LLNL-PROC-415380

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August 6, 2009

International Conference of the APS Topical Group on Shock Compression of Condensed Matter
Nashville, TN, United States
June 28, 2009 through July 3, 2009

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TIME-SEQUENCED X-RAY OBSERVATION OF A THERMAL EXPLOSION

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Abstract. The evolution of a thermally-initiated explosion is studied using a multiple-image x-ray system. HMX-based PBX 9501 is used in this work, enabling direct comparison to recently-published data obtained with proton radiography [1]. Multiple x-ray images of the explosion are obtained with image spacing of ten microseconds or more. The explosion is simultaneously characterized with a high-speed camera using an interframe spacing of 11 µs. X-ray and camera images were both initiated passively by signals from an embedded thermocouple array, as opposed to being actively triggered by a laser pulse or other external source. X-ray images show an accelerating reacting front within the explosive, and also show unreacted explosive at the time the containment vessel bursts. High-speed camera images show debris ejected from the vessel expanding at 800-2100 m/s in the first tens of µs after the container wall failure. The effective center of the initiation volume is about 6 mm from the geometric center of the explosive.

Keywords: Thermal explosion, radiography, HMX, x-ray.
PACS: 82.33.Vx, 87.59.B, 82.30.Lp, 47.40.Nm.

INTRODUCTION

For improved safety and effectiveness, it is of significant interest to understand the behavior of PBX 9501 (95% HMX, 2.5% Estane, 2.5% NC) in its thermally-damaged state, especially above the 162 C HMX β-to-δ phase transition temperature [2, 3]. In particular, it would be useful to develop a more robust predictive capability for the thermal runaway condition and better estimates of the violence of the resulting explosion. Recent studies with proton radiography revealed important details of thermal explosion phenomena [1, 4, 5]. These studies successfully synchronized the imaging system with the explosion using an active laser trigger. The present work employs flash x-ray radiography and builds on these studies by using a common test geometry and similar thermal measurement methods. However, work reported here differs in that the x-ray imaging system allows for greater flexibility with respect to image timing and viewing angle, although at somewhat lower spatial resolution compared with proton radiography. The x-ray system also allows a larger field of view to evaluate the evolving explosion at late time, and, for the first time, successfully employs a passive image trigger to capture a true self-initiated event.

EXPERIMENTAL PROCEDURE

The PBX 9501 containment system for these experiments is very similar to those used in published studies employing proton radiography [1, 4, 5]. This system consists of two cylindrical cavities machined from aluminum and assembled before the experiment to form a single sealed enclosure. The cavities are each designed to hold one pressed cylinder of PBX 9501, 25.4 mm diameter and 12.7 mm tall. Cylinders are pressed to 96% of theoretical maximum density. Resistive strip heaters are wrapped around the cylinders.

Power to the heaters is controlled with signals from thermocouples positioned on the outside of the cylinders under the heater strips. Internal temperatures are monitored by a six-thermocouple array embedded at the interface between the assembled cylinders.

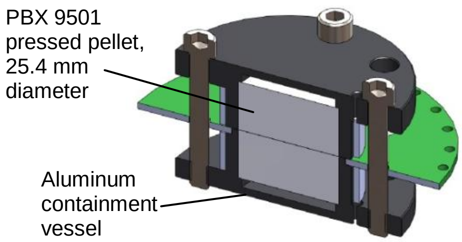

Fig. 1 Aluminum containment system for PBX 9501 pellets. Open volume near end caps allows for expansion of explosive during the β-to-δ phase transition.

When the assembled device is heated, the end caps cool more quickly than the central cylinder, providing for the evolution of a thermal profile with a temperature maximum in the center of the device as previously demonstrated [4]. End cap temperatures are measured by thermocouples mounted directly on the caps. A difference between the aluminum enclosures used here and those reported elsewhere [1, 4] is that this end cap thickness (1.6 mm) is half the thickness of the cylinder walls (3.2 mm). Previous experiments employed enclosures with end caps equal in thickness to the cylinder walls.

The assembled device is mounted in the Lawrence Livermore National Laboratory Hydra flash x-ray system as shown in Fig. 2. Hydra is a multiple-head x-ray system that has previously been used for observing dynamic phenomenon in various explosives and other materials [6-9]. In this experiment, three of the x-ray images are obtained from nearly collinear viewing angles, while a fourth image is obtained from a perpendicular viewing angle. A Vision Research Phantom v7 high-speed camera views the explosion from an angle 180° from the viewing angle of the perpendicular x-ray source (Fig. 2). Camera images are separated by 11.1 μs.

