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MEASUREMENT OF THE FLOW PROPERTIES WITHIN A COPPER TUBE CONTAINING A DEFLAGRATING EXPLOSIVE

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Abstract

We report on the propagation of deflagration waves in the high explosive (HE) PBX 9501 (95 wt % HMX, 5 wt% binder). Our test configuration, which we call the deflagration cylinder test (DFCT), is fashioned after the detonation cylinder test (DTCT) that is used to calibrate the JWL detonation product equation of state (EOS). In the DFCT, the HE is heated to a uniform slightly subcritical temperature, and is ignited at one end by a hot wire. For some configurations and initial conditions, we observe a quasi-steady wave that flares the tube into a funnel shape, stretching it to the point of rupture. This behavior is qualitatively like the DTCT, such that, by invoking certain additional approximations that we discuss, its behavior can be analyzed by the same methods. We employ an analysis proposed by G. I. Taylor to infer the pressure-volume curve for the burning, expanding flow. By comparing this result to the EOS of HMX product gas alone, we infer that only ~20 wt% of the HMX has burned at tube rupture. This result confirms pre-existing observations about the role of convective burning in HMX cookoff explosions.

1. Scientific Questions Motivated by Selected Previous Work

Although the term *deflagration* has a specific mathematical/wave interpretation in gasdynamics, in the high explosives (HE) business the term is often meant to describe any sort of burning for which the rate falls between that of slow decomposition and detonation. Thus deflagration, as the term is commonly used, need not refer to a combustion *wave* at all. On the other hand, deflagration is a wave in its primary application of interest, namely deflagration-to-detonation transition (DDT). Deflagration is also important apart from DDT, because sufficiently well-confined HE systems can cook off to a violent explosion even if detonation does not occur.

Deflagration behavior is more variable, and often more complex, than detonation behavior. This is largely because, as a subsonic phenomenon, deflagration is much more influenced by the system conditions—its confinement, and the HE state and temperature at ignition—than is detonation. Moreover, the attribute one calls "confinement" actually involves four physical attributes that control post-ignition behavior. These are: 1) inertia/weight, 2) strength/stress-to-failure, 3) ductility/strain-to-failure, and 4) stiffness/modulus. Note that HE porosity and/or ullage add compliance and decrease the effective system stiffness. The O[1000×] HE volume increase upon reaction generates tremendous pressures in sealed systems, in response to which no system is rigid, nor does any container remain sealed for long. But the degree of reaction violence, including the tendency for the system to undergo DDT, depends sensitively on how long the container *does* stay sealed, and how much it stretches prior to rupture.

Deflagration waves with simple near-classical flame structures are observed in strand burner experiments. However, even in this unconfined environment a flame will sometimes zip ahead through flaw(s) in the pellet. Although this effect (which in this context has been called erratic burning [1]) is most prevalent in neat-pressed pellets, it also occurs in binderless materials. Clearly, a different and more vigorous from of burning is possible. Over the past ~15 years cookoff work performed at Los Alamos has mostly focused on this effect, which can be described as convective burning in cracks pores, and flaws [2].

Our interest in convective burning began with a focus on the DDT problem in the early 1990's, and was piqued by the observations of Dickson et al. [3]. That study examined tablets of PBX 9501 (95 wt% HMX, 5 wt% binder), wherein the HE was weakly confined around its circumference by a steel or copper ring, and strongly confined on the faces. One face was a glass window through which the post-ignition response was photographed. Assemblies were heated to slightly subcritical temperatures (e.g., 200°C) and center-ignited with a hot wire, or else heated to auto-ignition at ~220°C. Upon ignition, burning crack networks formed which, depending on experimental details, exhibited what looked to be an almost fractal structure. This work was the first to demonstrate that post-ignition reaction can involve complex, self-organizing, multi-phase structures. A simple model of reaction runaway in this system is presented in Ref. 4.

