of the experiments was performed using the LS-DYNA hydrocode with the Ignition and Growth model with a previous parameter set with some adjustments. On the Pop-plot, Class 1 HMX shows a reasonable agreement to earlier work with minimal scatter in the data set. Additional work is underway to complete some additional experiments that will likely include an update of the parameter set and unreacted material descriptions in order to obtain a best fit over the range of experiments.

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