SHOCK INITIATION OF NEW AND AGED PBX 9501

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We have used an embedded electromagnetic particle velocity gauge technique to measure the shock initiation behavior in PBX 9501 explosive. Up to twelve separate particle velocity wave profile measurements have been made at different depths in a single experiment. These detail the growth from an input shock to a detonation. In addition, another gauge element called a "shock tracker" has been used to monitor the progress of the shock front as a function of time and position as it moves through the explosive sample. This provides data similar to that obtained in a traditional explosively driven wedge test and is used to determine the position and time that the wave attains detonation. Run distance-to-detonation vs. input pressure (Pop–plot) data and particle velocity wave profile data have been obtained on new PBX 9501 pressed to densities of 1.826, 1.830, and 1.837 g/cm^3. In addition, the same measurements were performed on materials aged from 10 to 17 years. All results to date, including the Pop – plot and wave profiles show shock sensitivity to be a function only of the initial density and not of age.

INTRODUCTION

In the life cycle of explosive components, there is often a long period of time between manufacture and either dismantlement or use. People responsible for transporting and storing explosive components wish to know that the explosive is aging gracefully from the perspective that it won't accidentally go off any easier than when it was made. Meanwhile, those interested in using the explosive in the mode it was designed for, want to know that, after years in storage, the explosive component will operate as intended. Ideally, from either perspective, the explosive properties should not change

Because of HMX's high detonation pressure, HMX based explosives are often used as main charge and booster explosives. These explosives are usually made by holding explosive crystals together using a plastic binder, and are called Plastic Bonded Explosives or PBXs. In the life cycle of the explosive, either the binder can degrade or change, or the explosive crystals can degrade or change. Degradation or change of either the binder or the explosive could have detrimental effects on safety or design mode operation.

As a specific perspective for studying these aging effects we have chosen to study the shock initiation of PBX 9501. Shock initiation involves introducing a shock wave into an explosive and observing this shock transition to a self supporting detonation wave. It is important from both a safety standpoint and a use as designed standpoint.

PBX 9501 consists of 95 wt.% HMX, and a binder consisting of 2.5 wt.% estane and 2.5 wt.% nitroplasticizer. In addition, there are minute amounts of antioxidant "preservatives." It is a very typical HMX based explosive.

The problem of accidental mechanical insult producing a violent reaction has prompted studies in the low stress regime by Dick et al.[2,3] using plane impacts, and by Idar et al.,[4-6] and Chidester et al.[7] using spherical impactors. Idar et al.[6] and Chidester et al.[7] have also applied their methods to aged PBX 9501.

This report details shock initiation using planar impacts at higher stresses of 30 – 50 kbar. Since there was not a large amount of baseline information on shock initiation of PBX 9501, comparisons between new and aged material were impossible. Furthermore, we needed a scale to understand how large aging effects might be. Combining the study of explosives of different density with aged explosives provided both a baseline and a scale.

Baseline data was obtained from samples made from one powder lot and pressed to three different densities. These results were compared with data obtained from material recovered from two different weapons that had been in the stockpile for 124 and 201 months, respectively.

EXPERIMENTAL DETAILS

PBX 9501 Samples

Three different "new" PBX 9501 sample materials were pressed at Los Alamos National Laboratory (LANL). Additionally, two sample materials were recovered from dismantled weapons and were therefore aged. These are summarized in Table 1 below. Jose Archuleta measured densities for all samples using the water immersion method.

All new sample materials were pressed from Holston PBX 9501 molding powder lot 89C730-010 which was manufactured in 1989. Material pressed from this powder has been used by Idar et al.,[4-6] and Dick et al.[2,3]. We will designate the new materials A, B, and C.

The material designated "124" spent 124 months in a weapon before the weapon was dismantled and the material recovered. Likewise, the material designated "201" spent 201 months assembled in a weapon before the weapon was dismantled and the material was recovered.

Overall Experimental Configuration

The overall configuration for the initiation experiments is shown in Figure 1. This is the same configuration developed by Vorthman and used in many earlier studies at LANL.[8-11] A projectile made of Lexan, or with a Lexan front half is faced with a non metallic impactor disk and launched in a 72-mm bore single-stage gas gun. When the impactor strikes the explosive sample, a planar shock wave is generated which begins the initiation process. Gauges embedded in the sample at various depths measure the particle velocity as well as the position of the shock front with time.