Dickson et al.'s experiments closely resembled a thin slice of an HE-filled pipe. If actually extended to form a pipe, one might expect a similar reaction structure as the tablets, but one that propagates as a wave down the tube. Experiments of this sort were performed by Leuret et al. [5] with interesting results who, like Dickson et al., used an HMX-based explosive. Unlike Dickson et al., Leuret et al. did not heat the HE prior to thermal ignition; nevertheless, because they used very thick-walled steel tubes in all cases, they achieved a vigorous reaction response.

Leuret et al. observed the interior pressure via wall-mounted gauges, and reaction light via wall mounted fiber optic probes. They observed a burn wave that propagated down the tube at 1.1 to 1.5 times the nominal HE sound speed. Because the first disturbance was supersonic, they believed these structures to be low-velocity detonations (LVD). However, this interpretation seems incompatible with another observation, namely that the lead disturbance was not a shock, but apparently a diffuse structure 10 to 15 mm thick. Some fraction of their "LVD" waves would, rather abruptly and seemingly at random, transition to high order detonation.

Whatever the interpretation of Leuret et al.'s waves, it is significant that their speed increased linearly with the nominal tube strength (the other three confinement attributes being essentially fixed). Consequently, holes drilled through the wall to pass instrumentation probes were likely perturbing. Although the authors do not discuss the mode of tube failure, it seems inevitable that these "flaws" compromised the tube strength so as to precipitate early gas venting and cause premature rupture. We have become sensitized to the phenomenon of venting-induced reaction quenching by our experiments involving flames in narrow PBX 9501 gaps, in which the HE was backed by a very heavy steel assembly. There, we observed substantial shot-to-shot variation in reaction violence, which we attributed to differences in the pressure at which the nominally identical test assemblies vented [6, 7].

The above background discussion motivates our interest in copper tubes. Clearly, Leuret et al. have uncovered some very interesting behavior; however, our experience with flames in cracks shows that early venting due to tube penetrations made for instrumentation access is likely to have an important effect. One solution is to avoid all case penetrations and to use a high strain-to-failure tube material, so as to delay tube rupture for as long as possible. One may use penetrating radiography to directly observe aspects of the interior HE behavior (e.g., Ref. 8), or, one may infer aspects of the interior behavior by observing the case motion (e.g., Ref. 9) until which time the tube ruptures.

2. The Deflagration Cylinder Test and its Behavior

We have discussed the design and instrumentation of the DFCT elsewhere [9−11], and therefore provide only the most essential features here. The DFCT is patterned after the standard DTCT: the annealed alloy C101 copper tube is 1-in (25.4 mm) i.d., 0.1 (2.54 mm) wall thickness, 12-in (304.8 mm long). Unlike the DTCT, the DFCT is well-sealed on both ends, such that the tube ruptures before the end seals fail. The DFCT is heated to a uniform elevated initial temperature, and is initiated at one end by a hot wire. The burning-induced wall motion is observed in silhouette by a high speed electronic framing camera.

All DFCTs performed to date used PBX 9501 as the test explosive. We have observed three classes of behavior, details of which are presented in Ref. 11. The first behavior occurred for soak temperatures of 155°C, for which the HMX was in the β-phase. In those tests, reaction occurred only at the HE/tube interface. A "peel-off" wave propagated down this interface at about 500 m/s, opening up a ~2 mm gap between the two materials. A description of that behavior and a simple model that reproduces its essential features are given in Ref. 10.

The second behavior was observed at 175°C and 190°C, for which the HMX was in the δ-phase. In those cases reaction was apparently triggered by a peel-off wave as before. However, instead of staying at the HE surface, reaction spread into the interior, causing much more vigorous reaction than for a peel-off wave alone. We believe that the reason convective burning is able to penetrate the interior in δ-phase tests is that the porosity and permeability are much higher than in the β-phase. We have called this phenomenon a peel-off convective, or "POC" wave. POC waves are nominally steady, although for reasons discussed in [9−11] they are prone to stalling/flame-out. Reaction is sufficiently vigorous that it expands the tube into a funnel shape to the point of rupture, in a manner analogous to the DTCT. We shall show that with certain assumptions, POC waves can be analyzed in the same way as the detonation cylinder test.

