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PHOTOINSTRUMENTATION FOR WARHEAD CHARACTERISATION

R. Campbell and C.R. Wilkinson

Weapons System Division, Defence Science & Technology Organisation,
PO Box 1500, Salisbury 5108, Australia

Experimental firing of warheads is performed to obtain data for characterisation of warhead damage mechanisms. This paper describes the use of photoinstrumentation techniques to measure charge breakout, fireball evolution and shock front propagation following detonation of a 2.6 kg thin-cased warhead. Shock front position estimates are fitted to obtain equations for peak overpressure as a function of either time or position. These peak overpressure estimates are compared with both semi-empirical and hydrocode estimates of overpressure, and agreement is found within 10–20%. Results from this work can be used to validate detailed computer models of warhead characteristics and terminal effects.

INTRODUCTION

Operational analysis wargaming codes and combat weapon systems require accurate estimates of weapon effects. This information is drawn from a variety of sources such as Vulnerability/Lethality codes, FE and CFD modelling, and from direct measurements of warhead effects. Computer modelling of warhead effects invariably requires experimental data for validation. Experimental characterisation of warheads is thus conducted to provide data on warhead effects.

Photoinstrumentation is image-forming instrumentation which enables visualisation and measurement of events that cannot be observed with the human eye. It offers a remote and accurate method for measuring warhead parameters such as the rate of charge break out, fragment distribution and average velocity, and the instantaneous shock wave velocity (from which we can calculate peak overpressures). In this paper we describe the application of high-speed and ultra high-speed photoinstrumentation techniques to characterise a 2.6 kg naturally fragmenting warhead detonated in the free-field. We describe the experimental configuration, the analysis of photoinstrumentation data, and its comparison with other sensors and modelling results.

EXPERIMENTAL SETUP

The warhead studied comprised 2.6 kg of PE4 (88%RDX) in a thin aluminium case with a 6:1 length to diameter ratio. The centre of the warhead was positioned at a height of 2 m to reduce ground reflections and allow measurement of free field behaviour. The warhead was end-initiated with an Exploding Bridge Wire (EBW) detonator.

Photoinstrumentation consisted of two Redlake Hycam I 16 mm rotating prism cameras and one DRS Hadland Imacon 468 digital framing and streak camera. The Imacon recorded images of charge breakout (0–0.2 ms over 0–0.6 m). The Hycams recorded the fireball expansion (0.1–0.7 ms over 0.3–1.7 m) and the shock front position (2.9–10.1 ms over 3.3–6.6 m). Measurement of the shock front position was achieved with a zebra backing board illuminated with flashbulbs.

Time of arrival (TOA) probes (piezo pins, glass break screens, and micro switches) were placed between 1.3 and 2.5 m. Pressure gauges were deployed at distances of 1.0, 1.5 and 2.5 m from the warhead.

The Imacon was positioned 50 m from the charge in a protective structure. A 300 mm lens was used to view the warhead via a first surfaced mirror (eliminating any double reflection). Warhead break out and fireball expansion were photographed using the light output from the explosive process for image formation.

To image the maximum expansion of the fireball one of the Hycams was fitted with a full frame head. The event was recorded at a framing rate of approximately 8500 frames per second with exposure settings bracketed between events to capture the full luminance range of the fireball. The detection of the edge of the fireball provides a lower estimate of the position for the shock front.

The Hycam observing the shock front was fitted with a half height head and the framing rate achieved was approximately 7000 frames per second. The camera was positioned so its focal plane was parallel to a zebra striped background to enhance detection of the change in refractive index of the air caused by the density changes at the shock front. Illumination of the zebra board was achieved using Sylvania PF-300 flash bulbs mounted in fluorescent lamp reflectors. The bulbs were positioned at the base of the zebra board screen and were triggered 18 ms before detonation to ensure the shock wave was travelling across the background at the peak intensity of the lamps. Each zebra board panel required 32 lamps for adequate illumination at the required framing rate. Lamps were initiated with a Flash Bulb Firing unit developed at DSTO [1].

