LLNL-CONF-656688

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October 30, 2014

15th International Detonation Symposium
San Francisco, CA, July 14-18, 2014

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Abstract. The Probabilistic Shock Threshold Criterion (PSTC) is a tool that provides a probabilistic assessment of margin of initiation at various interfaces through explosive initiation trains. Our current focus of work is to acquire the necessary data to parameterize the criterion with plastic bonded explosive LX-17-1 (92.5% wet-aminated TATB, 7.5% Kel-F 800 binder). As we accumulate data for LX-17 and other explosives, the form of the PSTC will be revisited. This paper provides an update on this work-in-progress with our latest data on LX-17 and PSTC parameter fits to this data.

Introduction

Shock initiation of 1,3,5-triamino-2,4,6-trinitrobenzene (TATB)-based explosives such as LX-17 (92.5% TATB, 7.5% Kel-F 800) has been studied extensively for applications in both explosive safety and performance regimes.[1,2,3,4,5] In particular initiation sensitivity has been assessed using gap tests, gun tests, flyer plates, bullet impacts, etc. To minimize uncertainty in the initiation threshold, the input pressure pulse duration and magnitude must be well characterized. Bullet or explosively formed projectile (EFP) experiments are generally more qualitative and often difficult to extend beyond the actual test. For small gap tests, the pressure pulse in the acceptor can be highly divergent and therefore complicate data interpretation. For large enough gap tests in which the pulse is effectively one-dimensional, handling and experiment costs become more prohibitive. Flyer plates that generate planar wave inputs are more easily characterized and therefore enable clearer data analysis.

To this end, we have obtained high quality initiation threshold data for high density (~98% TMD) LX-17-1 explosive using LLNL's electric gun.[6,7] The electric gun (e-gun) is essentially a large capacitor bank (44.8 kJ at capacity) that is discharged across a Kapton-coated, 50.8-µm thick aluminum foil. The aluminum foil rapidly expands and thereby propels a Kapton flyer over some adjustable distance to impact the explosive. The flyer area, cross-section, and impact velocity are all highly tunable to achieve a desired pressure pulse. Further, by reducing the size of the impactor below the failure diameter for sustaining an unconfined detonation (approximately 12 mm for LX-17)[8], we obtain data to parameterize the one-dimension James criterion over varying diameters.

The probabilistic shock threshold criterion (PSTC) is an extension of the James Initiation Criterion.[9] The purpose of the PSTC is to develop a phenomenological shock initiation criterion to be used in safety and performance assessments of high explosive trains. The probabilistic information in explosive initiation threshold series is used to fit parameters, which allow for quantifying margin of initiation in terms of a single parameter and also give a sense of what the margin means with the assigned probability distribution. The PSTC form also facilitates inclusion of two-dimensional initiation effects such as sub-failure diameter impact areas. In this paper, we describe further development of the probabilistic shock initiation criterion specifically for LX-17-1.

Theory

The PSTC is represented by the following equation.[9] This form extends the one-dimensional James criterion allowing it to account for varying excitation diameters.

$$\frac{1}{\psi} = \left(\frac{E_c}{E} + \frac{\Sigma_c}{\Sigma}\right)\left[1 + \left(\frac{d_c}{d}\right)^k\right] \quad (1)$$

where ψ = PSTC margin parameter
E = energy fluence ($pu_p\tau$)
p = pressure
u_p = particle velocity
τ = shock duration
Σ = specific kinetic energy density ($u_p^2/2$)
d = diameter
k = reduced diameter scaling exponent
subscript c = critical parameters

The shock duration, τ, for thin flyers in the energy fluence term is calculated using the minimum of the rod criterion given by James[10] (Equation 2) or the thin plate criterion as presented by Cooper[11] (Equation 3).

$$\tau_{rod} = \frac{d}{6c} \quad (2)$$

$$\tau_{plate} = \frac{t}{-U_f} + \frac{t}{R_f} \quad (3)$$

where c = sound speed in the shocked explosive
t = flyer thickness
U_f = shock velocity in flyer (negative)
R_f = release wave velocity in flyer

