Is the detonation “dead zone” really dead?

L. G. Hill ^a,

^a*Los Alamos National Laboratory, Los Alamos, NM 87545 USA*

Contact: Larry Hill
Mail Stop P918
Los Alamos National Laboratory
Los Alamos, NM 87545 USA
FAX: (505) 665-3407
Email: lgh@lanl.gov

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Fig. 2: 97

Fig. 3: 140

Fig. 4: 133

Fig. 5: 63

Fig. 6: 122

Fig. 7: 122

Fig. 8: 125

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Abstract

This paper explores the *Dead Zone* (DZ) phenomenon in solid *High Explosives* (HEs), whereby weaker regions of a detonation shock fail to trigger prompt reaction, leaving behind them isolated pockets of substantially unburned explosive. A key unanswered question is the extent to which DZs react in the following flow, and whether they contribute a significant amount of energy on timescales relevant to system deconsolidation. This paper comprises two parts. The first surveys the DZ phenomenon and discusses 1) the multiple contexts in which it arises, 2) what is observed and believed about it, and 3) how it may be broadly categorized. This general perspective sets the stage for the second part, which examines in detail one particular DZ variant called *transverse initiation*. This case was not chosen because it is the most common or important, but because it is most amenable to inquiry. (DZ quantification is quite difficult, and the presented experiment is apparently the first conceived to quantify DZs of any type.) The technique uses a modified *Cylinder Expansion* (CYLEX) test, wherein a faster HE core (PBX 9501, 95 wt% HMX) is surrounded by a slower HE annulus (PBX 9502, 95 wt% TATB). The fast HE drives detonation in the slow HE faster than the latter would naturally propagate; however, in doing so a largely unreacted initiation layer is left in the slow HE adjacent to the fast HE. Combining the usual CYLEX diagnostics with detonation front curvature measurements and invoking a novel analysis based on the Gurney and Taylor methods, the energy release vs time (and distance) is inferred. The result is a $\sim 0.3 \mu\text{s}$ induction time (3 mm induction lag), after which the energy release rises in $\sim 2 \mu\text{s}$ (15 mm) to half its asymptotic value: $\sim 86\%$ of the energy released by a PBX 9502 detonation.

Key words: Detonation, High Explosive, Dead Zone, Initiation Layer, CYLEX Test

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1 Introduction

Dead Zones (DZs) are isolated pockets of unburned post-shock *High Explosive* (HE) material in which a detonation shock has failed, due to insufficient local strength and consequent heating, to trigger prompt reaction. Although isolated unburned regions can occur in many types of explosives, present consideration is limited to DZs in heterogeneous solid HE materials. A natural question is whether DZs can exhibit delayed reactivity. The answer is important because the influence that DZs have on configurations in which they arise depends on both the amount and timescale of their reactivity.

Although DZ reactivity has been sporadically speculated upon for many years, the subject is by no means an organized sub-discipline. Neither DZ types nor the contexts in which they arise appear to have been well catalogued. Nor have experiments been devised that are able to quantify levels or timescales of DZ reactivity. This paper is a first attempt to address both of these needs.

The first part (§2) identifies contexts in which DZs occur, and briefly discusses 1) key experimental observations, 2) broad DZ behavioral categories, and 3) outstanding questions. The second part (§3) introduces an experimental and analytical methodology that allows inference of the reactivity history of a particular DZ type, called *transverse initiation*. Part one highlights the fact that the part-two example is just one DZ scenario among many, which are not expected to react identically.

2 Dead Zone Categorization

2.1 Detonation initiation and reinitiation

Intentional detonation initiation in engineered HE systems is a bootstrapping process, wherein smaller more sensitive explosives light progressively larger and less sensitive ones. While it must be strong enough to reliably initiate detonation, the shock stimulus received by each HE component need not initiate detonation throughout its entire volume. That is, DZs may occur in nominal, “robust” component function. It seems likely that such can be the case in detonator initial pressings, whether the stimulus is hot wire, exploding wire, or flyer disk.

