Preliminary investigations of HE performance characterization using SWIFT

M J Murphy* and C E Johnson*

*W-6 Detonator Technology, Los Alamos National Laboratory, Los Alamos, NM 87545, USA.
E-mail: mjauphen@lanl.gov

Abstract. Preliminary experiments are performed to assess the utility of using the shock wave image framing technique (SWIFT) to characterize high explosive (HE) performance on detonator length and time scales. Columns of XTX 8004, an extrudable RDX-based high explosive, are cured directly within polymethylmethacrylate (PMMA) dynamic witness plates, and SWIFT is employed to directly visualize shock waves driven into PMMA through detonation interaction. Current experiments investigate two-dimensional, axisymmetric test geometries that resemble historic aquarium tests, but on millimeter length scales, and the SWIFT system records 16-frame, time-resolved image sequences at 190 ns inter-framing. Detonation wave velocities are accurately calculated from the time-resolved images, and standard aquarium-test analysis is evaluated to investigate calculated shock pressures at the HE/PMMA interface. Experimental SWIFT results are discussed where the charge diameter of XTX 8004 is varied from 2.0 mm to 6.5 mm.

1. Introduction
The performance of high explosives (HE) in detonator-scale geometries (~10 mm) has historically been difficult to characterize using traditional 1-D experimentation. While under detonation, such HE charge geometries have small aspect ratios and non-negligible curvatures that yield multi-dimensional and divergent flows. With the exception of aquarium testing (see [1]), which employs a 2-D photographic technique, standard HE performance characterizations are typically performed using strictly 1-D diagnostics (see [2–4]) in order to avoid convoluted experimental results. However, in order to understand the performance of HE at detonator length scales, as well as to accurately model that performance using numerical hydro-codes, multi-dimensional experimental data is required to calibrate HE performance parameters and validate model results.

In this work the shock wave image framing technique (SWIFT) (see [5]) is employed to investigate detonator-scale HE charge output in a manner similar to aquarium testing, but on millimeter length scales. Experiments directly visualize explosive output within polymethylmethacrylate (PMMA) confinement using higher temporal, spatial, and multi-frame resolution than was available and/or practiced decades earlier. Since the SWIFT system effectively observes HE charges perform work on transparent solid media in real time, the resulting image sets are rich in information that is directly relevant to the understanding and characterization of how the explosive performs in detonator-scale geometries.

In the discussion that follows, preliminary results are presented for a series of SWIFT
experiments with the intent of introducing the novel extension of the diagnostic to detonator-scale HE performance characterization for the first time.

2. Experimental
Current experiments examine the output of XTX 8004, an extrudable high explosive, having a composition by weight of 80% RDX and 20% Sylgard 182 silicone elastomer. Uncured XTX 8004 has a putty-like consistency that allows it to be easily loaded and cured within PMMA dynamic witness plates that are pre-machined with precise cylindrical cavities to lightly confine the cured HE charges. Each witness plate is machined from optical grade PMMA to have two opposing surfaces that are flat, parallel, and hand polished to a high-quality finish. PMMA is chosen based on its optical clarity, mechanical properties, machinability, and known shock Hugoniot parameters (provided in [6]). Density and longitudinal sound velocity are measured as $1.187\pm0.001\ \text{g/cm}^3$ and $2.73\pm0.03\ \text{mm/\mu s}$, which compare well with historic PMMA material characterized in [6].

The SWIFT test series consists of ten experiments, where the HE charge diameter is systematically reduced from 6.5 mm to 2.0 mm in 0.5 mm decrements. Since the charge length is kept fixed at 23 mm, nominal length-to-diameter ($L/d$) ratios range from 3.5 to 12 in the test series. Conventional wisdom suggests $L/d \geq 10$ for the development of a steady detonation wave within cylindrical HE charges. However, such a large aspect ratio potentially precludes performance effects due to detonator scaling that are under investigation in this work, such as the transient development of steady detonation. Hence, by design, focused efforts are not made to ensure steady detonations develop in all of the test charges.

All SWIFT data presented in the ensuing discussion are recorded using a SIMD-16 (Specialised Imaging) ultra-high-speed framing camera coupled with a pulsed, spoiled-coherence, laser backlight (Cavilux OEM diode laser, distributed by Specialised Imaging as an SI-LUX model). The high-power laser source is optimized for operation with SIM cameras, and has the flexibility to output 400 W in pulse widths that range from 10 ns up to 30 $\mu$s with a nominally flat intensity profile. The SWIFT system is configured for 5 ns camera exposures to effectively freeze the motion of the visualized shock waves, 190 ns inter-frame delays to capture detonation of the entire HE charge length in a 16-frame image sequence, and a single 3 $\mu$s laser pulse to backlight the event. Currently, the SWIFT system can record sixteen total images at frame rates up to 16 MHz or eight images at frame rates up to 200 MHz; however, the system is not limited to operating at fixed frame rates, and is frequently operated at variable framing to record highly unsteady phenomena. Additional details on the SWIFT diagnostic can be found in [5].