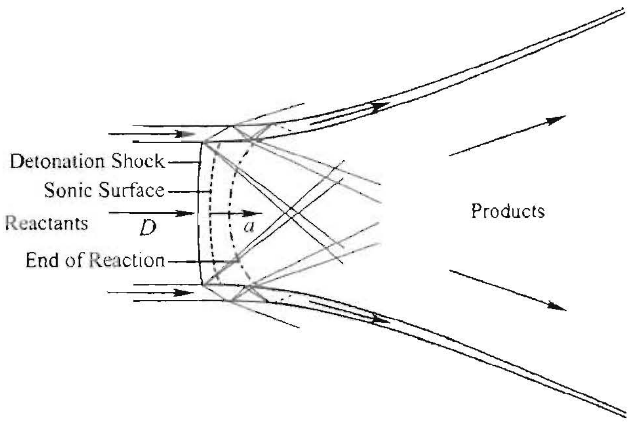
The third behavior also occurred for one 175°C δ-phase test. On this occasion the deflagration wave was more vigorous from the start than in any of the other cases, and transitioned to detonation about 2/3 of the way down the tube. In a repeat test with a nominally identical configuration and initial conditions, only a POC wave transpired. The cause and mechanism of DDT is not understood at this time.

3. G. I. Taylor's "Long Bomb" Analysis

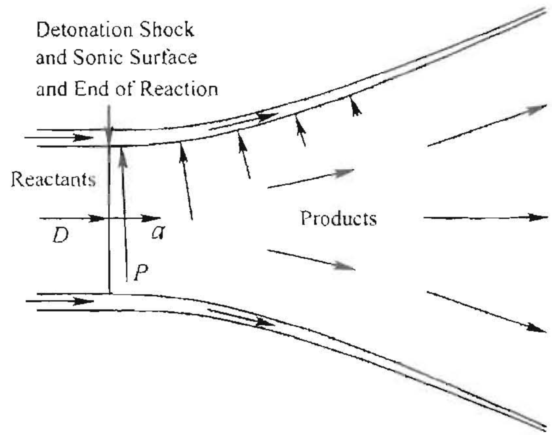
During World War II, G. I. Taylor studied several problems of interest to the war effort. In 1941 he wrote a paper for the British Ministry of Home Security entitled *Analysis of the Explosion of a Long Cylindrical Bomb Detonated at One End* [12], in which he considered a detonation propagating in an HE-filled pipe. Taylor noted that the flow is steady in the wave-fixed frame. Furthermore, the expansion of the pipe in response to the detonation product pressure is analogous to the diverging section of a supersonic *De Laval nozzle*—albeit one that is self-forming and for which the nozzle walls are also flowing.

Gasdynamic theory indicates that the flow is sonic at the nozzle throat. Although the long bomb problem has no "throat" per se (because there is no contraction section), one may consider the throat to be the beginning of the expansion section located at the detonation wave. In order for nozzle theory to apply, the flow emerging from the detonation in the wave-fixed frame must be sonic. This is in fact true: there exists a sonic surface just downstream of a free-running detonation shock, which constitutes a satisfactory initial condition.

The real long bomb problem has many details as depicted in Fig. 1a (see Ref. 13 for a detailed discussion), which Taylor idealized as shown in Fig. 1b. In Taylor's simplified picture, the flow pressure at each axial position can be simply related to the wall trajectory. Combining this relationship with the conservation equations for mass and momentum, together with a pressure/specific volume (P-v) relation for the adiabatic expansion, one may solve for the wall motion. That this may be done without invoking the energy conservation equation is greatly simplifying. Taylor observed that the inverse problem could also be performed, whereby the P-v adiabat could by inferred from the measured wall motion. Taylor believed that the fundamental difficulty in doing so would be the accuracy to which the tube expansion could be measured. Such was in fact the case in 1941; however, by 1945, precision streak cameras developed for the Manhattan project could measure the wall motion precisely.



a) Details of the wave and reaction structure



b) G. I. Taylor's Long Bomb Idealization

Figure 1: Schematic diagrams of the cylinder expansion test in wave-fixed coordinates.