Accidental initiation scenarios (whether the stimuli are thermal, mechanical, or some combination) are typically more marginal, and the outcome often depends on a myriad of unrepeatable details. DZs are often expected in sce-

narios leading to detonation transition, as is significant variability from one configuration to the next, and even between nominally identical tests.

Various tests have been devised to understand and characterize intentional initiation. For example, the *Wedge Test* drives a plane (usually supported) shock wave into an HE test sample [1]. Each HE has a range of shock input pressures in which the shock transitions to detonation following a temporal and spatial delay. The reactivity induced by the shock is small at first, and increases nonlinearly to the point of detonation transition. The transition event is quite sudden, and the HE material behind that point defines a distinct *Initiation Layer* (IL) in which rather little prompt reaction occurs.

When a detonation encounters an interface between two dissimilar HEs, a reinitiation process ensues. Two common examples are the lighting of a main charge by a booster, and HE lenses. If the donor HE is more powerful than the acceptor and if wave incidence is nearly head-on, then no IL will occur. This is the case near a *Plane Wave Lens* axis; however, incidence becomes more oblique as the detonation propagates, such that an IL forms in the acceptor HE adjacent to the donor HE. In the late stages of device function incidence becomes tangential [2]; we shall consider this case in detail in §3.

In the *Gap Test* an inert barrier is inserted between the donor/acceptor HE interface to create a sensitivity test based on detonation reinitiation attributes. Various barrier thicknesses are tested, and the metric is the thickness causing reinitiation in 50% of trials. The test is popular (with many variants) because it is simple and uses only a witness plate as a go/no-go indicator. Yet gap-test reinitiation is complex, involving short/curved shocks and producing 2D axisymmetric initiation regions.

2.2 Unfavorable charge geometry

DZs are prone to forming in regions where a detonation shock has high convex curvature, such as occurs in response to a sudden widening of the charge. This is because high convex curvatures are associated with low shock pressures, which hinders reaction. The quintessential unfavorable geometry problem is called *corner turning* or *detonation diffraction* [3].

In the simplest variant, one end of a cylindrical HE stick with a diameter slightly above its failure value (the donor) is placed against a much wider HE charge (the acceptor). Under these conditions detonation struggles to bloom into the apparently unbounded space. As it does, reaction may fail surrounding the entrance corner, forming a half-torus-shaped DZ pattern.

2.3 Reaction failure at charge boundaries

The detonation reaction rate near a bare charge edge is lower than near its center. This is because the shock pressure is lower there, and because the streamline divergence after the shock is large and prompt. For certain HE/geometry combinations, the reaction rate may be low enough to be considered dead in a layer near the edge. Such behavior is also predicted by some reactive burn models [4].

For many assemblies in which a solid HE charge is nominally confined, a small gap exists between the two materials. Even for narrow gaps, HE products jet ahead of the detonation; these shock the HE ahead of the detonation in a region near the charge edge. If the shock is sufficiently strong and the HE is sufficiently insensitive, the latter may be deadened in a layer near its boundary.

2.4 Unburned pockets in detonation reaction zones

Indirect evidence suggests that detonation reaction in TATB-based HEs is substantially heterogeneous, such that burn fronts propagate outward from supercritical hot spots to consume the interstitial reactants [5]. There is randomness in the burn-front center locations, creating a situation where some unburned regions in the partially-reacted HE are much larger than others.

At the same time that reaction fronts burn outward, the reacting bulk forms an expanding flow through which the pressure drops and remaining unburned regions cool. It may be that, as a result, the burn front propagation rate drops to the point that reaction essentially freezes, leaving unburned pockets.

2.5 Discussion

Although each of the above DZ scenarios has unique elements, one may usefully divide them into two broad subcategories. The first is an *initiating region*, so-called because it produces sufficient prompt reaction to trigger detonation initiation or reinitiation. Initiating regions often take the form of thin layers (ILs), which were introduced in §2.1.