3. Results and Discussion
Representative SWIFT images are displayed in figure 1 that capture the evolution of explosively-driven shocks resulting from detonation of a 2.0 mm diameter cylindrical charge of XTX 8004 confined within PMMA. Notice the 3 $\mu$s pulse width of the laser backlight uniformly illuminates all 16 image frames, and only minor interference fringes are visible due to internal reflections within the beam-splitting architecture of the camera. The spherical shock wave propagating above the HE charge results from the output of the detonator used to initiate the charge from the top end. The angled shocks correspond to the radial loading of PMMA by detonating XTX 8004 as the detonation front propagates downward at velocity $D$.

Figure 2 displays a plot of measured shock positions along the PMMA/XTX 8004 interface as a function of discrete camera exposure times. Both left- and right-hand sides of the HE charge are examined to investigate the developed symmetry of the flow. A pronounced linear trend is observed in the measurements that suggests a steady detonation wave has developed for $L/d = 12$. Since velocity transients exist while steady detonation is developing, an iterative fitting method is employed to help identify and exclude appropriate data points from subsequent
fitting. Specifically, initial data points are systematically excluded from a linear, least-squares fit until the calculated slope converges to within ±10 m/s. As depicted in figure 2, convergence is reached after excluding the first two data points from the fit calculation. Resulting detonation velocities from the left- and right-hand sides agree to within a 0.22 percent difference. Notice by excluding two data points from the linear fit one can bound the run distance to steady detonation as ≥4.6 mm, or 2.3 charge diameters.

Historic results for the detonation velocity of XTX 8004 as a function of charge diameter and polycarbonate confinement (see [7]) are plotted in figure 3 along with the results of current SWIFT experiments. Both data sets are in good agreement which suggests PMMA and polycarbonate provide similar explosive confinement. The uncertainty bounds on detonation velocities obtained from SWIFT data increase with charge diameter due to an increase in the number of data points excluded from the linear, least-squares fitting routine. In other words, the run distance to steady detonation increases with charge diameter, as expected. For the case of the 6.5 mm XTX 8004 charge diameter, $L/d = 3.5$, and the calculated fit suggests the detonation

---

**Figure 1.** Representative SWIFT data for a 2.0 mm diameter cylindrical charge of XTX 8004 confined in PMMA.

**Figure 2.** Evolution of detonation wavefront position for XTX 8004 in PMMA confinement.

**Figure 3.** Dependence of XTX 8004 detonation velocity on HE charge diameter for polycarbonate and PMMA confinement.

**Figure 4.** Comparison of historic $U_s - u_p$ velocity-Hugoniot data for PMMA and polycarbonate.
wave propagates at least 8.1 mm before steady detonation appears to develop. Figure 4 compares velocity-Hugoniot data for 1.186 g/cm$^3$ PMMA and 1.193 g/cm$^3$ polycarbonate (from [6]) to support the observation that both materials confine XTX 8004 similarly. Notice the $U_s$-$U_p$ data for each material are nearly identical for shock pressures up to nominally 19 GPa, and the material densities compare to within a 0.6 percent difference.

From figure 3, the sub-percent fractional uncertainties on detonation velocities extracted from SWIFT data are on par with measurements obtained using established pin-switch techniques in 1-D rate-stick experiments (see [3]). However, the extraction of $D$ only utilizes axial information from the 2-D axisymmetric data. By considering the recorded SWIFT images as pseudo-aquarium data, where PMMA replaces water as the immersion medium, standard aquarium-test analysis described in [8, 9] is under evaluation to calculate radial shock pressures at the PMMA/XTX 8004 interface based on the angled shock-front data.

Shock-front curves are extracted from SWIFT images using a Canny edge-detection algorithm, and example curves are included in figure 5 that correspond to the SWIFT images displayed in figure 1. The circular data points plotted along the PMMA/XTX 8004 interfaces denote the measured shock positions used for the determination of $D$. Additionally, the interface points also act as reference points for combining all of the edge-detected curves into an ensemble that describes the radial position of the shock waves in PMMA as a function of axial position behind the detonation wave. Grouping of the individual curves into a tight ensemble provides additional evidence that the developed detonation waves are steady. The intersection points of the slanted, dashed lines with the edge-detected curves qualitatively denote cropping points for each curve that are used to exclude detonator shock information from affecting the trend of the ensemble shock-front data.

![Figure 5](image)

**Figure 5.** Compilation of edge-detected curves representing dynamic shock-front data from a pseudo-aquarium SWIFT experiment.

![Figure 6](image)

**Figure 6.** Ensemble shock-front data from pseudo-aquarium SWIFT results and corresponding aquarium analysis results.

Two ensemble curves corresponding to 2.0 mm and 6.5 mm diameter XTX 8004 charges are included in figure 6 along with corresponding curve fits obtained using the following model equation from [8]

$$r(z) = r_0 + \tan(\theta_{\text{min}}) \left[ z + \frac{1}{a} \left( \frac{\tan(\theta_{\text{max}})}{\tan(\theta_{\text{min}})} - 1 \right) (1 - e^{-az}) \right],$$  \hspace{1cm} (1)

where $r_0$, $a$, and $\tan(\theta_{\text{max}})$ are parameters obtained from least-squares fitting methodology. The parameter $\tan(\theta_{\text{min}})$ is calculated for each experiment using the measured value for detonation...
velocity ($D$) and the known bulk sound velocity ($C_0$) for PMMA as

$$\tan(\theta_{\text{min}}) = \frac{C_0/D}{\sqrt{1-(C_0/D)^2}}.$$  \hspace{1cm} (2)

For simplicity, only data corresponding to the smallest and largest XTX 8004 charge diameters are displayed in figure 6 to cover the full range of measurements.

