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Abstract. Shock experiments were performed on the plastic bonded explosive (PBX) LX-17 (92.5% TATB, 7.5% Kel-F binder) using a single low amplitude shock wave at one end of a cylindrical sample to pre-compress the material just prior to detonating the LX-17 charge from the other end to investigate the possibility of shock desensitization. A 101 mm diameter propellant driven gas gun and LX-17 sample containing manganin piezoresistive pressure gauge packages were utilized to qualitatively measure the shock desensitization effects. At pre-shock pressures of ~0.68 and ~1.1 GPa, LX-17 showed failing detonation waves in the pre-shocked region. However, at a pre-shock pressure of ~0.52 GPa, the detonation wave proceeded through the LX-17. This shock desensitization effect has been observed in other explosives containing PBX 9404 and Composition B-3. The LX-17 Ignition and Growth model including a time dependent shock desensitization model was used to explain the rate of decay of the detonation wave in the shock desensitized LX-17 and the detonation of more weakly shocked LX-17.

Introduction

Shock desensitization or "dead pressing" of porous solid explosives can either be a useful property, if one wants to prohibit detonation in some or all of an explosive charge, or an unwanted property, if one requires full detonation of the charge. In the classic paper of Campbell and Travis on PBX 9404 (94% HMX, 3% nitrocellulose, and 3% chloroethylphosphate) and Composition B-3 (60% RDX and 40% TNT) [1], it was shown that, within a certain range of weak shock strengths, the pressures were sufficient to compress all of the voids and other discontinuities without causing significant exothermic reaction. When detonation waves entered these pre-compressed "dead zones," they were extinguished after propagation times determined by the weak shock pressures. For PBX 9404 and Composition B-3, the measured pressure range for shock desensitization was 1 – 2.4 GPa. Below 1 GPa, the shock waves were too weak to close all of the "hot spot" sites. The approaching detonation wave did falter but initiated enough remaining voids and other discontinuities to continue to detonate through that region. Above 2.4 GPa, the shock wave was strong enough to create reacting "hot spots," which provided extra ignition sites for the oncoming detonation wave. This detonation wave continued to propagate with no fluctuations.

Insensitive high explosives based on triamino trinitrobenzene (TATB) are very difficult to shock initiate, have relatively large failure diameters, fail rapidly when their detonation waves are perturbed, and leave "dead zones" of partial or no reaction when their detonation waves encounter changes in

geometry. Several researchers have speculated about the shock desensitization properties of TATB based explosives. Several qualitative experimental studies have observed shock desensitization of TATB in various geometries. These are discussed by Tarver [2], who used quantitative experimental data (X-rays and PDV probes) plus Ignition and Growth reactive flow modeling to analyze a series of shock desensitization experiments by Hart [3]. Hart used hemispherical ultrafine TATB booster charges placed on steel plates of various dimensions to detonate LX-17 (92.5% TATB, 7,5% Kel-F binder), creating spherically diverging detonation waves. Upon reaching the top and bottom edges of the steel plates, the LX-17 detonation waves turned these corners, leaving small "dead zones" of partially reacted LX-17, but continuing to propagate. Upon turning the bottom corners of the steel plates, the detonation waves traveled into 1 or 2 cm wide channels of LX-17 between the bottoms of the steel plates and the tops of 5 mm thick aluminum plates holding the entire charges. These 1 or 2 cm thick LX-17 layers had been "pre-shocked" by the shock waves formed in the steel plates by the original detonations. Upon entering the pre-shocked LX-17 channels, the LX-17 detonation waves quickly failed. This was confirmed by X-rays taken of the expansion of the aluminum plates at several times and by PDV probe free surface velocity records of the aluminum plates at several distances from the center points. The PDV probes showed low velocities at all points on the aluminum free surfaces under the steel plates, indicating shock desensitization, and high velocities on all aluminum free surfaces outside the steel plates, indicating detonation. The Ignition and Growth LX-17 model parameters, which include time dependent pressure-time dependent shock desensitization rate equations, accurately calculated: the shock desensitization for the LX-17 in the channels; the aluminum plate jump-off times; and the aluminum plate free surface velocity histories of the PDV probes for all 5 experiments. The calculated shock pressures in the pre-shocked LX-17 in the channels were 1.2 to 1.4 GPa. The weak shocks traversed through the LX-17 in the channels approximately 2 to 3 microseconds before the LX-17 detonation waves entered the "pre-compressed" LX-17 region. This research clearly showed rapid shock desensitization of LX-17 within a few microseconds at 1.2 to 1.4 GPa.