Triggering of cameras and lighting was synchronised with the warhead detonation to ensure all parameters were recorded within the narrow time frame. 18 ms before the Hycam reached the desired framing rate, the illumination for the background was triggered. When the camera had reached the desired framing rate, and lamps had reached their peak intensity, triggering signals were sent to initiate the detonator and trigger the Imacon and remaining instrumentation.

Kodak Tri-X Reversal (7278) was used in both Hycams. Film was processed as a negative in Kodak HC-110 developer at 30°C for 4.5 minutes. Processing occurred during the trial to refine exposure settings through the course of the experiment.

IMAGE ANALYSIS

Digital image analysis was achieved using the Imacon 468 software, and Adobe Photoshop 5.0 for image manipulation and measurement of X/Y co-ordinates based on pixel referencing.

The early expansion (0-0.6m) of the fireball was recorded using the Imacon 468 Framing channels and is presented in Figure 1. It should be noted that since the warhead was cased, the initial detonation point could not be seen due to the case obscuring the light output from the detonation of the explosive fill. The position of the warhead at 2 m was obtained from the calibration images via pixel positioning, and the diameter of the fireball measured across this axis.

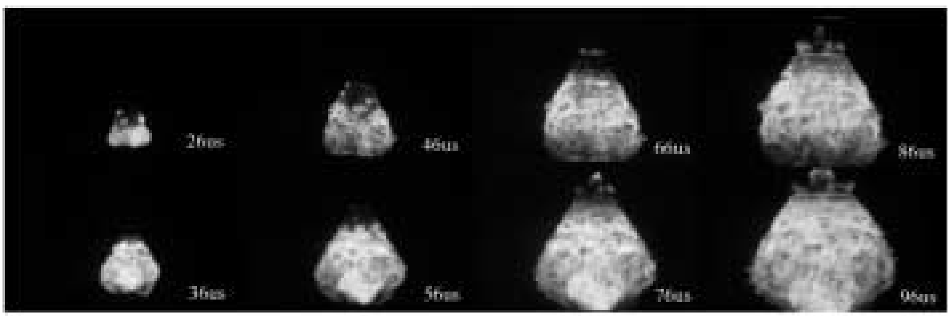

Figure 1. Imacon images of fireball expansion, compiled from two experiments with staggered timing. Time shown is delay from zero.

16 mm film data extraction was completed using a NAC 160F Motion Picture Analyser. Later expansion of the fireball (0.3–1.7 m) was obtained with a Hycam. As the fireball expanded its edges became undefined. Fragments from the warhead casing penetrated the fireball causing instabilities in its 'normal' expansion. This is evident in the last 3 images in Figure 2. Limitations of the exposure latitude of the film did not allow the full luminance range of the fireball to be imaged in a single firing. To compensate, bracketing of exposure was required for separate firings.

The fireball expanded to a maximum size and then cooled fairly rapidly once the static state had been achieved. The total fireball duration was approximately 40 ms.

A NAC 160F Motion Picture Analyser was used to measure the shock front position as a function of time. Figure 3 presents a single frame from the Hycam data illustrating the aberration caused by the change in refractive index at the shock front.

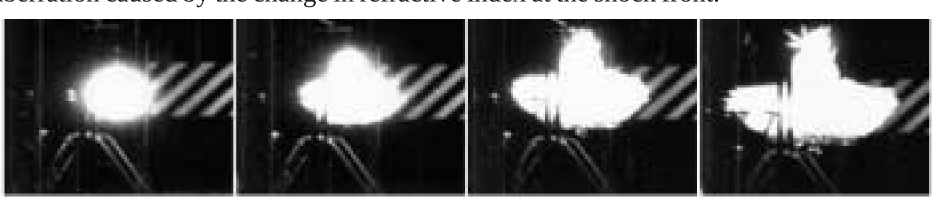

Figure 2. Hycam frames illustrating expansion of the fireball and fragment interruption of fire ball edge.