Evidence of IL reaction in gas-gun-driven wedge tests is apparent in embedded magnetic-gauge records; yet, the companion shock trajectories suggest that the layer as a whole is relatively inert. Such instrumentation does not indicate whether initiating-region material significantly reacts in the following flow [1].

The second category is a *failed region*, in which an established detonation becomes too weak in one or more isolated regions to trigger prompt reaction there, but which remains robust enough to avoid global extinction. Whereas initiating regions must exhibit a degree of reaction to explain the detonation-initiation outcome, failed regions need not exhibit any reaction to explain the qualitative behavior.

Initiating regions have been observed for a wide range of HE material sensitivity, but failed regions have only been observed in the highly-insensitive TATB-based explosives (via penetrating radiography). Although the data is qualitative, these pictures suggest that failed regions are not significantly reactive on the $O[10] \mu s$ timescales associated with charge consumption by detonation.

Viewed radiographically, DZs appear as higher-density lumps for which boundary distinctness, opacity (indicative of density) and projected area are preserved while the feature warps and advects [6][7]. In proton-radiography-diagnosed corner turning tests, Ferm et al. [8] described evidence of reactivity near the DZ boundary but not in its interior, over an $O[10] \mu s$ period.

This impression of deadness has prompted a modeling method whereby DZs are observed in radiographs under the desired conditions, then manually inserted into the domain as “inert” HE. The composite material is then computed by the Detonation Shock Dynamics model [?]. This method may be best for computing the DZ effect on detonation wave propagation, in that Reactive Burn Models have difficulty predicting DZ size. In fact, the widely used pressure-dependent models (e.g., Ignition & Growth) do not predict persistent DZs [3] at all.

Although DZs have only been observed for TATB-based HEs, conventional wisdom says that failed regions *should not* be limited to insensitive explosives. Instead, one expects the phenomenon to scale with the detonation reaction zone thickness. Thus, would argue that an outward bend in an HMX-based charge would need to be $O[10-100] \times$ sharper to create a DZ than one in a TATB-based explosive, and that the resulting DZ in an HMX-based charge one would be $O[10-100] \times$ smaller.

Reaction-zone dependence explains why DZs have only been noticed in, and practically concerning for, TATB-based HEs. By this schema, it is because their size and overall energy decrement is significant in human-scale systems. This is not true of most explosives; however, the recent emergence of microdetonic applications may cause small DZs to become important.

Virtually nothing is known about DZ reactivity on timescales longer than $O[10] \mu s$, which means that little is known about how DZ reactivity may contribute to the disassembly of many engineered HE systems, or how very

late DZ reactivity might contribute to afterburn and blast enhancement.

3 A novel experiment to quantitatively infer delayed DZ reactivity for transverse reinitiation

3.1 Details of slab transverse-initiation behavior

The basic transverse initiation problem comprises two HE slabs of differing detonation speeds joined along one of each of their two faces. Both layers are simultaneously initiated along one of the narrow edges [2]. After running a distance of several slab thicknesses a steady wave structure emerges, which is led by the fast HE (the donor) detonation. The donor detonation transmits an oblique shock into the slow HE (the acceptor).

The oblique shock transitions to detonation in the acceptor, but not immediately. The temporal initiation delay maps to a spatial initiation lag, which takes the form of an IL in the acceptor HE adjacent to the donor. The perpendicular distance from the material interface to the transition locus defines the IL thickness.

The phase speed of the steady structure along the material interface is set by the donor, which (assuming that the face opposite the material interface is unconfined) travels at essentially the speed of a bare donor slab. So far as the donor speed is concerned the acceptor HE behaves as inert, and plastic-like materials generally offer no detonation *wave* confinement [10].