Quantitative pressure - time measurements of the direct interaction of weak shock waves and LX-17 detonation waves are needed. In this paper, experiments are reported that use the LLNL 101 mm gas gun to impact LX-17 targets containing embedded manganin pressure gauges to measure the pressure histories of weak precursor shock waves, detonation waves, and the failure (or continued detonation) of the detonation waves in the pre-compressed region. Teflon flyer plates were fired at low (277 to 491 m/s) velocities into LX-17 charges. This created weak shocks of 0.52 to 1.1 GPa in LX-17 targets. At the correct times, detonators initiated HMX charges at the opposite ends of the LX-17 charges. The HMX detonation waves promptly initiated LX-17 detonation waves that then traveled through the charges and interacted with the weak unreactive shock waves in LX-17 within the charge. At shock pressures above 0.68 GPa, failures of the LX-17 detonation waves occurred within one μs after the collision of the waves. The Ignition and Growth calculations predicted the detonation wave failures and the rates of decay of the peak shock pressures in the shock-desensitized LX-17. At an impact shock pressure of 0.52 GPa, the LX-17 detonation wave propagated through the pre-compressed LX-17. Thus a shock desensitization region between 0.52 and 0.68 GPa was determined.

Experimental Procedure

Figure 1 shows a description of a typical experiment. The projectile consisted of a sabot with a Teflon flyer plate on the impact surface. The explosive was in the form of thin disks with gauge packages inserted in between with the total explosive thickness approximately 28 mm. The manganin piezoresistive foil pressure gauges placed within the explosive sample were "armored" with sheets of Teflon insulation on each side of the gauge. Manganin is a copper-manganese alloy that changes electrical resistance with pressure (i.e. piezoresistive). Also used were PZT Crystal pins to measure the projectile velocity and its tilt (planarity of impact). During the shock

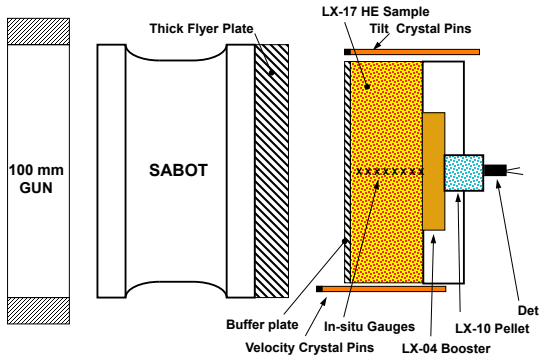

Figure 1. A schematic diagram for the shock desensitization experiments 4817 and 4829. Experiment 4812 used a similar experimental design except a Composition B booster was used.

experiments, oscilloscopes measure change of voltage as result of resistance change in the gauges, which were then converted to pressure using the hysteresis corrected calibration curve published elsewhere [4,5]. Table 1 lists the flyer velocities, calculated shock pressures, and calculated shock durations for the three shots.

Table 1. Shock Desensitization Experiments.

Shot #	Flyer Velocity (km/s)	Shock Pressure (GPa)	Shock Duration (μs)
4812	0.491	1.10	2.8
4817	0.341	0.68	3.0
4829	0.277	0.52	3.3

Experimental Results

In-situ gauge records for experiments 4812, 4817, and 4829 are provided in Figs. 2 - 4 respectively. The detonator in shot 4812 fired late and caused the Composition B detonation to initiate the LX-17 about 10 μs late. Side rarefactions caused gauge stretching before the detonation wave arrived. The detonation wave was extinguished, but the measured pressures are uncertain. Shots 4817 and 4829 fired on time and produced excellent pressure histories.

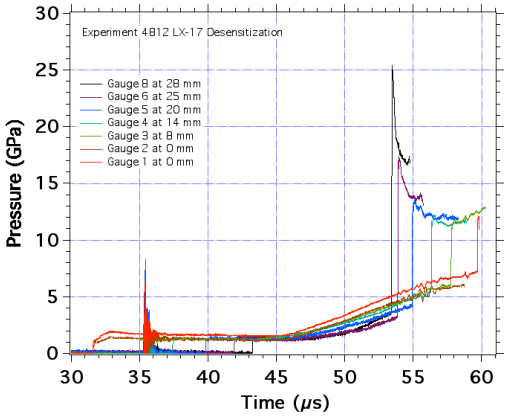

Figure 2. Manganin gauge records for shot 4812.