We used Jacob's approximation as given by Allison[12] to determine the sound speed, c, in the shock explosive:

$$c = \frac{(U_s - u_p)(U_s + Su_p)}{U_s} \quad (4)$$

where U_s = shock velocity
S = slope of linear Hugoniot

James[13] states that this relationship for shocked explosive sound speed is for metals and proposes another for explosives. However, with the Gruneisen gamma, Γ, varying from 0.5 to 1.5, the difference in sound speed between the two equations is at most 3% in the range of particle velocities that are relevant in this study. It is not until much higher pressures that the two equations deviate substantially.

Parameterization of the coefficients E_c, Σ_c, d_c, k is accomplished by assigning a probability distribution and using a maximum likelihood estimator (MLE) to simultaneously fit the PSTC parameters and distribution parameters to the available threshold series data. We have found that using a convolution of a normal and Pareto distribution provides the best fits to the data, though have also evaluated normal, log-normal, and Weibull distributions.

Experimental Methods

The electric gun is a large capacitor discharge unit (CDU).[6] The CDU is comprised of four Kraft paper/Castor oil capacitors mounted on a cart. Each capacitor is nominally rated at 14 µF and 40 kV for a total of 56 µF. At full charge, the bank is capable of storing 44.8 kJ of energy.

A copper/Kapton laminate with a square aluminum bridgefoil is used to produce a Kapton impactor (see Fig. 1). The bridgefoil is 0.0508 mm thick with areas ranging from 3 mm x 3 mm to 25.4 mm x 25.4 mm. A Kapton layer 0.0508 mm-1.27 mm thick is adhered over the bridge using Pyralux (DuPont) adhesive. A barrel with a square opening of the same dimension as the bridgefoil is adhered to the uppermost Kapton layer. The laminate is attached to the e-gun via a rigid transmission line that includes a thin dielectric barrier to isolate the laminate from the capacitor bank. Two shaped charge detonators are mounted against a dielectric barrier to serve as a puncture switch thereby allowing current to flow to the laminate.

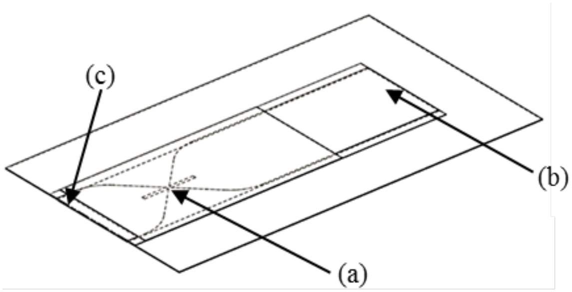

Fig. 1. Illustration of the laminate with (a) a thin aluminum bridge beneath a Kapton layer and (b) a copper sheet that attaches to the e-gun which (c) bends around the Kapton substrate.

A flyer is generated by charging the e-gun capacitors to a specified voltage and then firing the detonator switch. The capacitor bank discharges into the laminate bursting the aluminum bridge and accelerating the Kapton cover layer down the barrel, thus creating an impactor of the desired size and thickness. The velocity, planarity and stability of the impactor are adjusted by varying barrel length and charge voltage. Shock duration is varied via selection of the Kapton flyer thickness.

Impactor characterization and high explosive (HE) threshold experiments are performed separately. The impactor characterization shot measures the velocity of the impactor using photonic Doppler velocimetry (PDV)[14] and captures a streak image of the impact using a rotating mirror camera. An impactor is fired into an acrylic window installed at the end of the barrel rather than into an HE sample. A cold mirror placed above the laminate reflects visible light at a right angle to the rotating mirror camera. The mirror allows the 1550 nm laser light from a 240 mm focal length PDV probe to pass through to the laminate surface where it reflects and is recollected (see Fig. 2). To enhance the reflectivity of the Kapton surface, a 300 Å aluminum coating is vapor deposited on the Kapton—this is especially important for impactors with thickness of 0.127 mm or less.