TABLE 1. SUMMARY OF MATERIALS

Material	Powder Lot	Piece No.	Pressing Method*	Density (g/cm^3)
A	730-010	96-741319	Hydrostatic	1.826 ± 0.001
B	730-010	97-525099	Hydrostatic	1.830± 0.001
C	730-010	97-264309x	Ram	1.837± 0.001
124	730-006	76-1100830	Hydro/Mandrel	1.838± 0.001
201	685-006	78-1020331	Hydro/Mandrel	1.838± 0.001

* All pressings were made at 100º C.

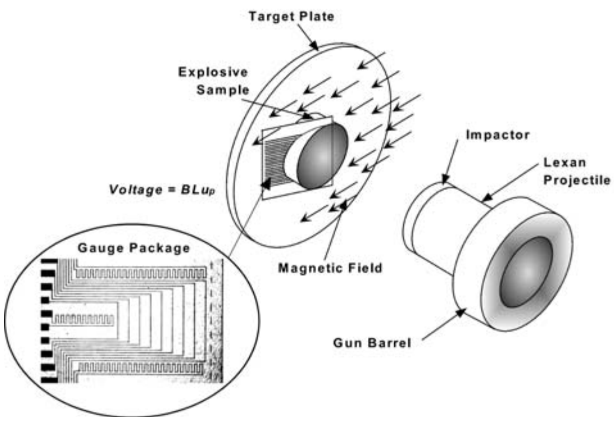

FIGURE 1. OVERALL EXPERIMENTAL CONFIGURATION. EXPLOSIVE SAMPLE INSTALLED IN GUN TARGET CHAMBER AND MAGNETIC FIELD.

For the experiments discussed here, the impactors were 2¼ inch (57 mm) diameter by 0.43 inch (11 mm) thick, and the explosive sample (or target) was 2 inch (51 mm) diameter by ≈ 1 inch (25 mm) thick.

Calculation of Impact Stresses

The projectile impact velocity and the choice of impactor material determine pressure input to the sample. With gas guns the impact velocity can be precisely controlled by varying the combination of the gas pressure used to drive the projectile and the projectile mass. Further, we can measure impact velocities to 0.1% using precisely spaced electrical shorting pins.

Because they are elastic at stresses less than 9 GPa, we know the Hugoniots of the impactor materials (Z-cut quartz crystals, Z – cut sapphire crystals, and Vistal, a high density aluminum oxide ceramic sold by Coors) to an accuracy of about 1%.[12-14]

Using the theoretical density of 1.86 g/cm^3 (Ref. 1) for PBX 9501, we see that the porosity for these samples varies between 1.2% and 1.8%. If we do not account for this porosity, the effect on the calculated pressure will be less than 1%. This is far less than the scatter in the data from which the Hugoniot is constructed.

Jerry Dick et al.[2,3] have made Hugoniot measurements on 1.826 g/cm^3 PBX 9501. Combining their measurements with the 1.832 and 1.844 g/cm^3 measurements reported in Gibbs and Popolato,[15] they suggested a Hugoniot of

$$U_S = 2.40 \pm 0.03 + 2.39 \pm 0.07 u_P \quad \text{km/s} \qquad (1)$$

for these three data sets. Recent work by Menikoff and Sewell[16] indicates that this straight line Hugoniot is only useful up to about 1 km/s. But, this is within the range generated at impact in our experiments.

EXPERIMENTAL RESULTS AND DISCUSSION

Wave profiles of particle velocity vs. time and *x-t* plots of the shock trajectories were obtained at impact stresses of about 3.1, 3.9, and 5.2 GPa for each of the five PBX 9501 materials described previously in Table 1. Table 2 (following page) summarizes data for all of the experiments described in this report. Data are grouped by pressure. That is, there is a ≈ 5.2 GPa group, a ≈ 3.9 GPa group and a ≈ 3.1 GPa group. Within each group, shots are ordered by increasing sample density. Presented in the table are the material identification, the sample density, the projectile impact velocity, the impactor material, the calculated impact conditions (based on the projectile velocity, and known Hugoniot of the impactor). The remainder of this section will cover first, an example of the wave profiles, including how density and age affect them, and second, a discussion of the position time shock trajectories and the run distance to detonation vs. initial pressure or Pop – plot for each material.

