The Los Alamos detonating pellet test (DPT): PBX 9501 evaluation tests

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Abstract. High explosive (HE) Velocity of Detonation (VOD) measurements are usually conducted using rate-stick-type tests. This method is highly accurate if carefully implemented, but is relatively costly and may require kilograms or more of HE depending on its sensitivity. We present a novel technique for inferring VOD using a single HE pellet, which for Conventional High Explosives (CHEs) can use 10 gm of HE or even less. This attribute makes the Detonating Pellet Test (DPT) ideal for the preliminary performance characterization of newly synthesized HE materials. On the other end of the size spectrum, the DPT can be scaled to very large dimensions so as to minimize the HE load necessary to characterize highly insensitive HEs such as ANFO. The DPT exploits the fact that the detonation emerging from the pellet face can be made highly spherical over some central region. Spherical detonation breakout on the Sample Pellet (SP) face is described by a simple analytic equation, which depends on the VOD and the Center Of Initiation (COI). The latter is determined by separate characterization of the detonator, with a wave refraction correction at the detonator/SP interface. The SP VOD is then determined by fitting the ideal breakout equation, with specified detonator COI, to detonation breakout data obtained via streak camera. We develop the DPT method and appraise it using sample PBX 9501 data in particular, while discussing its benefits and limitations in general.

1. Introduction
The rate stick is the ubiquitous method for measuring Velocity of Detonation (VOD). This configuration has traditionally used shorting pins as the diagnostic [1]. Recently, Photon Doppler Velocimetry (PDV) probe beams have sometimes doubled as time-of-arrival gauges, and (new at this symposium) a modern adaptation of the cable crush technique called Pulse Correlation Reflectometry (PCR) [2] shows great promise for rate sticks and many other detonation applications.

Well-executed rate-stick experiments can have data scatter of order 1 m/s—a nominal error of about one part in ten thousand [1]. Rate-stick diameters vary between the failure diameter of the considered HE on the low end, to one for which the detonation travels at virtually the plane wave VOD (the Chapman-Jouguet, or CJ speed) on the high end. The latter diameter is roughly proportional to the reaction zone thickness, which depends inversely on the HE sensitivity. For insensitive HEs, then, rate sticks can be quite large—using kilograms of material and potentially much more.

We present a novel method for determining detonation velocity, which we call the Detonating Pellet Test (DPT). The DPT HE sample size can be any size, down to ~10 gm and potentially even less. This size is ideal for characterizing newly-synthesized HE molecules or other materials in short supply. Alternatively, the DPT can be exceedingly large—tens of pounds of ANFO spread in an open tray on the ground, for example. Just as for rate sticks, the optimal DPT Sample Pellet (SP) size is roughly proportional to the reaction zone thickness. For example, ANFO will not detonate in a 10 gm SP, and detonates non-ideally in human-scale charges. The optimal SP size is relatively massive.
For the purpose of this paper we will assume that, whatever the HE sensitivity, the SP is large enough that the VOD is near the CJ value throughout the breakout process. If this is not the case, one can actually use the speed variability to estimate the Detonation Shock Dynamics (DSD) model calibration, called the intrinsic relation [3]. We will present that technique at some later date.

2. Experimental

The preliminary DPT experiments presented here are of the small-scale variety, with HE masses under 10 gm. This value is significant as the cutoff mass for the High Explosive Development (HED) phase 1 process at LANL. This size is appropriate for most Conventional High Explosives (CHEs). We began DPT evaluation with the HMX-based Polymer Bonded Explosive 9501 (PBX 9501, 95 wt% HMX, 5 wt% binder) because it operates in the desired sensitivity range, and because its VOD is well-characterized for a range of densities. This allows us to appraise the DPT measurement accuracy.

PBX 9501 SPs, 1/2 inch (12.7 mm) high by 7/8 inch (22.2 mm) diameter, were pressed to ~97% Theoretical Maximum Density (TMD). The SPs were initiated using a RP-1 Exploding Bridge Wire (EBW) detonator, which has a PBX 9407 (94 wt% RDX, 6 wt% binder) Output Pellet (OP). Streak images were taken of the detonation breakout using a Cordin model 132 camera. Three DPTs were fired per shot. The SPs were configured in a line and the slit was located across their diameters.

We tried both bare pellets and those coated with a magnesium oxide (MgO) flasher coating. The self-light of the bare HE was sufficiently intense to obtain the desired film exposure, and although the two methods were comparable, the overall image quality of the bare pellets was as good or better than that of the coated pellets, which (importantly) eliminates an operator-dependent step. The detonation breakout traces were digitized using an optical comparator at a density of about 200 points per record.