The HE threshold experiments are a go/no-go initiability test. The acrylic window is replaced with a 25.4 mm thick LX-17-1 puck with a 25.4 mm or 50.8 mm diameter depending on the size of the impactor. The side of the HE opposing the impacted surface is covered with an aluminum foil and an acrylic disk. Two 5.5 mm focal length PDV focusing probes are mounted on the disk and directed at the aluminum foil. The probes record the velocity of the HE surface and the recorded value clearly indicates whether full order detonation is achieved.

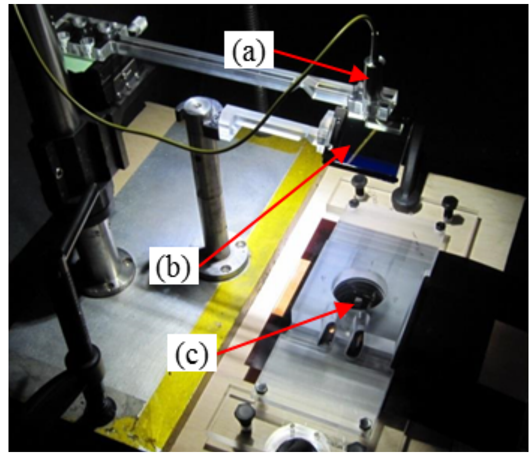

Fig. 2. For the diagnostic shot, a PDV probe (a) is directed through a cold mirror (b) at the barrel and the Kapton that will be thrown (c).

It is critical that the impactor be thrown consistently at a given set of firing parameters because the impactor is not characterized directly during the initiability test and the impact velocity must be inferred from a separate diagnostic shot. Three diagnostic shots of 25.4 mm x 25.4 mm impactors were fired to verify the repeatability of flyer velocity and to study the impactor shape. In all three cases the PDV probe was focused on the center of the Kapton flyer while the streak plane was varied for each shot.

The streak results are shown in Fig. 4. Streak (a) demonstrates a very planar impact—the 20 mm center section of the impactor arrives at the impact plane in a span of less than 35 ns. The edges of the impactor drag along the barrel edges and arrive approximately 250 ns after the center impact. Streaks (b) and (c) demonstrate how the flyer shape changes as the streaked plane approaches the barrel edge. The shape of the impactor is three-dimensional, but has a largely planar region in its center.

The PDV velocity histories corresponding to the same three impactors are shown in Fig. 3. The center point of the flyers followed a repeatable path, with the same velocity steps characteristic of a shocked flyer ringing. All three flyers achieve a peak velocity just under 3.3 mm/µs at impact.

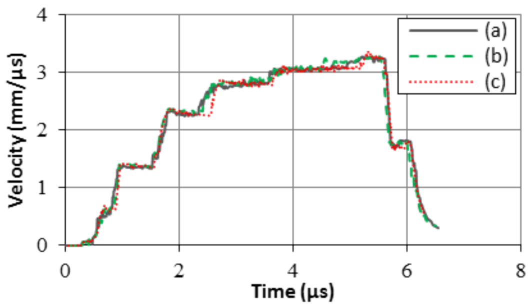

Fig. 3. Velocity traces measured at the center of the impactor for the three shots described in Fig. 3.