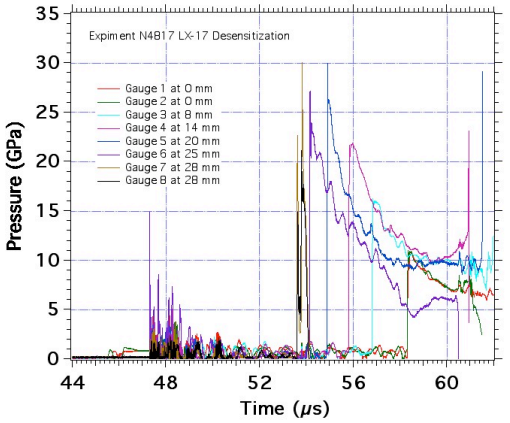

Figure 3. Manganin gauge records for shot 4817.

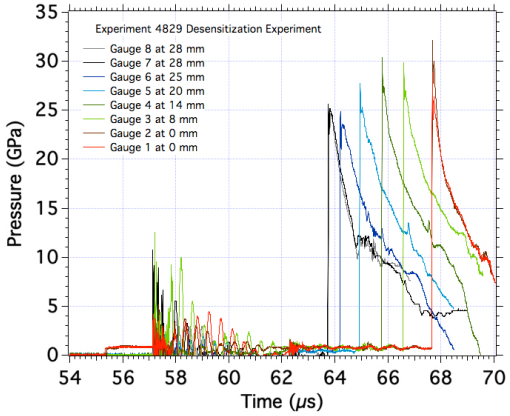

Figure 4. Manganin gauge records for shot 4829.

Shot 4817 exhibited detonation at 28, 25, and 20 mm positions and decaying shocks at the 14, 8, and 0 mm gauges. Shot 4829 showed detonation pressures at all 6 gauges, indicating that the 0.52 GPa input pressure did not completely desensitize this LX-17 charge.

Ignition and Growth Desensitization Model

The Ignition and Growth reactive flow model of shock initiation and detonation has been used to understand many shock initiation and detonation studies of solid explosives and propellants in several 1D, 2D, and 3D codes [6]. The set of Ignition and Growth parameters for detonating LX-17 was established by modeling many 1D, 2D and some 3D experiments. The model uses two Jones-Wilkins-Lee (JWL) equations of state, one for the unreacted explosive and one for its reaction products, in the temperature dependent form:

$$p = Ae^{-R_1 V} + Be^{-R_2 V} + \omega C_v T/V \qquad (1)$$

where p is pressure in megabars, V is relative volume, T is temperature, ω is the measured Gruneisen coefficient, C_V is the average heat capacity, and A, B, R_1, and R_2 are constants. The reaction rate law for the conversion of explosive to products is:

$$dF/dt = I(1-F)^b(\rho/\rho_o - 1 - a)^x + G_1(1-F)^c F^d p^y \quad (0<F<F_{igmax};\ 0<F<F_{G1max})$$

$$+ G_2(1-F)^e F^g p^z \quad (F_{G2min}<F<1) \qquad (2)$$

where F is the fraction reacted, t is time, ρ is the current density, ρ_o is the initial density, and I, G_1, G_2, a, b, c, d, e, g, x, y, z, F_{igmax}, F_{G1max}, and F_{G2min} are constants. The mixture equations assume pressure and temperature equilibration between the unreacted explosive and its reaction products.

The unreacted JWL for LX-17 is fit to experimental shock compression data and nanosecond time resolved von Neumann spike data for detonating LX-17 [7]. The weak shock pressures listed in Table 1 for the three experiments are calculated using the unreacted elastic-plastic JWL form. This equation of state form modeled previous low-pressure (<1 GPa) manganin gauge data on unreacted LX-10 (95% HMX/5% Viton) [8]. The reaction product JWL equation of state is fit to the wall velocity expansion data from cylinder tests and laser interferometric plate push data for steady and overdriven detonations [9]. The three-term rate law describes the three stages of reaction generally observed in shock initiation and detonation of heterogeneous solid explosives. For solid explosive detonation modeling, the first term of Equation (2) represents the ignition of the explosive as it is compressed by the leading 3D shock wave creating hot regions at the triple shock interactions [10]. The fraction of explosive ignited is assumed to be equal to the void volume of the pressed explosive and is reacted in less than a nanosecond. For LX-17 at 1.905 g/cm^3, the initial void volume is 2%. The second reaction rate in Eq. (4) models the rapid formation of the major reaction product gases (CO_2, N_2, H_2O, CO, etc.) in highly vibrationally excited states and their subsequent expansion and equilibration [10]. This process for LX-17 has been measured to take approximately 80 nanoseconds by several techniques [11,12]. The third term in Eq. (4) is used to describe the relatively slow diffusion controlled formation of nanometer size solid carbon particles (diamond, graphite, or amorphous carbon) from single or small groups of carbon atoms. For LX-17, the last 20% of the chemical energy release is assumed to be due to solid graphite nanoparticle formation by a diffusion controlled process. Experimentally, the graphite formation in LX-17 has been observed to take approximately 300 nanoseconds [13]. The reaction zone length for detonating LX-17 is 3 mm (400 ns). The LX-17 parameters are listed in Table 2.