Following [9] as a guide, momentum conservation across a shock is used to combine $\theta_{\text{max}}$ and $D$ with the known shock-compression behavior of PMMA to calculate the shock pressure at the explosive interface as

$$p_s(\theta_{\text{max}}) = \frac{\rho_0}{s} [D \sin(\theta_{\text{max}}) - C_0] D \sin(\theta_{\text{max}}).$$  \hspace{1cm} (3)

In equation (3), $\rho_0$ is the material density, and $s$ is the slope of a straight-line fit to the 1st leg of the $U_s$-$u_p$ Hugoniot data for PMMA displayed in figure 4. Calculated results for shock pressure at the PMMA/XTX 8004 interface as a function of charge diameter are plotted in figure 7 with estimated errorbars of ±0.5 GPa. The upward trend in the data suggests the interface pressure, and subsequent radial shock-loading, increase with HE charge diameter. Figure 8 supports this observation visually by comparing corresponding image frames from each SWIFT experiment.

At this time, there is no way to validate the accuracy of the calculated pressure results obtained using aquarium analysis without historic or existing data to compare to. Analysis is ongoing to evaluate the results of applying additional fit-model equations to pseudo-aquarium SWIFT data with the intent of establishing a converged set of fit parameters, with emphasis on $\theta_{\text{max}}$.

**Figure 7.** Calculated pressure at the PMMA/XTX 8004 interface using traditional aquarium analysis.

**Figure 8.** Select frames from each of the ten SWIFT experiments that depict the dependence of radial explosive loading on HE charge diameter. Nominal $L/d$ ratios increase from 3.5 to 12 as the charge diameter decreases from 6.5 mm to 2.0 mm. Transparent regions behind the shocks become more pronounced as the pressure reduces.

4. Conclusions

The SWIFT diagnostic is successfully extended to the performance characterization of millimeter-sized explosive charges through a miniaturized method similar to aquarium testing. In the new method the confinement medium is extended to transparent solids in place of water, and specific results are presented for charges of XTX 8004 confined in PMMA. Detonation velocities extracted from the results are obtained to within sub-percent fractional uncertainties for ten different HE charge diameters, and the results significantly extend the understanding of how charge diameter affects the detonation velocity of XTX 8004. Standard aquarium-test
analysis is applied to 2-D shock-front data to calculate shock pressures at the explosive/PMMA interface, and the results are consistent with raw SWIFT images that demonstrate a significant decrease in radial shock loading of PMMA as HE charge diameter is reduced. Additional analyses are under development to investigate the accuracy of aquarium analysis results.

Acknowledgements
Funding was provided by the Joint DoD/DOE Munitions Program. The authors wish to thank Michael Martínez and Dennis Jaramillo for handling, fixturing, and firing the explosive shots, as well as Kristen Wilding for assisting with SWIFT data reduction. Los Alamos National Lab is operated by Los Alamos National Security, LLC, under Contract No. DE-AC52-06NA25396.

References
[1] Craig B G, Johnson J N, Mader C L and Lederman G F 1978 Characterization of two commercial explosives Los Alamos Scientific Laboratory Tech. Rep. LA-7140
[2] Kury J W, Hornig H C, Lee E L, McDonnel J L, Ornellas D L, Finger M, Strange M L and Wilkens M L 1965 Metal acceleration by chemical explosives Proceedings Fourth Symposium (International) on Detonation (October 12-15, 1965 White Oak) pp 3-12
[3] Campbell A W and Engelke R 1976 The diameter effect in high-density heterogeneous explosives Proceedings Sixth Symposium (International) on Detonation (August 24-27, 1976 Coronado) p 642
[4] Alcon R R, Sheffield S A, Martínez A R and Gustavsen R L 1998 Magnetic gauge instrumentation on the LANL gas-driven two-stage gun AIP Conf. Proc. 429 p 845
[5] Murphy M J and Clarke S A 2013 Ultra-high-speed imaging for explosive-driven shocks in transparent media Dynamic Behavior of Materials, Volume 1: Proceedings of the 2012 Annual Conference on Experimental and Applied Mechanics (June 11-15, 2012 Costa Mesa) eds. V Chalivendra et al. pp 425-432
[6] Marsh S P 1980 LASL Shock Hugoniot Data (University of California Press)
[7] Gibbs T R and Popolato A 1980 LASL Explosive Property Data (University of California Press)
[8] Johnson J N 1982 Calculated shock pressures in the aquarium test AIP Conf. Proc. 78 pp 568-572
[9] Johnson J N, Mader C L and Goldstein S 1983 Performance properties of commercial explosives Propellants, Explosives, Pyrotechnics 8 pp 8-18