Transverse initiation behavior can be understood by tracking a point on the acceptor-HE shock in the *Detonation Shock Dynamics* sense [?], i.e., by following a trajectory that is everywhere normal to the wave, starting from its inception at the material interface and moving through transition. Such a path—which represents all paths in this steady problem—is illustrated by the red curve in Fig. 1. The dashed lines are hypothetical oblique shock paths, if the acceptor behaved as inert. The dashed line slightly lags the real shock because a finite amount of reaction occurs in the IL.

Viewed in this manner, transverse initiation behaves qualitatively like the Wedge Test, where the normal propagation distance in the latter, x , is replaced by the arc length, s , of the red curve in Fig. 1. As illustrated in Fig. 2, the transverse initiation s - t trajectory looks qualitatively like the x - t trajectory associated with normal initiation. In fact, if the normal shock-speed component is used to compute a shock pressure via the inert Hugoniot curve, then the IL thickness is fairly well predicted by Pop-Plot data [2].

3.2 *Concept: a copper cylinder test based on cylindrical transverse-initiation behavior*

The Pop-plot analogy explains the physical origin of ILs and estimates their thicknesses, but gives no indication of IL reactivity in the following flow. To examine that question, a transverse-initiation-type experiment was conceived within a *Cylinder Expansion* (CYLEX) test [11]. The modified test used the same HE materials that have been used in Los Alamos slab transverse-initiation tests—PBX 9501 (95 wt% HMX, 5 wt% binder) and PBX 9502 (95 wt% TATB, 5 wt% binder)—but configured an annular geometry where the 9501 forms a cylindrical core and the 9502 forms an annular shell.

By measuring the tube-wall motion by standard CYLEX techniques, one may infer the overall energy release via the *Gurney Method* [12]. The total energy is split between that released by the 1) donor HE, 2) acceptor HE in the detonating region, and 3) acceptor HE in the IL region (if any). Having measured the composite energy release from the annular CYLEX test, one may subtract the first two contributions to determine the third.

The size of the two subtracted terms depends on the amount of each constituent and its specific energy. The latter contributions are determined in like manner from CYLEX tests performed on 9501 and 9502 alone. The 9501 and 9502 mass fractions are known a priori, but the split between the detonating 9502 and its IL region is not. To determine this quantity, one measures detonation front curvature at the downstream tube end, exploiting the fact that detonation transition is sharp. Thus the IL can be accurately partitioned and the three mass fractions can be determined.

The IL energy release obtained from the Gurney method is for arbitrarily large tube expansion. While this quantity is certainly interesting, one would also like to estimate the IL energy release profile at earlier (and indeed all) stages of tube expansion. The desired function can be estimated by combining the Gurney-based result with G.I. Taylor’s “long bomb” CYLEX analysis method [13].

3.3 *Design details*

The standard 1-in dia. CYLEX configuration was employed, for which the copper tube is 1-in (25.4 mm) i.d., 12-in (304.8 mm) long, with a 0.1-in (2.54 mm) wall thickness. The basic CYLEX test is ubiquitous and is detailed elsewhere [11], allowing us to focus on how the present configuration deviates from the norm. Because the desired information is inferred from relatively small effects, experimental details are important and will be explained in some detail.

The 9502 annulus o.d. equaled the tube i.d. less a small insertion tolerance. The 9502 i.d.—equal to the 9501 core diameter plus a small insertion tolerance—was tuned by trial and error to achieve the near-optimal IL size. The tradeoff is that 1) the IL should span a significant fraction of the annular thickness so that its energy decrement is adequately resolved by CYLEX, but 2) the IL should not span the entire acceptor because a DZ is, by definition, an *isolated* region of detonation failure.

The first trial used a $\frac{1}{2}$ -in (12.7 mm) dia. core, for which the IL spanned nearly the entire tube. The second trial used a 15-mm dia. core, for which the IL was very small. Both trials were scoping tests with reduced length and instrumentation. Having bracketed the desired behavior, a full test (analyzed in this paper), using a 14-mm dia. core, was fielded. As intended, this produced an IL that spanned about half the acceptor HE thickness.