Particle Velocity Wave Profiles

Figure 2 show wave-profiles from Shot 1133 where PBX 9501 of type A (see Table 1) was impacted with a Vistal impactor at a velocity of 0.817 km/s, producing an input of 5.12 GPa. There are eleven wave profiles at depths from 0 to 5 mm into the explosive. The first profile is from a gauge on the front of the sample and the remaining ten are from the embedded gauges. The input particle velocity is about 0.7 km/s and this grows to over 2 km/s, very near a full detonation, by the time the wave reaches the last gauge at 5 mm into the sample. Note that these

TABLE 2. SUMMARY OF PBX 9501 EXPERIMENTS

Shot	PBX 9501 Description		Impact Parameters		Calculated Impact Conditions		Measured Run to Detonation		Comment
	Type	ρ_0	Material	u_I	P_I	u_P	x^*	t^*	
1133	A	1.825	Vistal	0.817	5.12	0.697	5.1	1.13	
1134	B	1.830	Vistal	0.814	5.13	0.694	5.8	1.27	
1144	C	1.837	Vistal	0.816	5.21	0.694	5.6	1.23	
1145	C	1.837	Vistal	0.811	5.17	0.690	5.9	1.28	
1154	124	1.838	Vistal	0.819	5.24	0.696	5.6	1.22	
1156	201	1.838	Vistal	0.817	5.22	0.694	5.3	1.17	
1162	A	1.826	Vistal	0.663	3.89	0.572	7.2	1.71	
1161	A	1.826	z-quartz	0.798	3.92	0.575			Tracker broke
1164	B	1.830	Vistal	0.667	3.95	0.574	8.4	1.99	
1155	B	1.830	Vistal	0.663	3.92	0.571			Tracker broke
1150	C	1.837	Vistal	0.653	3.90	0.562	8.8	2.12	
1179	124	1.838	sapphire	0.620	3.68	0.538	10.5	2.57	Only tracker gauge worked
1178	201	1.837	sapphire	0.638	3.82	0.553	9.6	2.33	
1075	A	1.826	Vistal	0.586	3.32	0.508			Tracker broke
1163	A	1.825	Vistal	0.552	3.07	0.480	10.58	2.76	
1171	B	1.830	z-quartz	0.656	3.09	0.478	12.2	3.14	
1146	C	1.837	z-quartz	0.652	3.10	0.474	13.7	3.56	
1147	C	1.837	z-quartz	0.651	3.10	0.473			Off tracker end
1165	124	1.838	Vistal	0.550	3.13	0.476	13.6	3.47	
1177	201	1.837	Vistal	0.552	3.14	0.478	12.6	3.26	

ρ_0 : Initial density (g/cm^3)
u_I : Impact velocity (km/s)
P_I u_P : Impact stress (GPa) and particle velocity. These are calculated by impedance matching the impactor Hugoniot with the Hugoniot for the PBX 9501.
x^* : Run distance to detonation (mm).
t^* : Time to detonation (µs).

gauges measure reliably even under detonation conditions.

Figure 2 shows the profiles in a 3-D time–gauge depth–particle velocity plot, a format that provides a good picture of the wave as it evolves. We often show the data in a 2-D time – particle velocity plot, making it easier to see the magnitude of each of the profiles.

Effect of density on wave profiles

Figure 3 shows the effect of initial density on the particle velocity wave profiles. Two experiments are shown in Figures 3a, and 3b. In both experiments a projectile faced with a Vistal disk impacted a PBX 9501 sample at 0.665 ± 0.002 km/s producing an input stress of ≈ 3.9 GPa. Both experiments had gauges located at 0 and 3 through 8 mm depths. Figure 3a shows particle velocity wave profiles from Shot 1162 which used material A with initial density 1.826 g/cm^3 and Figure 3b shows wave profiles obtained from Shot 1164 which used material B with initial density 1.830 g/cm^3. Note that the input