3. Analysis

3.1 Methodology

DPT analysis is based on the following analytic equation (a hyperbola), which describes the breakout time, \( \tau \), of a cross-section of the spherical detonation through the flat pellet surface, as a function of the radius along the pellet, \( r \):

\[
\tau (r) = \frac{z_p}{D_p} \left( \sqrt{1 + \left( \frac{r}{z_p} \right)^2} - 1 \right),
\]

where \( D_p \) is the pellet VOD, and \( z_p \) is the distance of the COI below the pellet observation surface. If \( z_p \) is prescribed, then \( D_p \) can be determined by fitting equation (1) to the breakout data.

Note that, because \( z_p \) and \( D_p \) appear separately in equation (1) (and not as a single consistent grouping), each can formally be determined by a joint least-squares fit of equation (1) to the breakout data. In practice, one finds that real data is insufficiently clean to accurately determine both quantities simultaneously. Instead (for mathematical reasons beyond the scope of this paper) many combinations of \( z_p \) and \( D_p \) reproduce the data with essentially equal accuracy. This means that we must specify one quantity; then, we may find the value of the other quantity that is most consistent with it and the data set.

One measure of the validity of the spherical wave assumption is how well the optimal fit of equation (1) to the breakout data actually works. If the emerging detonation is spherical then, provided that the data set is minimally aberrant, equation (1) will fit the breakout data to within its scatter. If it is only approximately spherical, then the fit will be compromised.

We have noted that \( z_p \) must be pre-determined, and substituted into equation (1), so as to determine \( D_p \) in conjunction with the breakout data. Because the detonator has a finite size, the detonation does
not appear to initiate from its output face (which is butted up against the Sample Pellet [SP] base), but rather from a position in its interior. That point is determined by performing the same type of experiment on RP-1 detonators alone. In this exercise, equation (1) is used “in reverse.” That is, we specify the VOD of the OP, $D_d$, from characterization tests of PBX 9407 at the correct density (1.60 g/cc). Then, we determine the detonator COI from breakout data.

The center-of-initiation (COI) so-determined is that looking back from the output pellet, ignoring the actual detonator interior. This is what is needed for the present analysis. If we were to use our knowledge of the RP-1 interior and account for the Initial Pressing (IP), we could make a refraction correction for the VOD change. This would put the COI close to the bridge wire, where reaction actually starts (although the detonation initiation process in an IP is complex and poorly understood).

Although we do not need to make that refraction correction for this application, we do generally need to make one at the OP/Test-Pellet interface, because the VOD disparity between the two HE components causes $z_p$ to depend on $D_p$. Although this adds a second equation, it minimally complicates the analysis because it does not introduce any additional unknown quantities.

The last technical issue, which is somewhat more complicating, has to do with angular apertures introduced by the various HE components. At this level of analysis we use ray tracing—exactly as in geometrical optics. Experience with detonators shows that any ray that has refracted line-of-sight from the emerging detonation back to the Bridge Wire (BW) is associated with a highly spherical portion of the emerging detonation. Any ray that does not have refracted line-of-sight to the BW passes through a “shadow zone,” and is not generally spherical.

There is one caveat, in that spherical waves approaching a flat interface are not exactly spherical upon transmission. However, provided that the VOD disparities are modest, the transmitted wave tends to be indistinguishable from a spherical one that proceeds from a properly-shifted COI. We have verified that using the exact non-spherical solution does not significantly alter the result.

The bottom line is that the emerging detonation will only be highly spherical within some angular window, and we should design the geometry such that the SP diameter is just slightly larger than the spherical wave region. This exercise is approximate because we do not know the latter’s extent, due to refraction at the OP/SP interface (i.e., the answer depends on the unknown value, $D_p$). But we can make a satisfactory guess. Similarly, we should use all of the data in the spherical wave region, but no more. For the same reason (refractive coupling), this problem is coupled to the other elements.

3.2 Summary of Operational Steps

It is helpful to summarize the operational steps listed above:

1) Determine the detonator COI using equation (1) applied to RP-1 detonator breakout data sets. Incorporate all data within the OP radius, $R_d$, and substitute an independently-measured $D_d$-value.

2) Derive the refraction-induced COI shift, and substitute it into equation (1). This will use the known values of $z_d$, the detonator COI, and $D_d$, leaving $D_p$ as an unknown.

3) Perform a series of least-squares calculations using the result of step (2), in which data points are sequentially pruned from the data set ends. Construct a plot of inferred VOD vs. data window radius. That is, construct all the $D_p$-value possibilities for consideration.

4) Given the known test geometry and HE detonation speeds, find the geometric relation between $D_p$ and $R_s$, where $R_s$ is the radius on the sample pellet surface within which the detonation is spherical. Both $D_p$ and $R_s$ are unknowns.

5) Overlay the curves from steps 3 and 4. The point where they cross gives the inferred speed, $D_p$, which corresponds to the condition that uses all data points within the spherical region, $R_s$, but no more, whilst accounting for refraction at the OP/SP interface. It also gives the $R_s$ value. Note that
if the sample pellet dimensions were optimally determined, then $R_s$ should be slightly smaller than the sample pellet diameter, and a relatively small number of points should have been pruned.