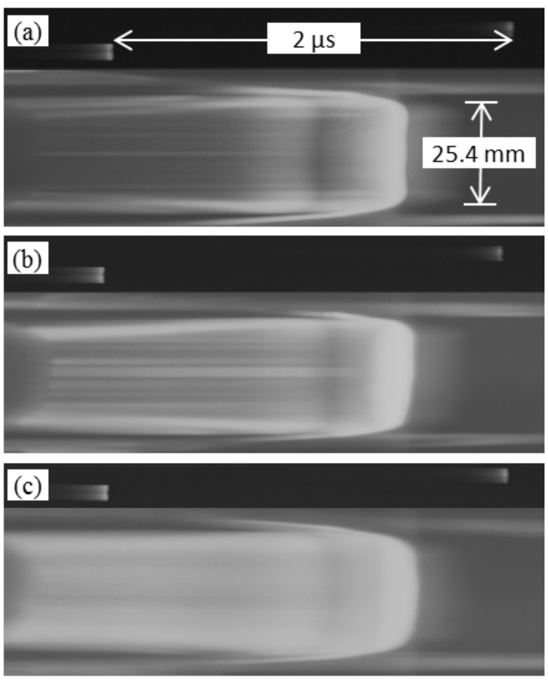

Fig. 4a. Streak images (time moving right to left) from three diagnostic shots fired with the same parameters and imaged at the approximate streak locations shown. The initial light corresponds to flyer impact into the acrylic window.

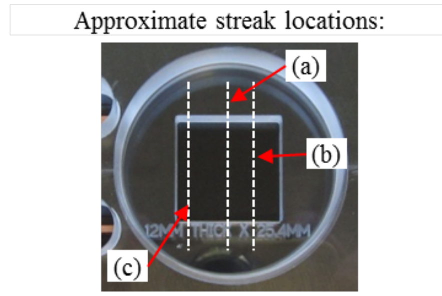

Fig. 4b. Approximate locations of streak images shown in Figure 4a.

Results

A total of 79 explosive shots were fired with flyers ranging from 0.0508-mm thick to 1.27-mm thick and flyer diameters ranging from 3 mm up to 25.4 mm. Significantly more shots were fired without explosive to characterize flyer and e-gun performance. The data that is used in parameter analysis for the PSTC is the flyer material, velocity, thickness, and critical dimension as well as explosive density.

Fig. 5 shows the resulting data for shots fired with Kapton flyers with a critical dimension of 25.4 mm. Note that the two shots fired with 1.27-mm thick flyers appear to be the same and both have the same flyer velocity at impact of 3.25 mm/µs. The threshold series for 1.27-mm thick, 25.4-mm diameter flyers is limited by the performance of the e-gun. The NO-GO shot here was fired at the maximum charging voltage of 40 kV with an LX-17 density of 1.901 g/cc. In order to produce a detonation, the density was reduced to 1.892 g/cc and the shot fired at 40 kV.

Fig. 5 compares the threshold shots presented here with the threshold data collected in the 1970s and 1980s and presented in 2010 (labeled "Old Data").[9] The two lines in the figure represent the highest NO-GO and the lowest GO and bound the original threshold. The current data's thresholds are better resolved and are consistent with the old data, falling within the expected range. The old data represents various lots of RX-03-BB (LX-17 development designation) and dry- and wet-aminated LX-17 with densities from 1.88 g/cc to 1.92 g/cc.

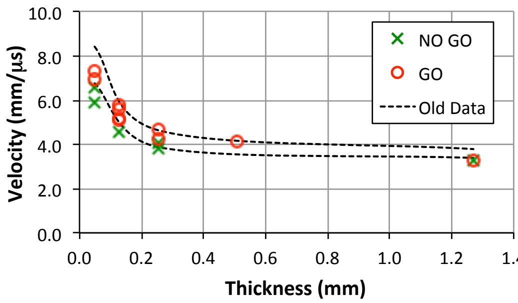

Fig. 5. Threshold series on LX-17 with Kapton flyers at a diameter of 25.4 mm. The density of LX-17 for all the shots in this series ranged from 1.892 g/cc to 1.904 g/cc. Old data ranges from 1.880 g/cc to 1.920 g/cc and includes various development lots of LX-17, which are designated as RX-03-BB.

The energy fluence, E, and the specific kinetic energy density, Σ, are calculated from flyer velocity/thickness data as discussed earlier. Fig. 6 illustrates the same data shown in Fig. 5 in the Σ-E space. Fig. 6 shows the 50% threshold curve that represents the James criterion one-dimensional shock threshold.