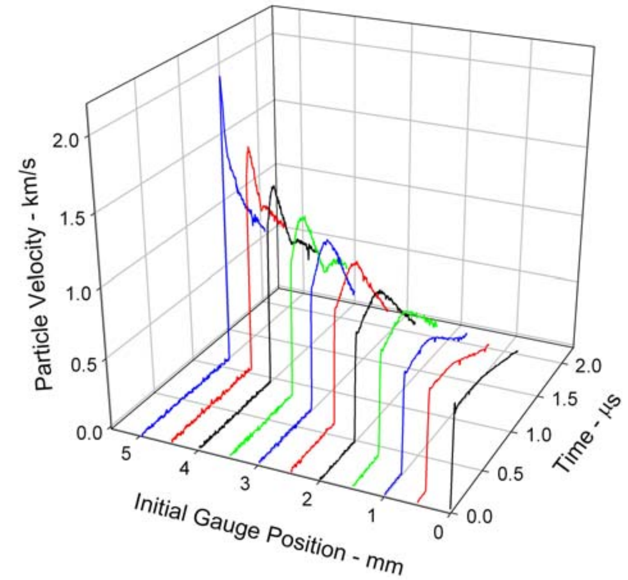

FIGURE 2. PARTICLE VELOCITY WAVE PROFILES FROM SHOT 1133. THE INPUT IS 5.15 GPa AND WAS CREATED BY IMPACTING VISTAL ON THE PBX 9501 AT 0.817 km/s. THE PBX IS TYPE A.

stress for Figure 3a was actually slightly lower (0.06 GPa) because of the lower density sample.

In the 1.826 g/cm^3 sample, detonation was achieved at 7.2 mm, near the second to last gauge. This is quite apparent in Figure 3a, as C-J particle velocity of 2.2 km/s (Ref. 41) is reached at the second to last gauge. In the 1.830 g/cm^3 sample, detonation was not achieved until 8.8 mm, well beyond the last gauge. The last wave profiles do not even begin to approach the C-J condition. These figures clearly show that small changes in initial density significantly affect the wave profiles in the buildup to detonation. As expected, higher density materials do not build to detonation as quickly as low-density materials.

Effect of age on wave profiles

Figure 4 shows the effect of sample age on the particle velocity wave profiles. Wave profiles are presented from three experiments using the same input, the same sample density, but varying the age of the explosive. In all three ex-

(a)

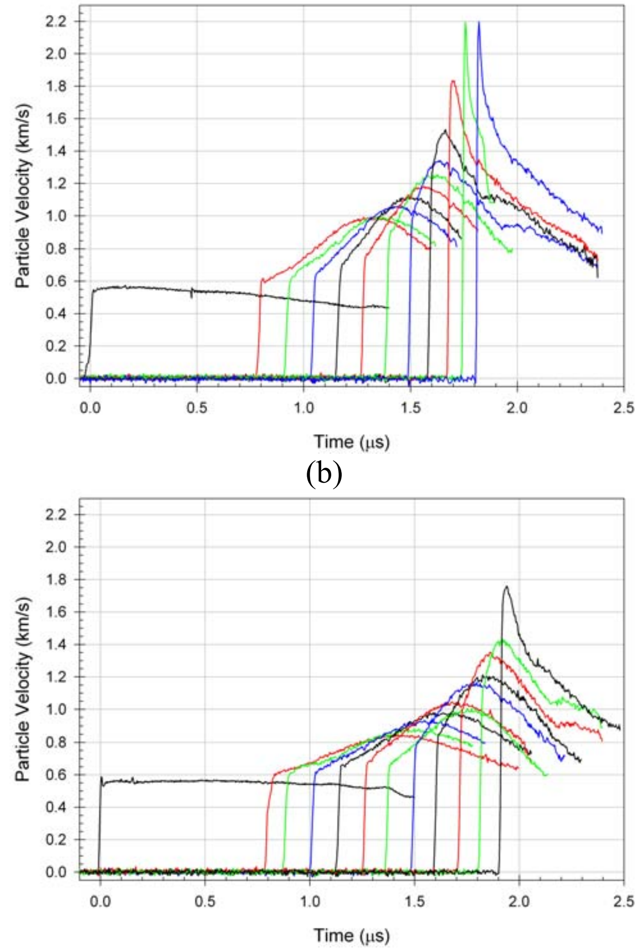

FIGURE 3. EFFECT OF DENSITY ON WAVE PROFILES. PARTICLE VELOCITY WAVE PROFILES FOR SHOT 1162 (a) (MATERIAL A, 1.826 g/cm^3) AND SHOT 1164 (b) (MATERIAL B, 1.830 g/cm^3). THE INPUT STRESS IS NEARLY IDENTICAL 3.89 ± 0.03 GPa IN BOTH EXPERIMENTS.

periments the input stress of 5.22 ± 0.02 GPa was produced by impacting Vistal on the 9501 with a velocity of 0.817 ± 0.002 km/s. The red trace is from newly pressed material, the blue trace is from the material that was aged 124 months, and the green trace is from the material that was aged 201 months. Gauges were located at roughly, but not exactly, the same positions, and spanned depths of 0 through roughly 5 mm.