### 3.3 Equations

Next we derive the equations used in the above six steps, and show how to implement them. The notation is defined in figure 1.

![Figure 1](image)  
(a) System geometry relating $z_d$ to $z_p$. (b) Shadow zone created due to geometry of system.

Although $z_p$ cannot be directly measured, it can be mathematically related to the detonator COI, $z_d$, and the detonator VOD, $D_d$. Determination of the distance $z_d$ for these shots is discussed in [4]. The relation between $z_p$ and $z_d$ is obtained by applying Snell’s Law to the detonation wave refraction at the pellet-detonator interface. Referring to figure 1, we find that

$$
\delta_z = \frac{z_d}{n} \sqrt{1 - (n^2 - 1) \frac{R_d^2}{D_d^2}},
$$

where $R_d$ is the detonator radius and $n = D_p / D_d$ is the refractive index of the SP VOD with respect to the detonator VOD. $R_d/z_d$ is order one, and $n^2 - 1$ is very close to zero. Thus the second term in the square root can be dropped relative to the first. This approximation corresponds to the paraxial approximation in optics, wherein only rays near the axis are considered in the refraction calculation. Making the paraxial approximation and using the geometry in figure 1, we obtain

$$
z_p = h_p + \frac{D_d}{D_p} z_d.
$$

Substitution of equation (3) in equation (1) gives $r (r, D_p)$, and then a fit (least squares) to the data gives $D_p$. The SP shadow zone is illustrated in Fig. 2; this occurs because $R_d$ is less than the test pellet radius. The detonation does not propagate spherically from the pellet COI in the shadow zone, hence
τ(r) data from this region must be excluded from the fit of equation (1) to the breakout data. However, the radius of the shadow zone, $R_s$, depends on $D_p$, so $R_s$ and $D_p$ must be determined simultaneously. The relation between $D_p$ and $R_s$ is readily derived by again applying Snell’s Law to the detonator-pellet system:

$$D_p(R_s) = D_s \left( \frac{R_s - R_d}{R_d} \right) \sqrt{\frac{R_s^2 + z_d^2}{(R_s - R_d)^2 + h_p^2}}, \quad R_s \geq R_d.$$  (4)

$D_p(R_s)$ is a monotonically increasing function.

4. Results and Discussion

Figure 2 shows the experimental results. Row 1 renders the streak images. For bare pellets, the exposure fades in due to pre-light, and terminates abruptly when the shock emerges. Exposure starts anew as the HE products burn in air. The trace is read from the abrupt cutoff prior to combustion light.

Row 2 shows fits to the functional form $\tau(r, D_p)$, respectively. The data points are black and the fits are the superimposed colored curves. The high fit quality confirms our spherical wave propagation assumption. Row 3 plots the VOD vs breakout data width as determined by least-squares fits to variable numbers of points, and also equation (4), which is the dependence of $D_p$ on aperture from Snell’s law. The optimal solution is the point where the curves cross.

Figure 2. PBX 9501 DPT data: (a) 1.817g/cc, (b) 1.816g/cc, and (c) 1.812. In rows, from top to bottom, are streak images, least squares fit to equation (1), and last, determination of VOD in sample pellet. Note that in the third row, $D_p(R_s)$ is a monotonically increasing function and $D_p(R_w)$ is a monotonically decreasing function.
Table 1 lists the DPT velocities with rate-stick VODs for PBX 9501. Shot-to-shot variability in $z_d$ appears to dominate the error, and the quoted DPT uncertainty comes from carrying the uncertainty in $z_d$ (obtained from [4]) through the VOD calculation. Note that the DPT VOD values agree with the rate stick values to within the quoted uncertainty.

Our strategy for reducing the DPT uncertainty is to use the smallest and most precise detonator available to us, perhaps with a booster pellet if necessary. The current error level is of order 100 m/s, and our goal for this and possibly other refinements is to achieve an error of order 10 m/s. Higher accuracy is unlikely with this technique. However, these error levels are acceptable for many purposes, and DPT has a compelling advantage when the HE loads are either very small or very large.

Finally, it is worth noting that DPT is not a “quick and dirty” test, but rather a “simple and precise” test. A significant amount of attention to experimental and analytical detail is necessary to achieve error levels of 10 m/s, or even 100 m/s. Economy relies on implementing simplifications that do not entail a loss of accuracy.

5. Conclusions
The DPT shows promise for becoming a standard technique for measuring HE detonation velocities. It has been proven to be reliable with the test explosive PBX 9501. The accuracy of the tests presented here is limited by the RP-1 detonator repeatability. By using a smaller and more precise detonator with perhaps other refinements, we hope to reduce the error to order 10 m/s, which is sufficient for many purposes. A compelling advantage of the DPT technique is that it can accommodate a wide range of sizes from very small to very large.

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