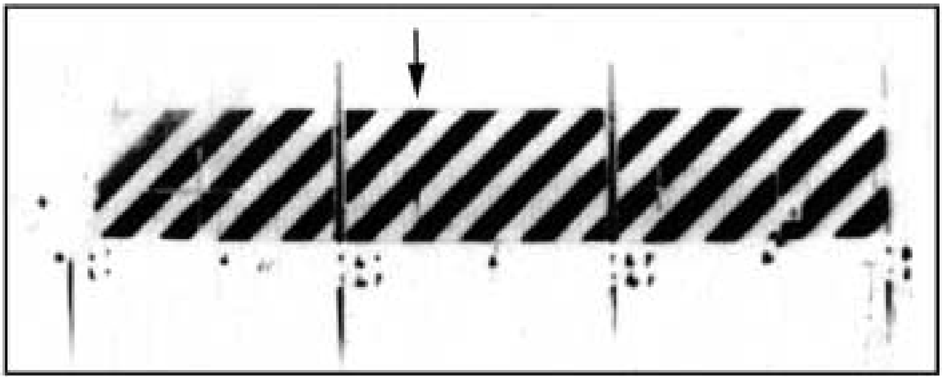

Figure 3. Hycam frame of shock front (negative image). The arrow indicates the projected position of the shock front, which is detected due to the change in the refractive index of air at the shock front.

An internal light emitting diode, which marks the film at rate of 1000 Hz, enabled the time base to be obtained from the film record. Individual frame times have been determined by calculating the average film velocity from the timing marks.

The charge was excluded from the field of view to maximise the size of the background in the frame. Two reference marks were placed on the background and their position surveyed relative to the charge position. The projected position of the shock front was measured with respect to the two reference marks in each frame. The reference marks allowed extrapolation of the projected position of the shock front relative to the charge position in a horizontal plane, eliminating the problem of film jitter.

Once the projected position of the shock front relative to the charge position was determined, the actual position of the shock front was calculated using simple geometry as illustrated in Figure 4. The method used, based on that of Audet [2], was adapted to measure the radius rather than diameter of the shock front. Each frame was analysed to provide the radial shock position as a function of time.

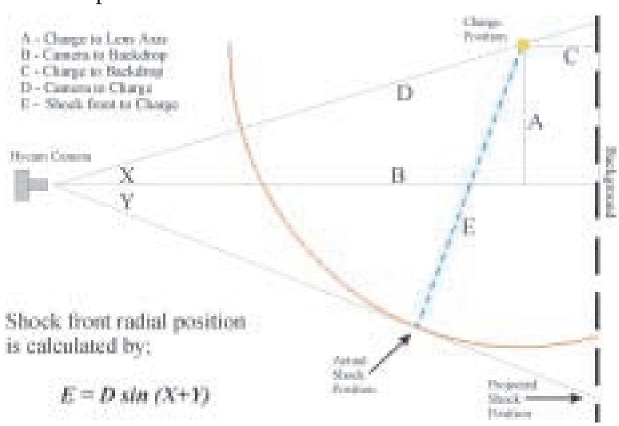

Figure 4. Geometry for determining actual shock front position.

PHOTOINSTRUMENTATION BASED OVER-PRESSURE ESTIMATES

Peak overpressure can be determined from the shock front velocity according to equation (1) which is based on the Rankine-Hugoniot relations [3]:

$$\frac{\Delta P}{P_0} = \frac{7}{6}\left(M^2 - 1\right) \tag{1}$$

Where ΔP is the peak overpressure, P_0 is the ambient air pressure and M is the Mach number of the shock front. Since velocity is the time derivative of position, peak overpressure can be derived if the position of the shock front is measured at sufficiently high spatial and temporal accuracy.