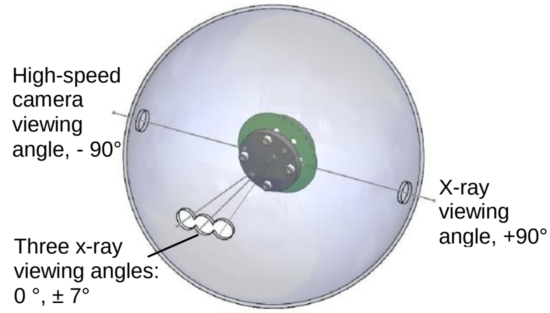

Fig. 2 X-ray and high-speed camera imaging configuration for thermal explosion inside the firing tank; containment system not to scale.

The sample heating profile is similar to that reported in previous proton radiography studies of PBX 9501 thermal explosions: ramp at 5 C/minute to 70 C, hold for about 8 minutes, then ramp again at 5 C/minute to 178 C (above the 162 C HMX β-to-δ phase transition) and hold for 42 minutes. Finally, ramp at 5 C/min to 205 C and hold until the explosion self-initiates. Unlike previous experiments, where the thermal explosion is triggered with a laser pulse to ensure appropriate timing for imaging, these experiments do not employ an active trigger input. Instead, the same thermocouple array which monitors the internal explosive temperature also provides the trigger signal for the x-ray imaging system.

RESULTS AND DISCUSSION

A complete x-ray image series of a PBX 9501 thermal explosion is shown in Fig. 3: 0, 10, 20, and 60 μs post-trigger. These images are created by first aligning static to dynamic images for each view, then building a new image by taking contrast values for each new pixel to be equal to the ratio of the contrast value of the static image pixel to the contrast value of the registered dynamic image pixel. Darker areas correspond to areas of lower density in the dynamic image, relative to the pre-experiment static image.

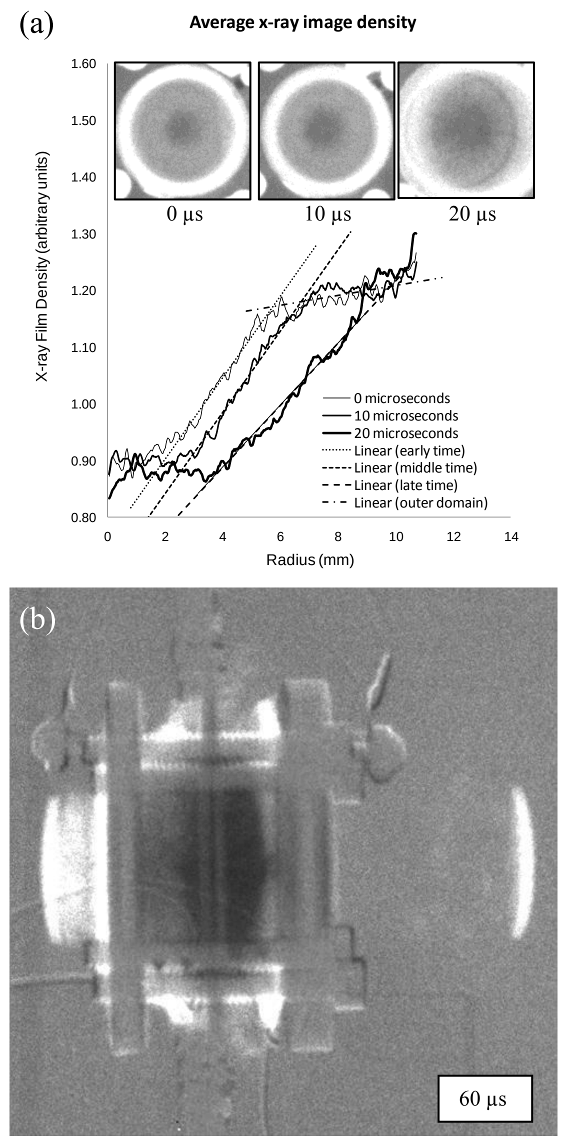

Fig. 3 X-ray image time sequence: (a) axial view, with average image densities, function of radius, and (b) perpendicular view, showing ejected end caps

The corresponding fast camera image sequence for this explosion is shown in Fig. 4. Images are separated by 11.1 µs. The camera image closest in time to the 60 µs x-ray image is frame 5. Note that the debris cloud velocity can be estimated by sequential images, and falls in the range of 800-2100 m/s. Initially debris exits at 1800-2100 m/s, slowing to 800-1000 m/s within 10 µs.