Instead, the main experimental challenge was to make the tube to stretch by a large amount without breaking. Lawrence Livermore National Laboratory (LLNL) solved this problem in the early 1960's by constructing the pipe from high purity annealed copper. LLNL's development of the DTCT was unrelated to Taylor's analysis; rather, the intent was to infer EOS information via hydrocode analysis [14]. Taylor's scientific works were published during DFCT development. Presumably, few workers knew of his obscure wartime report prior to that time. Even if they did, no one would be likely to use it because 1) HE workers, like everyone else, were enamored with the emerging numerical computing capability; and, 2) Taylor's inverse problem is ideally suited for symbolic manipulation programs, which did not mature until the early 1990's.

Ultimately, the main limitation of Taylor's method is associated with a phenomenon that he might of, but apparently did not, anticipate. The technique relies on the simple connection between the wall trajectory and the pressure bearing upon it, which in turn requires that the wall is incompressible. In reality the wall is nearly incompressible, except in response to the first shock driven into it by the detonation wave. This shock abruptly turns the wall, sending an expansion wave into the interior flow. Although this feature may appear to be minor, a substantial part of the expansion occurs through this rarefaction wave.

The only option available to the theory is to fit a smooth curve to the real wall motion, ignoring the actual ring-up of the tube, with the hope that the result will (like quasi-1D gasdynamics) work better than it has a right to. The accuracy obtained by using a smooth fit depends weakly on the fitting form (provided that the form is admissible [15]), and more upon the HE. For high density explosives, Taylor analysis causes the pressure to be ~10% low over most of the expansion. Although this level of accuracy is not quantitatively useful, one may reasonably correct for it. For a low bulk density HE such as ANFO, for which the detonation speed is less than, or comparable to, the copper sound speed, little or no shock is transmitted to the wall. Incompressibility effects are small, and little if any correction is needed. Rather than present the equations for Taylor's method, which have been adequately disseminated elsewhere, [12, 15], we shall focus on the application of the Taylor's inverse problem to deflagration waves.

4. Application of G.I. Taylor's Method to Deflagration

Except for the issue of wall compressibility, the application of Taylor's method to the DTCT is robust. However, its application to the DFCT is much more tenuous. Firstly, the fluid conservation equations place definite limits on deflagration behavior [16]. For example, a steady 1D deflagration wave propagating in a tube requires an outflow downstream boundary condition, and the pressure must drop through that outflow. Both of these attributes are incompatible with the properties of a sealed system. For example, if one fills a tube with a flammable gas mixture and ignites it at one end, the resulting behavior is complex and far from steady.

If the reaction-generated pressure is high enough that the tube stretches to the point of rupture, then an outflow boundary condition is created which, in principle, could enable steady or quasi-steady deflagration. A steady wave would presumably occur for a simple conductive burn front, as is observed in strand burner tests. For convective burning it seems less clear that an outflow condition alone would ensure steadiness. To consider the question of steadiness for convective burning, let us examine the POC wave scenario, which—at least for modest propagation distances—we have actually observed to be quasi-steady.

Based on circumstantial evidence discussed in Refs. 9-11, we imagine the interior reactive flow structure to be as idealized in the wave-fixed coordinates of Fig. 2. The peel-off wave propagates at a speed $V_w \sim 500$ m/s. We believe that a pressure spike associated with the peel-off wave [9] drives convective burning into the HE interior. If the convective wave propagates at a speed v normal to itself, then the head of the wave makes an angle $\theta = \arctan[v/V_w]$ to the axis. Downstream of the wave head, there must be a deconsolidation locus at which burning grains (and/or larger chunks) separate. Beyond that point the flow consists of burning HMX particulates in a hot product gas flow. A sonic surface likely occurs in the deconsolidated flow.