For CYLEX tests using solid HE cylinders, the charges must fit very precisely in the tube, or else the latter will rupture prematurely and spoil the measurement [11]. For the annular variant, the core/annulus interface must also be intimate to achieve good shock coupling from the donor to the acceptor HE. Each core segment was custom-matched to a specific annulus segment, such that insertion was slightly resistant.

Besides maintaining tight mechanical tolerances, the residual gaps should be filled with condensed-phase material as opposed to air. A specialized device was conceived and developed for this experiment that completely eliminated air gaps in favor of a gel filler. Separate optimized devices were employed to insert the HE core into the HE annulus, and the HE annulus into tube.

A sparing amount of silicone grease was applied to the HE segment faces, as is common practice for Rate Stick tests to remove air gaps. The consistency of silicone grease was too thick to work well with the annular gap-filling technique, and it fouled optical preparation (to be discussed) of the charge end. Water-based “KY Jelly^{TM}” was found to have the right viscosity and lubricating properties, and excess gel was easily rinsed.

The detonation front curvature measurement used the mirror destruction technique, wherein explosively-driven Argon-flash light is reflected off the mirrored charge end toward a streak camera [4]. PBX 9502 is unusual in that it can be polished to a fairly specular finish, eliminating the need for a separate mirror. Although PBX 9501 is not polishable, its white color gives an adequate signature that is modestly enhanced by the application of a thin grease layer.

The tube wall expansion was measured by *Photon Doppler Velocimetry* (PDV). Despite widespread use, PDV interpretation is ambiguous for multidimensional experiments, because target surface-features sweep across the beam while moving toward it. It does *not* measure the rate of decrease of beam

length as one would like, but something closer to the component of mass velocity in the beam direction [14].

For CYLEX, one may minimize multidimensional ambiguity by setting the probe-beam angle in the direction of the asymptotic mass velocity, which is approximately realized during most of the expansion. For the standard CYLEX test, this angle is $\sim 6^\circ$ forward from tube normal. One must make the appropriate geometric transformation using the probe angle and detonation phase speed to properly reconstruct the tube shape.

The shot configuration is pictured in Fig. 3. The copper tube (visible through the foreground features) is clamped between Delrin^{TM} plastic end plates. An angularly-relieved slit is machined across the horizontal diameter of the observation end to allow the streak camera optical access to the charge end. The tube wall and the test explosives are visible through the slit. Fine-wire shorting pins are employed in the standard fashion [11] to measure the detonation speed.

The black ring is the PDV probe mount. Four probes were located at the optimal axial location, 2/3 of the tube length from the initiation end [11]. Two probes were focused and two were collimated; two were set at 6° and two were set at 0° (all permutations explored). There was no obvious effect of focused vs collimated probes.

3.4 Data Analysis

Figure 4 shows a scale schematic diagram of the tube end. The PBX 9501 area is denoted by A_1 , the PBX 9502 detonating area is A_2 , and the IL area is A_{2^*} . Figure 5 shows the digitized streak data superimposed upon the color-coded regions.

The first task is to compute the mass fractions of the three regions. Let the densities ρ_1 and ρ_2 refer to 9501 and 9502, respectively. (Note that ρ_2 applies to regions 2 and 2*, because the mass fractions are computed for pre-detonated HE.)