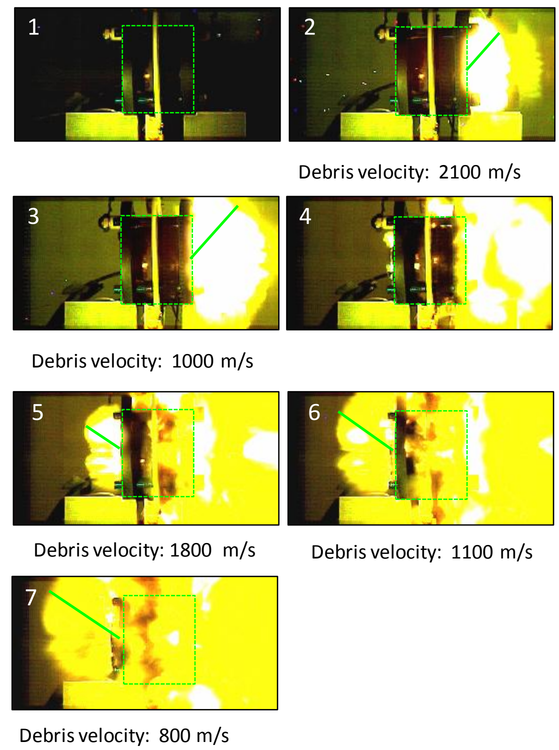

Fig. 4 High-speed camera image time sequence; lines indicate distances used for debris velocity calculations. Images are separated in time by 11.1 µs.

Fig. 3(a) insets shows a low-density circular domain getting larger over time. The image density is averaged over a 10 degree cone containing the area with least parallax, and is plotted as a function of radius. Linear fits to the data are also shown. The line labeled "outer domain" corresponds to the lighter area outside the nominal burn front. In the 60 µs image (Fig. 3(b)), the aluminum containment vessel side walls have burst radially away from their original positions, and end caps have been ejected. Two other experiments on similar test articles exhibited similar behavior in terms of the explosive and containment vessel evolution with time.

Based on the size of the low-density domains in Fig. 3(a) and the 10 µs time between images, we estimate a radial conductive burn front velocity of about 100 m/s between 0 and 10 µs, accelerating to 310 m/s between 10 and 20 µs. Time 0 is the time at which the first embedded thermocouple registers a voltage response above a set threshold. Observed velocities are comparable to the ~165 m/s previously measured by proton radiography in similar experiments [4], though more x-ray data is needed to establish uncertainty in the present data.

With information from the combined fast camera and x-ray image sequence in this experiment and two others (data not shown), we estimate end cap velocities, v_c, of ~800 m/s within 10's of μs from the time of initial vessel rupture. If the reacting front acceleration, a, in the axial direction is assumed to be the same as the front acceleration in the radial direction, then the effective location of the center of the initiation volume can be estimated with timing data implicit in the late-time image. In the experiment shown in Fig. 3, the effective initiation center is found to be about 6 mm on the right side of the center plane, assuming $a = 2\times10^7$ m/s^2 and $v_c = 800$ m/s. However, the lack of knowledge of the spatially-dependent pressure distribution in the vessel and the details of the end cap rupture dynamics preclude a definitive assignment of the actual initiation center.

On the left side of the vessel in Fig 3(b), dense material appears to be ejected from the containment vessel immediately after rupture of the end-cap. On the right side of the vessel, where the end-cap was ejected tens of microseconds earlier, this material has already dissipated, reacted, or both. In the fast camera images (Fig. 4), the bright areas are attributed to the explosive reacting as it is ejected. However, the x-ray image shows the explosive is not fully reacted to gas phase completion at the time of vessel rupture.

CONCLUSIONS

A thermal explosion in a PBX 9501 cylinder, 25.4 mm in diameter and 25.4 mm tall, has been radiographically and optically imaged in the absence of an active thermal trigger. X-ray images show an accelerating boundary of a lower-density domain in the PBX 9501 in the tens of microseconds immediately following the trigger signal. A later side-view x-ray image allows the effective initiation location to be estimated at 6 mm on one side of the geometric center of the explosive. High-speed camera images show debris clouds expanding initially at above 2000 m/s, decelerating within tens of microseconds of the vessel burst time to as slow as 800 m/s. X-ray data suggest the debris cloud consists of unreacted and reacting explosive, which subsequently reacts or dissipates, or both, within about ten microseconds of exiting the burst vessel.

ACKNOWLEDGEMENTS

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This research was supported by Science Campaign 2 and the Surety Program administered by Los Alamos National Laboratory, as well as the Joint Munitions Program administered by both the Departments of Energy and Defense.

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