Simple theory says that a peel-off wave propagates at the sound speed of the detonation products within a tiny gas jet that propagates the wave forward [9]. This this speed is about five times smaller than the sound speed of the pristine explosive. Consequently this deflagration wave is subsonic by a considerable margin. As such, acoustic pressure waves propagate forward to pressurize the HE ahead of the convective wave head. As the upstream HE is pressurized the tube expands laterally. Once the tube has reached the elastic limit—which occurs promptly for our design—it expands at (for copper at least) an approximately constant plastic flow stress. Thus, to a good approximation the upstream pressure will be clamped to that consistent with the plastic flow stress. Nominally, then, nonsteadiness will manifest as a progressive swelling of the tube ahead of the burn front.

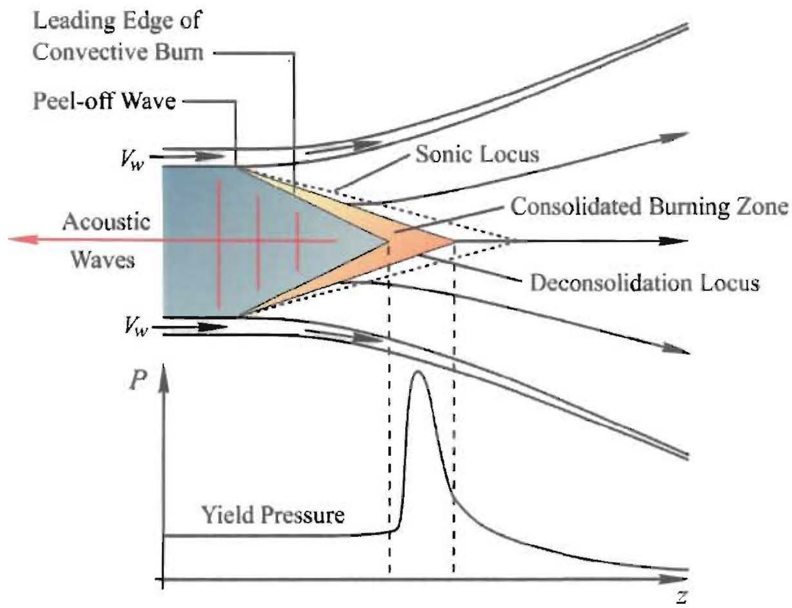


Figure 2: Inferred, idealized reaction structure of the observed POC wave, together with the approximate shape of the axial pressure profile that (logically) must have caused it.

If this were the only effect then non-steady behavior might be subtle, at least over modest propagation distances. A more important issue is that peel-off waves require a starter gap in order to propagate [9-11]. In our test, this starter gap is created over a period of a few minutes by smoldering reactions prior to HMX ignition. In theory at least, the POC wave can only propagate as far as the starter crack has run prior to ignition. But even if the starter crack spans the entire tube length by this means, the progressive upstream pressurization just described would likely squeeze it shut, causing the POC wave to stall for that reason. For either or both reasons, the POC waves we have observed have all stalled after propagating one to five diameters. Reaction is completely quenched when stall occurs, and unburned HE is recovered from the remaining portion of the tube.

Figure 2 also shows what the axial pressure must qualitatively look like in order to generate the observed behavior. The upstream pressure is clamped to the value dictated by the tube flow stress. The region of convective, consolidated burning builds pressure, due to 1) the material strength (which is likely negligible for these hot systems), and 2) inertial confinement. That is, flames zip into cracks and pores in the thermally damaged δ-phase HMX [4]. Over a short time period, the solid explosive is confining and is essentially stationary. After a short time, the gas pressure starts to expand the material. The particles deconsolidate soon after start-of-motion, and a flow is established that qualitatively conforms to the classical assumptions [16].

How can we know for sure that the interior burn is not a simple conductive front, as nominally occurs in a strand burner test? In that situation the equations of fluid motion dictate that the pressure would be uniform in the reactants ahead of the wave. That pressure would be the highest value in the system, and would drop through the burn front and the products. But in that scenario the tube would stretch and rupture ahead of the burn front, not behind it. The only way to explain the observed POC behavior, and to achieve a DTCT-type response, is if the burn is convective. Only then can a burn front (like for a detonation wave) generate pressure.