The mass fraction of region 1 (9501) is

$$\chi_1 = \frac{A_1 \rho_1}{A_1 \rho_1 + (A_{2^*} + A_2) \rho_2} = 0.296; \quad (1)$$

the mass fraction of region 2 (detonating 9502) is

$$\chi_2 = \frac{A_2 \rho_2}{A_1 \rho_1 + (A_{2^*} + A_2) \rho_2} = 0.428, \quad (2)$$

and the mass fraction of region 2* (9502 IL) is

$$\chi_{2^*} = \frac{A_{2^*} \rho_2}{A_1 \rho_1 + (A_{2^*} + A_2) \rho_2} = 0.276. \quad (3)$$

Let q_1 and q_2 be the specific energy release for the 9501 and 9502 detonating regions, respectively. Let q_m be the specific energy release for the mixture. Then the burn efficiency of the IL layer, q_m/q_2 , is

$$\eta = \frac{q_m - q_1 \chi_1 - q_2 \chi_2}{q_2 \chi_2^*}. \quad (4)$$

The quantity q_m is obtained from the Gurney method, which computes the combined kinetic energy of the HE products and the tube subject to assumptions (see, e.g., [12]). The Gurney energy for cylindrical geometry is

$$GE[V] = \frac{V^2}{2} \left(\frac{1}{2} + \frac{\rho_w}{\rho_0} \left(\left(\frac{R_0}{r_0} \right)^2 - 1 \right) \right), \quad (5)$$

where, ρ_w is tube wall density (assumed constant), r_0 is the HE radius (equal to inner tube radius), and R_0 is the outer tube radius.

To deduce chemical energy from Gurney, one notes that in the large expansion limit the product gas pressure is negligible and no longer pushes the wall, which (neglecting wall strength), coasts at constant speed V_∞ . The product-gas temperature and the internal energy are also negligible. Thus, nearly all the late-time energy is kinetic, or ‘‘Gurney.’’

By the energy conservation principle, the final system energy is equated to the pre-detonated energy, which is the thermal energy $C_v T_0$ plus the chemical energy, q_m . Thus, $q_m = GE[V_\infty] - C_v T_0$. The thermal term is small but not entirely negligible.

While simple in principle, the method has important subtleties. First, V_∞ is usually not attained by point of first tube rupture. One must therefore generate an extrapolated value from a fitting form, and V_∞ is sensitive to its mathematical structure. We choose a form which, in the large expansion limit of Taylor’s method, is consistent with a constant ideal-gas isentropic exponent, γ_{ig} . Extrapolation depends on the numerical value of γ_{ig} , which we impose from a product composition estimate.

The notion that a coasting speed V_∞ exists neglects tube strength; however, if one assumes a constant flow stress then the pressure imposed by the tube strength diverges logarithmically as the inertial resistance vanishes. Under Gurney assumptions, for which the tube stretches without breaking, the wall eventually stops.

In actuality, the Gurney strategy constructs a model problem for which tube strength is negligible, and fits it to data in the high-pressure region where inertia dominates. It then extrapolates beyond the data whilst maintaining the no-strength assumption. To add a strength term would be inconsistent with this implicit strategy.

The analysis so-described yields $q_m = 3.60$ kJ/g for the annular test, and $q_1 = 4.89$ kJ/g and $q_2 = 3.23$ kJ/g for the respective 9501 and 9502 tests. Evaluating Eq. 4 using these values and the above mass fractions yields $\eta = 0.86$ (for infinite tube expansion, to vacuum).

One may further estimate how η approaches this final value by invoking G.I. Taylor’s method [13] for computing flow expansion. Taylor’s method treats the system as a self-forming Laval nozzle. It relates the tube trajectory to the flow pressure, P , bearing upon it, and thus computes P vs axial distance, z . By substituting the known pressure history into Bernoulli’s equation, one may integrate to obtain the flow specific-volume, $v[z]$. The resulting description is parametric, $P[z]$ vs $v[z]$.

Taylor’s method has one important shortcoming that arises from its implicit assumption that the wall is incompressible. In reality the wall rings up by a series of reflected waves. This causes a disconnect between the actual pressure and that associated with the smooth fit. The discrepancy is important only for about one tube diameter where ringing is pronounced, but the pressure drops significantly in that distance. It is not clear a priori what form this error will take; experientially, it causes an energy deficiency of about 10%.