To quantitatively model pressure and time dependent shock desensitization, a desensitization rate law was added to the Ignition reaction rate term in Eq. (2) by de Oliveira et al. [14]. The desensitization rate S is defined as:

$$S = A\, p\, (1 - \phi)\, (\phi + \varepsilon) \qquad (3)$$

where A is a constant, p is the shock pressure, ε is a constant, and ϕ varies from zero in a pristine explosive to one in a fully desensitized explosive.

Table 2. LX-17 detonation modeling parameters.

Initial density ρ_O =1.905 g/cm^3		
Unreacted JWL	Product JWL	Reaction Rates
A = 778.1 Mbar	A = 14.8105 Mbar	I = 4.0x10^6 μs^{-1} F_{igmax}= 0.02
B = -0.05031 Mbar	B = 0.6379 Mbar	a = 0.22 b = 0.667
R_1 = 11.3	R_1 = 6.2	x = 7.0
R_2 = 1.13	R_2 = 2.2	G_1 = 4500 Mbar^{-3}μs^{-1} F_{G1max} = 0.8
ω = 0.8938	ω = 0.5	c = 0.667 d = 0.866
Cv = 2.487x10^{-5} Mbar/K	Cv = 1.0x10^{-5} Mbar/K	y = 3.0
T_0 = 298°K	E_0 = 0.064 Mbar	G_2 = 30 Mbar^{-1}μs^{-1} F_{G2min} = 0.8
Shear Mod = 0.0354 Mbar	Det. velocity = 0.763 cm/μs	e = 0.667 g = 0.667
Yield Str = 0.002 Mbar	C-J pressure = 0.27 Mbars	z = 1.0

The density threshold a in Eq. (2) is redefined to be a linear function of ϕ:

$$a(\phi) = a_0 (1- \phi) + a_1(\phi) \qquad (4)$$

where a_0 and a_1 are constants. The relative density threshold for ignition of the pristine explosive becomes 1 + a_0, and, for the fully desensitized explosive, the relative density for ignition becomes 1 + a_1. Additionally, the second reaction rate term in Eq. (2) is modified so that it turns on only when F exceeds a minimum F_{G1min}, which is assumed to be a linear function of ϕ:

$$F_{G1min}(\phi) = F_c \phi \qquad (5)$$

where F_c is a constant related to the initial porosity. This second modification provides a competition between desensitization and reaction growth and thus determines an extinction mechanism. The desensitization model introduces four new parameters: A, ε, a_1, and F_c. Until now, no well-defined, time resolved experiments, such as those of Campbell and Travis [1], had been done on LX-17. de Oliveria et al. [14] estimated values of A = 1000, ε = 0.001, a_1 = 0.50, and F_c = 0.01 to produce reasonable "dead zones" for several corner turning [14] and desensitization experiments [2]. For low shock pressures, these values yield desensitization times of 1.29 μs for a 1 GPa shock and 0.26 μs for a 5 GPa shock. These parameters were used to model the shock desensitization experiments in this study.

Comparisons of Experimental and Modeling Results

The LX-17 Ignition and Growth model was first applied to shot 4812, in which a 1.1 GPa shock impacts an LX-17 charge before a Composition B booster initiates detonation at the opposite LX-17 boundary. Unfortunately this initiation was 10 μs late, and side rarefaction waves caused the manganin gauges to stretch before the LX-17 detonation wave arrived at the gauge positions. This caused the gauge resistance to increase as shown in Fig. 2. Since a sustained shock pressure of 6.5 GPa is required to initiate any exothermic reaction in LX-17 [15], the apparent increases in pressure before the arrival of the detonation wave cannot be real. Even though the gauges stretched, they clearly showed that the LX-17 detonation wave rapidly failed when it reached the pre-compressed explosive, but the measured decaying shock pressures are not reliable for detailed modeling. The Ignition and Growth model did predict rapid (~1 μs) shock desensitization for this 1.1 GPa shock, in agreement with the results of Hart [3].