Leuret's experiments, as well as the one DFCT experiment that underwent DDT, both serve to illustrate that a variety of behavior may occur depending on the system details. One question of particular interest is whether conditions exist, under which a bulk convective wave (steady or otherwise) can propagate into the HE without a peel-off trigger wave, in a manner analogous to Dickson et al's tablet experiments. The answer to this question must await further experiments.

5. Taylor Results for the Observed Peel-Off Convective Wave

In Ref. 9-11 we show pictures of various deflagrating assemblies and recovered shots. Here we shall focus on the Taylor analysis results, for which we present only the data actually used by the analysis. The wave position-time data, taken from the high speed pictures, is plotted in Fig. 3. Near the record end the wave "stutters", and then returns to essentially the original speed. The calculated speed (the slope of the fit line) prior to the stutter is 548 ± 8 m/s. The recovered shot indicates that the wave failed completely at about 135 mm total travel. Figure 4 shows the extracted tube shapes taken from the region where the wave runs steady. The scatter in the individual traces represents both experimental error and a time-varying fine structure [9-11]. The fitting form, shown in Fig. 4, is a special case of the more general form given in Ref. 15.

The only information Taylor's method needs besides the wave speed and expansion data, is the inner and outer tube dimensions and the wall density. In performing the analysis we must assume that the inferred reaction structure drawn in Fig. 2—the details of which are assumed based upon deduction—is sufficiently like the ideal detonation problem depicted in Fig. 1b. In doing so we idealize the pressure profile in Fig. 2 as a step rise followed by a decay, and the sonic surface is assumed to coincide with the wave head. Consequently the flow is modeled as Mach one at the throat, even though the structure of Fig. 2 would place it at about Mach 0.2. As a correction to this obvious error, one may modify Taylor's analysis to include a conical centerbody. This extension is too lengthy to include here; however, the P-v expansion curve it generates is nearly unchanged from that of the nominal model, if one takes as the specific volume the mean value across each section. This exercise serves to illustrate that the simpler , nominal Taylor analysis will be adequate for many purposes.

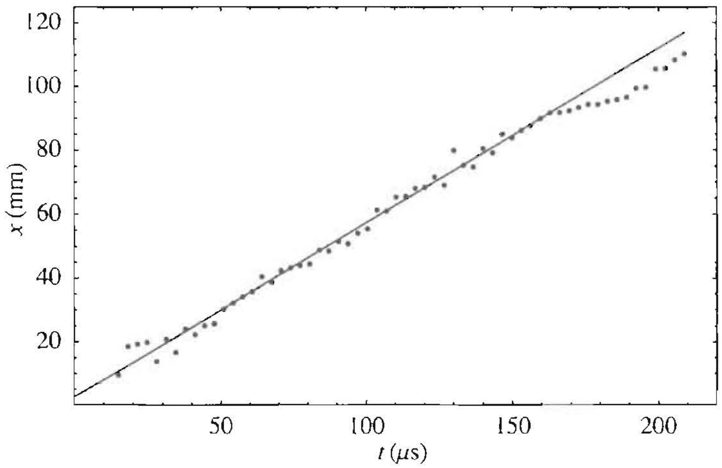


Figure 3: *x-t* diagram for the considered POC wave, with a linear fit to obtain the speed. The wave stutters near the record's end, returns to the original speed, and fails completely soon after.