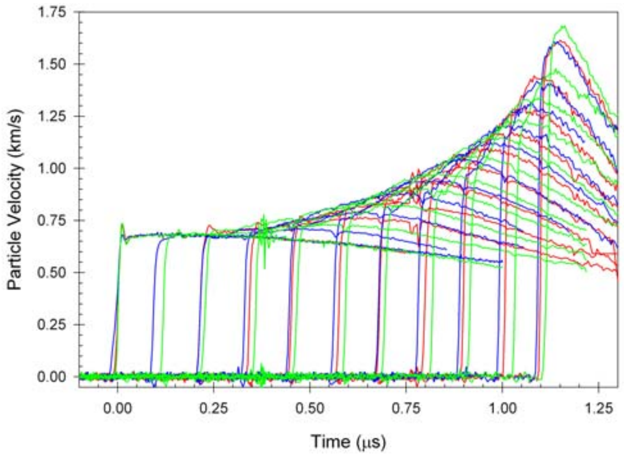

FIGURE 4. EFFECT OF AGE ON WAVE PROFILES. WAVE PROFILES FOR SHOT 1144 (RED CURVE, NEW MATERIAL C) SHOT 1154 (BLUE CURVE, 124 MONTH AGED MATERIAL), AND SHOT 1156 (GREEN CURVE, 201 MONTH AGED MATERIAL). ALL EXPERIMENTS HAD IMPACT STRESSES OF 5.22 ± 0.02 GPa PRODUCED BY IMPACTING VISTAL ON THE PBX 9501 AT 0.817 ± 0.002 km/s. ALL SAMPLES HAD DENSITIES OF 1.838 ± 0.001 g/cm^3.

Wave profiles clearly show very good repeatability from one experiment to the next, i.e., corresponding profiles from all three experiments fall almost exactly on top of one another. Any slight differences in wave arrival times are caused by slight differences in the depths of individual gauges. At the last gauge, where one would expect differences to be greatest, profiles from all three experiments are very nearly the same. Clearly, the age of the sample affects the wave profiles, and therefore the shock initiation process, very little.

Comparison of the wave profiles shown in Figure 4 with those of Figure 2, also clearly illustrates the effect of density on the wave profiles. All four of these experiments had inputs that were within 0.1 GPa in pressure. The 1.826 g/cm^3 (low density material) shown in Figure 2 has just reached detonation by the last gauge position of 5 mm. None of the higher density materials shown in Figure 4 have advanced the reaction to the same level. Thus, the wave profiles show that density affects the shock initiation process but sample age does not.

Position – Time (*x* – *t*) Shock Trajectories

The *x-t* plot showing the position of the shock front with time for Shot 1133 is shown in Figure 5. Red points were obtained from the shock tracker gauge. There are a total of about 40 measurements obtained by this gauge. They are spaced every ¼ mm, and cover about 10 mm in sample depth.

Green points were obtained from the particle velocity gauges using the initial gauge positions and the wave arrival times. The black points indicate times/positions where the explosive is fully detonating. Lines through the data indicate shock velocity (initial slope) and detonation velocity (final slope).

From plots such as those shown in Figure 5, there are a number of ways to determine the run distance (time)-to-detonation. One can pick the point by eye or use the point where the lines (whose slopes indicate the detonation velocity and shock velocity) cross. The line crossing method is shown in Figure 5. We have found