The excellent ignition timings of the LX-17 detonations in the other two experiments were created by using combinations of LX-10 (95% HMX/ 5% Viton) for prompt detonation by the detonators followed by LX-04 (85% HMX/15% Viton) to avoid significant LX-17 detonation overdrives. Shot 4817 with a calculated initial shock pressure of 0.68 GPa showed in Fig. 3 that the LX-17 detonation wave propagated from the rear of the charge at 28 mm to the gauges at 25 and

20 mm depths. Then it failed rapidly at the 14, 8, and 0 mm gauge positions. Figure 5 compares the experimental and calculated (using the parameters mentioned above) pressure time histories for shot 4817 in the time period (53 to 60 μs) of the shock and detonation wave interactions. The timing of the arrival of the detonation wave at the LX-04/LX-17 boundary is set equal to the experimentally measured times of the 28 mm deep gauges for comparison. While the overall agreement is encouraging, the calculated shock pressures for the 0, 8, and 14 mm gauges in the desensitization region are higher than the experimental values, and the calculated arrival times are earlier than the measured arrival times. This implies that the desensitization rate is faster than these calculations predict. The value of A in Eq. (3) controls this rate, and setting A equal to 1000 was based on indirect measurements. To better match the experimental data, the value of A was increased to 1200. Figure 6 shows the comparisons with the three gauge records that show desensitization (0, 8, and 14 mm) and the two desensitization rates. The use of this larger rate constant produced faster shock decays and later arrival times at the 14, 8, and 0 mm gauges.

The lowest shock pressure shot 4829 produced an initial shock pressure of 0.52 GPa, which did not completely desensitize the LX-17. Figure 7 shows comparisons of the experimental and calculated pressure histories. The calculations predicted that shock desensitization was not complete even at the 0 mm gauge, and that the detonation would not fail.

Conclusions

The shock desensitization experiments on the insensitive PBX LX-17 have provided unique quantitative data on the weak shock pressures, compressions, and pulse durations required to cause time dependent shock desensitization of a TATB-based explosive. An initial shock wave with a pressure of 0.52 GPa and pulse duration of 3.3 μs did not cause complete elimination of all the possible hot spot formation sites, and thus the oncoming detonation continued to propagate in the pre-compressed region. A shock pressure of 5.2 GPa corresponds to a compression of 4.1% using the LX-17 unreacted JWL equation of state. An initial shock wave with a pressure of 6.8 GPa and pulse duration of 3.0 μs did completely eliminate the hot spot sites, resulting in the time dependent failure of the detonation wave in the pre-compressed LX-17. A 6.8 GPa shock pressure corresponds to a compression of 5.1%.

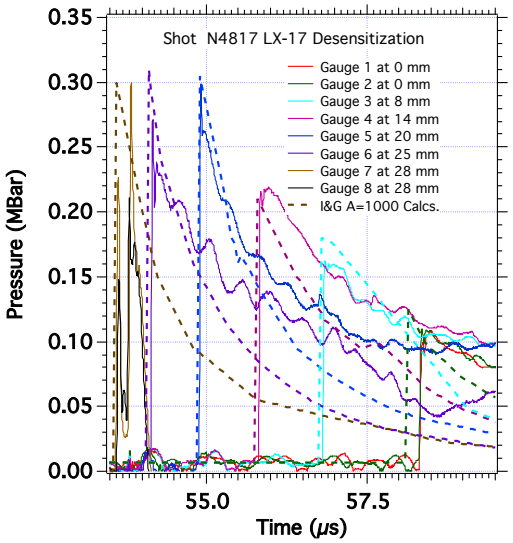

Figure 5. Experimental and calculated pressure histories for shot 4817 (0.68 GPa initial pressure).

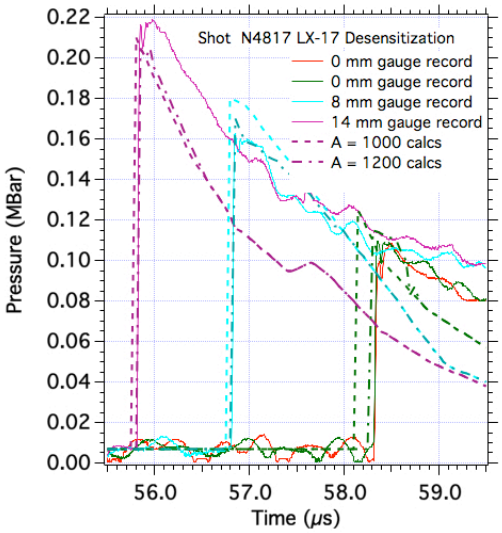

Figure 6. Experimental and two calculated pressure histories (using A = 1000 and 1200) at the 0, 8, and 14 mm gauge positions for shot 4817.