Following warhead detonation, the edge of the fireball trails behind the shock front. Hence charge breakout and initial fireball expansion measurements can be used as lower estimates of the position of the shock front at early times. Estimates of fireball velocity will underestimate the true shock velocity (and hence overpressure). This error increases with time as the velocity of the fireball expansion decreases compared to the shock front velocity. CFD simulations were performed to estimate these errors. The percentage increase in the shock front position compared to the fireball edge was found to increase linearly with time, from around 8% at 0.5 m rising to 25% at 1.35 m.

An error analysis was performed to obtain errors for both position and time from the raw measurement errors. The measurement errors of the fireball position were at least an order of magnitude less than the systematic error between the fireball and shock position obtained from CFD simulations. Thus the estimated systematic error from CFD simulations was used for fireball measurements. The relative time and position errors from the measurements of the shock front ranged from 0.2% down to 0.1% for time and 0.5% down to 0.25% for position (the errors decreased with time). Finally to account for far field behaviour where the shock speed approaches the sound speed, three artificial points were calculated based on scaling standard TNT air shock parameters [3]. Time of arrival and distance estimates for shock speeds of Mach 1.02, 1.01 and 1.001 were scaled to produce data points at 25 m, 49 m and 350 m. As these estimates are based on spherical charges, and are at large distances from the charge errors were overestimated and fixed at 10%.

The Levenberg-Marquardt algorithm was used to fit a smooth equation for the shock position as a function of time taking into account measurement errors and the constraint that the velocity approach the speed of sound at large distances. The shock front position data is presented in Figure 5 along with the fitted equation. The time of arrival probes triggered prematurely for this event so no data was obtained. However data from two similar events is presented for comparison purposes.

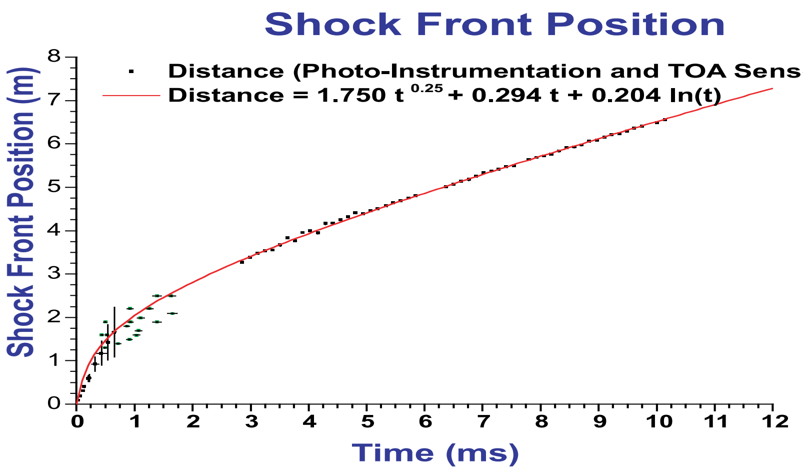

Figure 5. Shock front position as a function of time from photoinstrumentation and time of arrival measurements. Data points and one standard deviation (1σ) errors are plotted. The fit was performed only on photoinstrumentation data, and fit parameter errors were between 0.3 and 0.5%. The scatter between 0.5 and 2 ms arises from the use of several different time of arrival sensors taken from two similar experiments and are provided for comparison purposes only.

Overpressure as a function of time was then obtained by differentiation of the fitted equation. Of more direct application to damage estimates is peak overpressure as a function of distance. Therefore overpressure estimates were plotted as a function of distance, and a non-linear fit was performed as indicated in Figure 6.