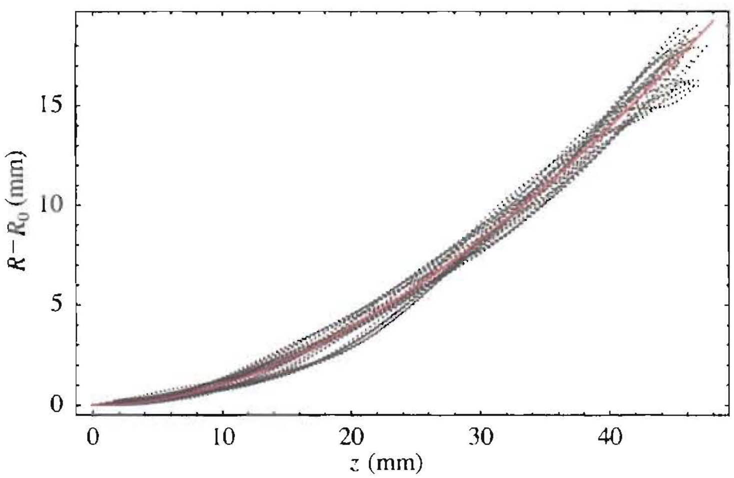


Figure 5: Ensemble of tube expansion contours taken from the steady wave region. The superimposed analytic fit (the red curve) is the form given in Ref. 15.

The deflagration problem differs from the detonation problem in other important ways besides detailed flow structure. In the detonation problem the tube strength has a small effect at large expansions, which we account for in a simple way [15] (cf. Taylor's original analysis [12]). In the deflagration problem, where rates and pressures are much lower, the tube strength is a non-trivial factor. Secondly, in the detonation problem the peak pressure is so large that the upstream (ambient) pressure is taken to be zero. Whereas, in the deflagration problem, the initial pressure will maintain a value corresponding to the tube flow stress, which is non-negligible.

Thirdly, in the detonation problem the initial specific volume, which is used as the starting point in the differential equation for the flow volume, is the detonation value determined from the Rayleigh line. In the deflagration problem, the initial density is indistinguishable from the nominal HE value. Fourthly, in the detonation problem the expanding flow is (we hope) completely burned detonation products. Whereas, in the deflagration problem we have argued that the P-v relationship *must* correspond to a burning gas-particle mixture. However—and this is one of the most important points about Taylor analysis—because we have managed to avoid the energy equation, flow reaction is of no consequence to the analysis. Taylor's method makes no assumptions about the flow composition or its energetics; rather, the expanding fluid is simply a generic compressible substance, and reaction is merely something that affects the compressibility in a way that the method is able to sort out.

The inferred P-v expansion curve (solid) is plotted in Fig. 5. The peak pressure is about 100× less than for a PBX 9501 detonation. The dashed line is the fluid flow pressure corresponding to the tube plastic flow stress, which decreases as the wall stretches and thins.

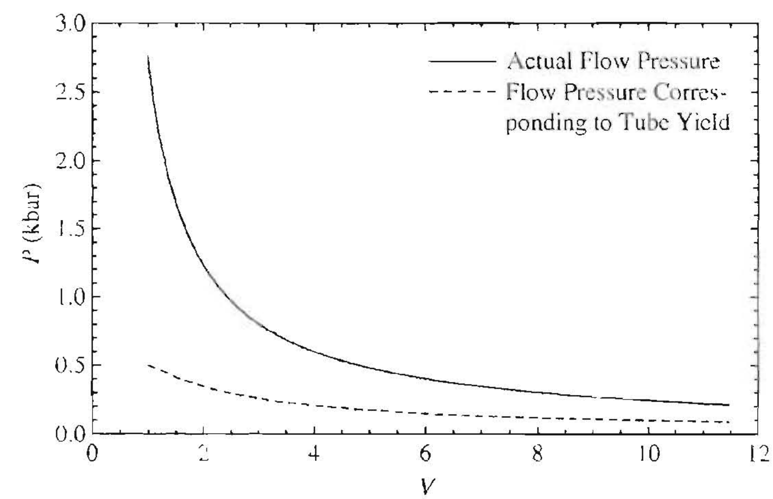


Figure 5: Pressure P vs. relative volume $V = v/v_0$. (solid curve). The dashed curve is the flow pressure corresponding to the wall plastic flow stress.