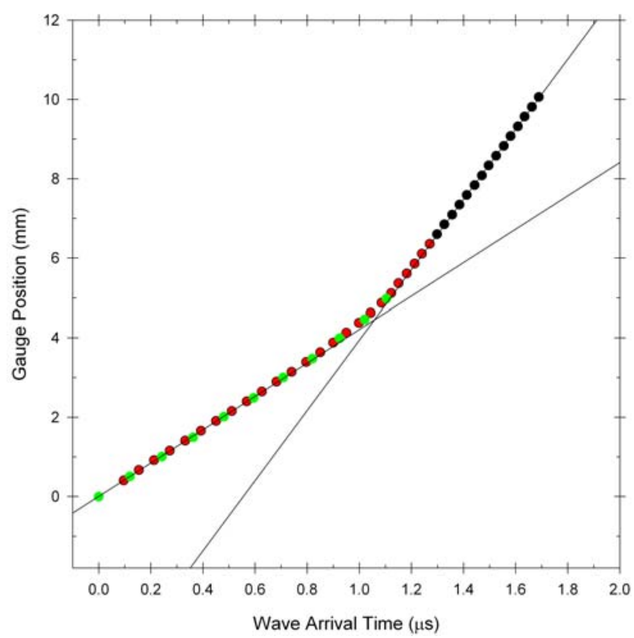

FIGURE 5. *X-T* PLOT FOR SHOT 1133 OBTAINED FROM SHOCK ARRIVAL AT SHOCK TRACKER ELEMENTS (RED) AND PARTICLE VELOCITY GAUGE ELEMENTS (GREEN).

both of these methods, as well as several others, to be unreliable.

The method we have found most reliable is to fit the $x - t$ data using special equations. The point where detonation is achieved can then be reliably, or at least reproducibly determined. A paper detailing the method will be presented at this conference.[17]

Pop–plots

The Pop–plot, named after one of its originators, Alphonse Popolato,[18] plots the run distance (time)-to-detonation as a function of the input stress (pressure). Most commonly a Log–Log format is used.[18] In this format, a material's Pop – plot usually appears as a straight line.

The Pop - plot has been found to be a very useful tool for measuring and ranking the shock sensitivity of explosives. The Pop–plot of a sensitive material will lie below and/or to the left of the Pop–plot of an insensitive material. In general, the differences between any two materials distance – to - detonation are most apparent at low pressure, and are rather small at high pressure.

In formulas and descriptions of shock initiation phenomena, the run distance-to-detonation is usually denoted by the symbol x^*, the run time-to-detonation by the symbol t^*, and the initial shock pressure by P.

Figure 6 presents Pop–plots for the 3 different density new PBX 9501 materials used in the present study; material A–1.826 g/cm^3, material B–1.830 g/cm^3, and material C–1.837 g/cm^3. For these materials we see an increase in sensitivity with decreasing density. For a given input stress, run distances (times)-to-detonation are shorter for lower density materials than those for higher density materials. As is generally the case, differences are more distinct at low pressures and less distinct at high pressures. This result parallels the differences in wave profiles for different density materials which were seen in Figure 3. Those results also showed much faster buildup to detonation for lower density material.

Our error bars for x^* were set at 10% of the run distance; The error bars for pressure were set at 2%. Even with these generous error bars, there is much less scatter in our data than in historical data measured using explosive plane wave lenses and streak photography. This could be due to a number of factors such as: (1) gas guns provide a better supported pressure pulse than explosive drivers; (2) the pressure is more accurately known because of the precisely measured impact velocity and the use of elastic impactors; (3) our analysis technique for finding the run distance (time)-to-detonation is more consistent than what has been previously used. Finally, (4) the materials we used could be more uniform and better characterized than those used by previous researchers. Many Pop – plot data sets are measured while a material is still under development.

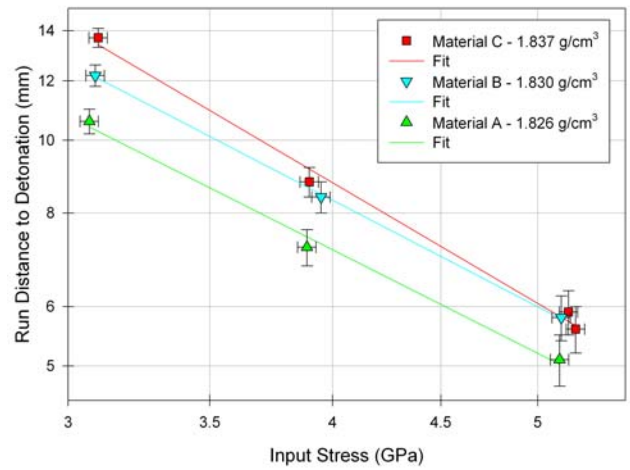

FIGURE 6. POP–PLOTS FOR THREE DIFFERENT DENSITY NEW PBX 9501 MATERIALS.