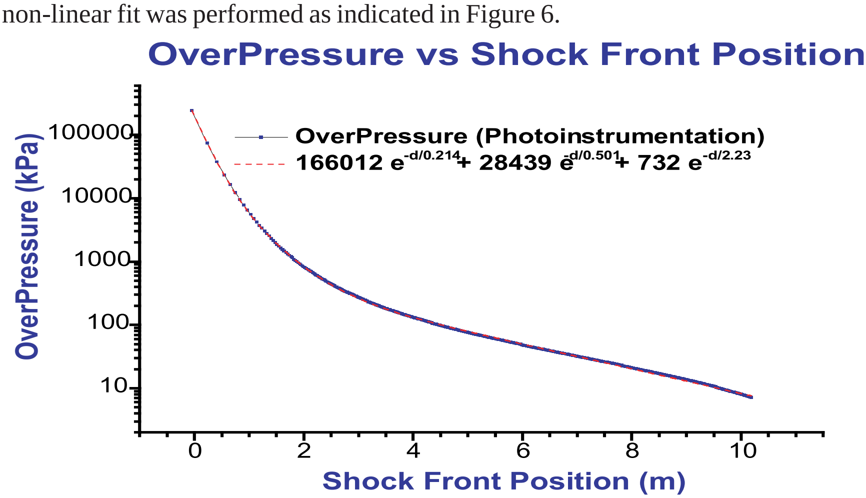

Figure 6. Fitted overpressure as a function of shock front position. Units were kPa and metres, and errors in the fit parameters were 0.7%, 0.6%, 4%, 1%, 2% and 0.9% respectively.

Comparison with semi-emprical and hydrocode estimates

To validate the method used above, photoinstrumentation results were compared with estimates from the semi-empirical code ConWep [4] and hydrocode simulations performed by Zimmerman *et al.* [5]. Pressure gauges results were found to be unusable due to photo-sensitivity of the gauges to the explosive flash.

The semi-empirical code ConWep was used to estimate the peak overpressure from a spherical charge of TNT of equivalent mass. An overpressure equivalency factor of 1.28 was used, based on the explosive C4 which has a similar composition to PE-4 (91% and 88% RDX respectively). Zimmerman *et al.* have performed hydrocode simulations of spherical and end initiated cylindrical charges of C4 which were validated with six firings of 1.95lb C4 charges. Large variation was seen in these experimental firings, with maximum and minimum values approximately 70% larger and 30% smaller than the median peak overpressure. Hydrocode simulations were between 0% and 30% less than the median peak overpressure.

Table 1 compares overpressure estimates from ConWep and Zimmerman *et al.*, with photoinstrumentation estimates. The estimates from ConWep and the spherical simulations of Zimmerman *et al.* agree at the 10–20% level, with ConWep estimates generally being larger. At 1m the photo-instrumentation estimate is approximately 30% larger than the Zimmerman *et al.* cylindrical estimate. At greater distances the agreement is within approximately 10%, with the photoinstrumentation estimates generally larger than Zimmerman *et al.* cylindrical estimates.

Table 1. Overpressure estimates from several sources for a 2.6 kg PE-4 charge.

R	Z	ConWep[4]	Zimmerman *et al.*[5]		Photo-Instrumentation
		Spherical	Spherical	Cylindrical	
M	$Mkg^{-1/3}$	MPa	MPa	MPa	Mpa
1.0	0.67	2.20	2.24	4.44	5.85
1.5	1.00	0.93	0.84	1.91	1.94
2.0	1.34	0.48	0.39	0.84	0.83
2.5	1.67	0.29	0.23	0.44	0.43
3.0	2.01	0.19	0.16	0.24	0.26

CONCLUSIONS

High-speed photoinstrumentation can provide reliable data from experimental firings of warheads. Information on the spatial nature and velocity of charge breakout and fireball evolution can be used to validate hydrocode models. Measurement of the shock front position produces reliable estimates of the peak overpressure as a function of distance. Such information can be used as validation data for detailed computer models of warhead terminal effects.

However photoinstrumentation is currently an expensive and time-consuming method of data reduction when a high level of accuracy is required. Technological improvements in high-speed imaging technology has the potential to make this process both cost effective and timely.

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