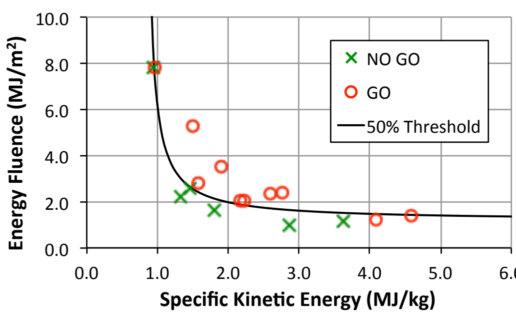

Fig. 6. Threshold series at 25.4 mm in Σ-E space with the fitted 50% threshold line (E_c = 1.054 MJ/m^2 and Σ_c = 0.811 MJ/kg).

Fig. 7 shows the PSTC fit to all the LX-17-1 data (79 shots). There are 10 points that cross-over that establish the probabilistic part of the PSTC. Because the asymptotes at various critical dimensions are not resolved fully by the data, there is higher uncertainty in this data than that previously presented, though the results here better describe the threshold space. The previously presented PSTC for LX-17 was fit solely to 25.4-mm diameter flyer data to establish the James criterion parameters and probability distribution parameters.[9] Reduced area terms were fit based on limited reduced diameter data along with hydrocode calculations of reduced diameter flyers.

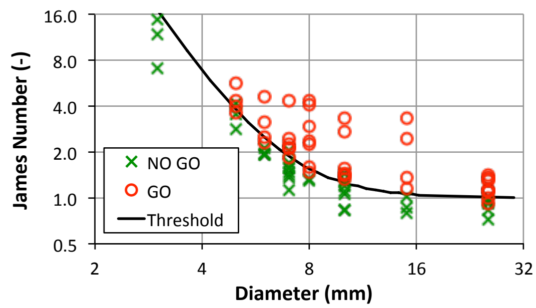

Fig. 7. PSTC fit to all data from a diameter of 25.4 mm down to 3 mm. No detonations were observed at 3 mm. The solid threshold line corresponding to a $\psi = 1$ is shown.

The PSTC parameters for the LX-17-1 fit shown in Fig. 7 are as follows. The units of E_c are MJ/m^2 and Σ_c are MJ/kg. Density is in g/cc. As was shown in Reference 9, the critical energy fluence and specific kinetic energy are functions of density to reduce the spread in the final fit. The following equations are valid over the density range of 1.809 g/cc–1.909 g/cc at ambient temperature.

$E_c(\rho) = 1.174 + 3.265 \times (\rho - \rho_0) + 12.215 \times (\rho - \rho_0)^2$
$\Sigma_c(\rho) = 1.404 + 16.129 \times (\rho - \rho_0) + 60.339 \times (\rho - \rho_0)^2$
$\rho_0 = 1.944$ g/cc (TMD)
$d_c = 6.74$ mm
k = 1.673 (dimensionless)

Parameters for the convolved normal-pareto distribution are given below with the probability distribution functions (Equations 5 to 8) and cumulative distribution function given in Equation 8.

$\mu = 0$
$\sigma = 0.045$
$x_m = 0.953$
$\alpha = 18.011$

$$PDF_N(y) = \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{(y-\mu)^2}{2\sigma^2}\right) \qquad (5)$$

$$PDF_P(x) = \frac{\alpha {x_m}^{\alpha}}{x^{\alpha+1}} \quad (6)$$

$$PDF_{NP}(x) = \int [PDF_N(y) \cdot PDF_P(x-y)] dy \quad (7)$$

$$CDF_{NP}(x) = \int PDF_{NP}(x) dx \quad (8)$$

This new data fits all PSTC parameters to the experimental data with one maximum likelihood estimator calculation resulting in the threshold at reduced area shifted lower than that presented previously.[9] In the past, critical values for diameter were fortuitously calculated at roughly 13 mm (near the critical diameter for LX-17).[8] This new data results in a calculated critical diameter of 6.74 mm. Note that this critical diameter, d_c, is defined by Equation 1 and is not equivalent to the critical diameter to sustain a detonation with an unconfined charge. The reasons for the shift are not unexpected as the basis for the previous reduced area scaling was the available data which consisted of limited experimental data on undefined rods along with hydrocode simulations using the Ignition and Growth reactive flow model.[15] The hydrocode simulations used an Ignition and Growth model that was tuned to gun data and biased towards detonation and not initiation since there was insufficient data to calibrate the model at reduced diameters for short pulse initiation.