Table 3 summarizes straight-line fits to these data sets. Fits to two additional data sets obtained from the compilation of Gibbs and Popolato[15] are also presented.

Data has just been presented which indicates that density differences of only 0.004 and 0.007 g/cm^3 affect the buildup to detonation, i.e., the Pop-plot. The fact that this technique can consistently make this discrimination is impressive. These kinds of experiments should prove to be a powerful discriminator for small changes in material parameters which may take place in material aging.

TABLE 3. POP–PLOT FITS

Mate-rial	Density (g/cm^3)	Our Fits
A	1.826	$\log(x^*) = 1.71 - 1.43\log(P)$ $\log(t^*) = 1.28 - 1.74\log(P)$
B	1.830	$\log(x^*) = 1.80 - 1.47\log(P)$ $\log(t^*) = 1.37 - 1.78\log(P)$
C 124 201	1.837	$\log(x^*) = 1.94 - 1.66\log(P)$ $\log(t^*) = 1.52 - 2.00\log(P)$
Ref. 15	1.833	$\log(x^*) = 1.74 - 1.46\log(P)$ $\log(t^*) = 1.29 - 1.76\log(P)$
Ref. 15	1.844	$\log(x^*) = 2.17 - 1.96\log(P)$ $\log(t^*) = 1.70 - 2.23\log(P)$

Figure 7 presents Pop–plots for the two stockpile aged PBX 9501 materials; the 124 month old material, and the 201 month old material. These two materials had nominal densities of 1.838 g/cm^3. For comparison, the run distances/times and the linear fit for the new 1.837 g/cm^3 material (material C) is also shown. This data and fit provide a baseline so that we can make comparisons and see if age significantly affects the run distance (time)-to-detonation.

While there is some scatter about the material C or baseline data fit, there is no definitive trend. All of the data from the aged explosives lie about as far from the baseline fit as do the baseline data. In addition, the stress and distance error bars are such that the baseline fit goes through all the points if error bars are included. The lack of difference in the Pop–plots for new and stockpile aged materials clearly indicates that aging is not affecting the shock initiation properties of PBX 9501. Figure 4, which showed particle velocity wave profiles for these materials, also showed no effects. *Thus, in two ways we have demonstrated that stockpile aging does not affect the shock initiation properties of PBX 9501.* We find, both through particle velocity wave profile measurements and also through run distance (time)-to-detonation measurements, that age alone does not increase or decrease the shock sensitivity of PBX 9501. *If*

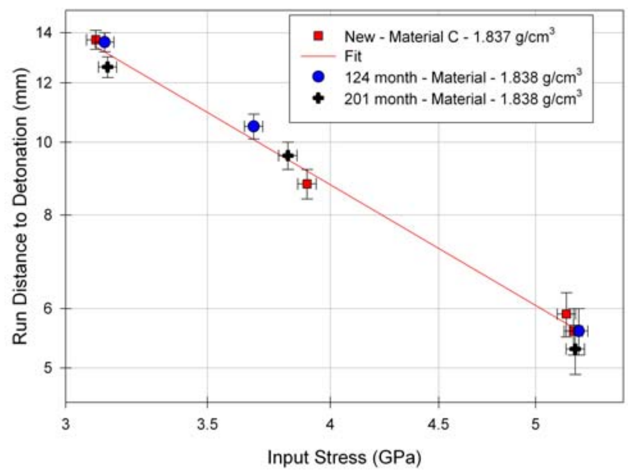

FIGURE 7. POP–PLOTS FOR NEW BASELINE AND AGED PBX 9501 MATERIALS.

the PBX 9501 density is held constant, we see no difference in the initiation of aged explosives when compared to new explosives.

For those concerned with safety issues this is important because it means that PBX 9501 is not becoming less safe or more safe, in reference to shock initiation, with age. Further, it means that safety models should not have to change the explosives shock initiation parameters to compensate for changing behavior with the explosive's age. It also means that initiability for design purposes does not change with age. *The PBX 9501 will initiate the same after 17 years in stockpile as it did on the day it was pressed.*

ACKNOWLEDGEMENTS

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