Various authors have proposed various corrections, even in these proceedings [15]. The present correction subtracts a constant value, ΔS , from the cross-sectional area when performing the volume integration. Though empirical it has all the desired properties, specifically it 1) influences the integration only at high pressures, 2) does not alter requisite hydrodynamic constraints, 3) provides a “handle” (via the parameter ΔS) by which to impose the Gurney energy as a constraint, 4) preserves the spirit of Taylor’s original proposal, and 5) works well as validated by more complex hydrocode methods.

The key attribute for the present analysis is that the P - v relationship is generic, the only material assumption being inviscid flow. No constraints are placed on the thermodynamic path; in particular, the flow is *not* assumed to be isentropic (although standard CYLEX analysis further assumes isentropic

flow to compute the specific internal energy, $e[z]$).

Thus, the P - v relationship applies to the 9501/9502 mixture whether or not the IL reacts. We may also interpret the specific volume, v , as a mixture quantity, v_m . The IL region is assumed to be partially-reacted, and, following standard practice for mixture equations-of-state (EOS) in reactive burn models, we express the IL specific volume as a mixture of its reactants and products. Then, v_m is expressed as

$$v_m = v_1 \chi_1 + v_{2^*r} \chi_{2^*r} + v_{2^*p} \chi_{2^*p} + v_2 \chi_2, \quad (6)$$

where the subscript r denotes reactants and the subscript p denotes products.

The mass fraction of IL products can be expressed as:

$$\chi_{2^*p} = \frac{m_{2^*p}}{m} = \left(\frac{m_{2^*p}}{m_{2^*}} \right) \left(\frac{m_{2^*}}{m} \right) = \eta \chi_{2^*}. \quad (7)$$

The third equality in Eq. 7 assumes that the heat release is proportional to the reacted IL mass.

Given that $\chi_{2^*r} + \chi_{2^*p} = 1$, the companion relationship to Eq. 7 is $\chi_{2^*r} = (1 - \eta)\chi_{2^*}$. Substituting these quantities into Eq. 6 and solving for η gives

$$\eta[P] = \frac{v_m[P] - v_1[P] \chi_1 - v_2[P] (\chi_2 + g[P] \chi_{2^*})}{\chi_{2^*} v_2[P] (1 - g[P])}, \quad (8)$$

where $g[P] = v_{2^*r}/v_{2^*p} = v_{2r}/v_2$.

The functions $v_1[P]$ and $v_2[P]$ in Eq. 8 are the (inverted) P - v curves for 9501 and 9502, generated by Taylor analysis of their respective CYLEX tests. The function $g[P]$ is the ratio of 9502 reactant specific-volume to product specific-volume. The inert EOS is taken from Wescott et al.'s "WSD" model [16].

The measured IL parameters (see Fig. 5) are listed in Table 1. The detonation phase speed is that of a bare 14-mm-dia. 9501 stick. The IL pressure, P_{il} , is computed by inserting the normal shock speed, U_{il} , into the 9502 inert Hugoniot, using parameters given in [1]. P_{il} arises as an initial condition, at which η must be zero. This attribute is enforced by choice of starting specific volume.

3.5 Results

With all parameters, functions, and initial conditions defined, we may evaluate $\eta[P]$ from Eq. 8. The results are plotted in Fig. 6. The curve is evaluated from 24 GPa (the estimated IL shock pressure) down to ~ 10 GPa, the approximate lower validity limit for the inert EOS. At this limit the Taylor result points toward the asymptotic Gurney value. To join the two results, a straight-line interpolation is used from the Gurney point to the Taylor curve, where the line slope is chosen to meet the Taylor curve tangentially.

Taylor analysis directly specifies $P[z]$. Substituting this function yields IL reactivity vs distance, as shown in Fig. 7. A 3-mm induction length is predicted, and reaction reaches half of its ultimate value ($\eta \sim 0.86$) at ~ 15 mm downstream of the IL.