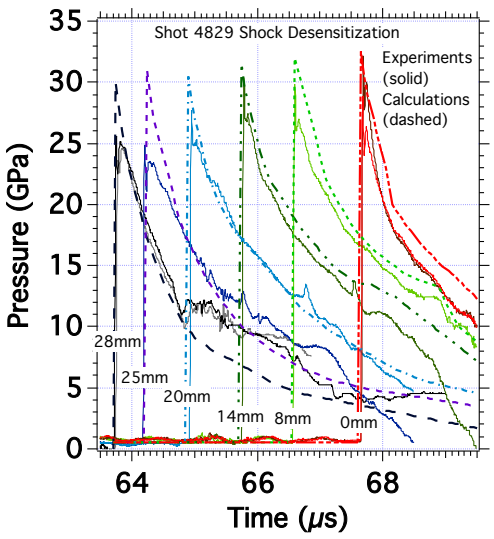

Figure 7. Experimental and calculated pressure histories for shot 4829

A narrow range of uncertainty of 0.52 to 0.68 GPa was found for the shock pressure required to cause shock desensitization of LX-17 with a pulse duration of approximately 3 μs. This shock pressure range is smaller than those found by Campbell and Travis [1] for PBX 9404 and Composition B-3, which were both approximately 1 – 2.4 GPa. The larger ranges for these two explosives are due to the higher shock sensitivity of PBX 9404 and Composition B-3, which created reacting hot spots in the pre-compressed region. When the detonation waves interacted with the reacting hot spots, they continued to detonate. Since LX-17 does not react in sustained shock waves at pressures below 6.5 GPa, oncoming detonation waves do not encounter reacting hot spots and either propagate or fail.

The pressure gauge records in the desensitized regions of LX-17 yielded quantitative data on the rates at which the LX-17 detonation waves failed. Campbell and Travis [1] found that the times required for PBX 9404 and Composition B-3 detonation wave failure were similar to the shock pulse duration times required for short pulse duration shock initiation of the two explosives. The oncoming detonation waves continued to react as they passed over regions of reacting hot spots and then failed when regions with only "burned out" and compressed, unreacted former hot sites. Since LX-17 does not react in the pre-compressed regions, its detonation waves continue to propagate if they encounter any remaining hot spot sites and fail when all of these sites have been eliminated. The high activation energy chemical kinetic decomposition rates of TATB-based explosives [16] are very sensitive to shock temperatures and pressures, and their detonation waves fail rapidly at velocities only 3% lower than the steady state Chapman-Jouguet (C-J) velocity [17]. The difficulty of corner turning by TATB detonation waves is also related to its sensitivity to pressure and temperature, which are lowered by the rarefaction waves produced by geometry changes [18]. The measured rapid decreases in shock pressure in the failing LX-17 detonation waves in shots 4812 and 4817 are consistent with both of these properties of detonating TATB-based explosives.

Finally, measurements of the pressure decrease rates and the critical shock pressure or relative density for complete shock desensitization of LX-17 are necessary to make progress in parameterizing the time dependent shock desensitization model. As shown in Figs. 5 and 6, the estimated value of the desensitization rate constant A = 1000 under-predicted the observed pressure decreases and the resulting arrival times. Better agreement was obtained using A = 1200. The measured compressions of 0.041 for little or no desensitization at 0.52 GPa and 0.051 for complete desensitization at 0.68 GPa can be used to estimate the values of a_0, the onset of desensitization, and a_1, the completion of desensitization, in Eq. (4). The value of F_c in Eq. (5) is related to the fraction of the explosive that has to react before complete desensitization occurs to possibility allow detonation to continue in the pre-compressed explosive. It would be very interesting to determine the value of F_c experimentally using different initial densities.

This experimental and modeling effort represents a good quantitative start toward understanding shock desensitization in insensitive high explosives, but more experimental and modeling work is required. For example, the shock desensitization of cold TATB-based explosives would be interesting to study. The desensitization behavior above 0.68 GPa, but

below the reaction threshold of 6.5 GPa would also be interesting to study.

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