Fig. 8 and Fig. 9 show two variations on goodness-of-fit that are used to determine which assigned probability distribution provides the best fit. PSTC fits were performed with assigned Normal, Weibull, log-normal, and the convolved Normal-Pareto distributions. Fig. 8 is qualitative in that it shows the "Go Fraction" which is the quotient of the running sum of the GO's by the running sum of the GO's and NO GO's and compares it to the fitted distribution. The data and probability line are related, but one is not calculated based on the other. Fig. 9 shows a quantitative goodness-of-fit where if the data is perfectly described by a convolution of a Normal distribution and a Pareto distribution, the linear fit would be y = x with $R^2 = 1$.

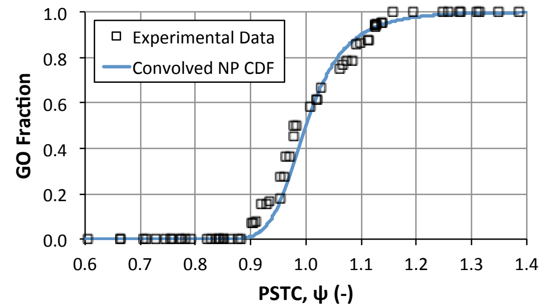

Fig. 8. Comparison of data's Go Fraction to the convolved Normal-Pareto distribution with the parameters given above.

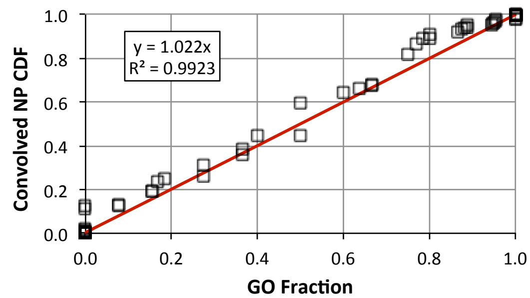

Fig. 9. Goodness-of-fit of the convolved Normal-Pareto distribution to the "Go Fraction" of the data. If the data is not well described by the assigned distribution, the data will deviate significantly from the y = x line.

Conclusions

We have fired 79 shots on a single lot of wet-aminated LX-17 to collect thin-flyer threshold data with thicknesses between 0.0508 mm-1.27 mm and diameters from 3 mm-25.4 mm. This data has been used to fit parameters to the PSTC and James criterion. The parameter fits match well with data.

Comparison of the PSTC fits here to those presented before[9] shows that there is a difference. It is unknown if this is due to differences between the Kapton used in the late 1970s and early 1980s[16] and the newly produced material used for this study. Future work will investigate both the Hugoniot of Kapton of the historical flyers (we have a limited quantity remaining) and the new Kapton used in our experiments. The offset in the thresholds could also be due to a large quantity of the previously collected data[16] having been produced using development lots of LX-17 (RX-

03-BB) which used dry-aminated TATB. Future work will investigate the differences in wet versus dry aminated TATB, different formulation lots of 92.5% TATB and 7.5% Kel-F 800, as well as density and temperature effects on initiation sensitivity.

The work presented here is a work-in-progress. The current form of the PSTC is an empirical fit to data that equally scales the two James sensitivity parameters for decreasing flyer diameters. Although the collected data set seems to support this equal scaling for LX-17, additional data and further analysis are required to indicate the final form more conclusively.

Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy (USDOE) by Lawrence Livermore National Laboratory (LLNL) under contract DE-AC52-07NA27344.

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Questions

Laurence Fried, LLNL
Do you have any experimental data on differing impactor shapes?

Reply by Kevin McMullen
We have performed limited tests with rectangular aspect ratios up to 4:1, however, there was not sufficient data to warrant inclusion in this paper.