Taylor analysis also gives the flow speed, by which $P[z]$ may be transformed to $P[t]$. Substituting this function yields IL reactivity vs time, as shown in Fig. 8. A $\sim 0.3 \mu\text{s}$ induction time is predicted, and reaction reaches half its ultimate value in $\sim 2 \mu\text{s}$.

3.6 Discussion

The considered analysis is not a physical model for DZ formation; rather, its purpose is to infer from experimental data the reactivity profile for one particular DZ variant, without appealing to assumptions about the downstream flow structure or reaction kinetics. Its relatively simple and generic methodology is advantageous for this purpose, as there are few material-specific modeling assumptions to go wrong.

Nevertheless, the considered analysis is not the only option for examining the cylindrical transverse-initiation problem. Numerical simulations would also be useful, especially for illuminating flow details that Gurney and Taylor miss. Such analysis is beyond the scope of this work, but the data set may be used as desired.

Moreover, the considered transverse initiation scenario is only one variant within its class. A core-thickness parameter study would be useful, as would a study of different HE pairs. It would also be instructive to swap the 9501 and 9502 charge positions. Further yet, tangential initiation is only one of several DZ scenarios presented in §2. We have argued that ILs are likely the most reactive of the DZ-type structures, and there is reason to suppose that transverse initiation is amongst the most reactive of the IL scenarios.

The reason is that the three layers (1, 2, and 2*) develop different post-shock flow speeds. Layers 1 and 2 burn and expand to a gaseous state. Both travel faster (by differing amounts) than the initially unreacted solid IL layer. Thus the ~ 3 -mm-wide IL becomes a shear layer, which promotes mixing and subsequent reaction between fluidized IL and hot detonation products. For this reason tangential initiation results cannot be generalized to other DZ classes, or even to different IL scenarios.

4 Conclusions

A modified CYLEX test was presented, which is significant as the first known experiment (fielded 16-Mar-2010) to quantitatively infer the level and timescale of DZ reactivity for *any* configuration. Using a novel analysis methodology, it was inferred that 1) a $\sim 0.3\text{-}\mu\text{s}$ induction time (corresponding to a ~ 3 -mm induction length) exists, 2) reaction reaches half its ultimate value in $\sim 2\text{ }\mu\text{s}$ (or ~ 15 -mm axial distance), and 3) reaction asymptotically approaches a value of $\sim 86\%$.

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Tables

Table 1

Measured Initiation Layer Metrics

Parameter	Symbol	Unit	Value
Detonation Phase Speed	D_0	mm/ μ s	8.765
Left IL Angle	ϕ_l	degree	41.3
Right IL Angle	ϕ_r	degree	42.4
Average IL Angle	ϕ_{avg}	degree	41.8
Normal IL Shock Speed	U_{il}	mm/ μ s	6.53
IL Shock Pressure	P_{il}	GPa	24.3

List of Figures

1	Schematic diagram of the transverse initiation problem.	12
2	Pop plot representation of transverse initiation.	13
3	Photograph of the annular cylinder test configuration, Shot# 8-1460.	14
4	Schematic drawing of the annular cylinder test end.	15
5	Digitized detonation shape data superimposed upon the respective material layers.	16
6	IL reaction efficiency vs pressure.	17
7	IL reaction efficiency vs distance after the IL shock.	18
8	IL reaction efficiency vs time after the IL shock.	19

Fig. 1. Schematic diagram of the transverse initiation problem.

Fig. 2. Pop plot representation of transverse initiation.

Fig. 3. Photograph of the annular cylinder test configuration, Shot# 8-1460.

Fig. 4. Schematic drawing of the annular cylinder test end.

Fig. 5. Digitized detonation shape data superimposed upon the respective material layers.

Fig. 6. IL reaction efficiency vs pressure.

Fig. 7. IL reaction efficiency vs distance after the IL shock.

Fig. 8. IL reaction efficiency vs time after the IL shock.