For a gas-particle flow, one can estimate the gas fraction by comparing the P-v curve for the gaseous combustion products to the Taylor result for the mixture. At deflagration pressures, the combustion product EOS is adequately represented by a general-purpose equations of state (in this case Redlich-Kwong [17]). The result is shown in Fig. 6, which plots the product volume fraction, denoted by β, and mass fraction χ, versus axial distance. The curves are plotted to the point of tube failure. At that point the flow is nearly all gas by volume; this is expected because the gas is ~1000× less dense than the solid. However, χ is only about 20%. This result confirms our reasoning about the convective structure.

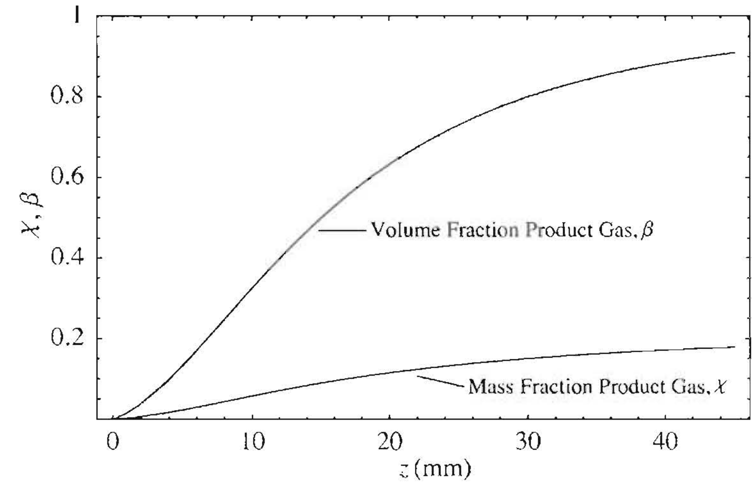


Figure 6: Inferred product volume fraction β and mass fraction χ, versus axial distance z.

The internal energy of the expanding flow follows from the first law of thermodynamics. The internal energy of the HE prior to combustion is cT_0, where c is the specific capacity and T_0 is the pre-ignition temperature. For a detonation, shock compression raises the internal energy essentially instantaneously. The reaction zone follows immediately, which adds an additional specific energy q over a small distance. This abrupt two-fold energy rise is followed by an extended expansion region, in which the fluid internal energy is converted to kinetic energy.

For a POC wave reaction energy is continuously added throughout the flow, while internal energy is simultaneously lost to flow kinetic energy. These two competing processes affect the energy in opposite ways. The net effect is plotted in Fig. 7 for several values of q, which is somewhat uncertain in this regime. (For thermal decomposition, $q \approx 2$ kJ/g; whereas for detonation, $q \approx 5.5$ kJ/g. The value for POC waves should fall between these two extremes.)

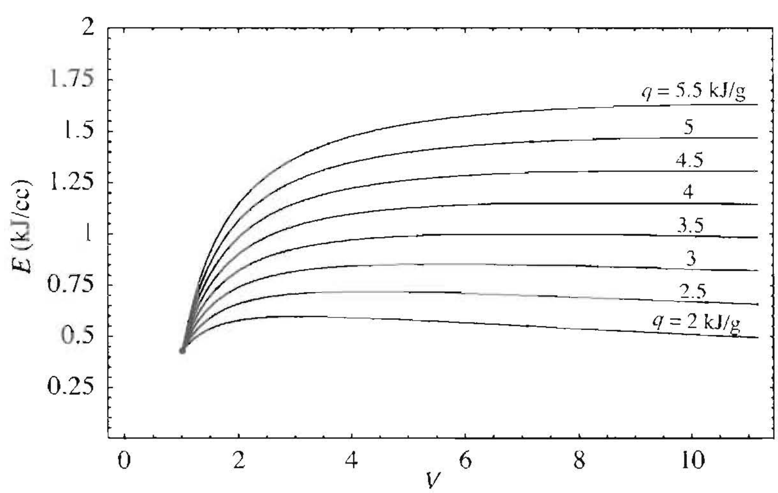


Figure 7: Internal energy/volume E, versus V v/v_0, for several values of the specific heat release q.

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