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Shock Initiation of Damaged Explosives

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SHOCK INITIATION OF DAMAGED EXPLOSIVES

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ABSTRACT

Explosive and propellant charges are subjected to various mechanical and thermal insults that can increase their sensitivity over the course of their lifetimes. To quantify this effect, shock initiation experiments were performed on mechanically and thermally damaged LX-04 (85% HMX, 15% Viton by weight) and PBX 9502 (95% TATB, 5% Kel-F by weight) to obtain in-situ manganin pressure gauge data and run distances to detonation at various shock pressures. We report the behavior of the HMX-based explosive LX-04 that was damaged mechanically by applying a compressive load of 600 psi for 20,000 cycles, thus creating many small narrow cracks, or by cutting wedge shaped parts that were then loosely reassembled, thus creating a few large cracks. The thermally damaged LX-04 charges were heated to 190°C for long enough for the beta to delta solid - solid phase transition to occur, and then cooled to ambient temperature. Mechanically damaged LX-04 exhibited only slightly increased shock sensitivity, while thermally damaged LX-04 was much more shock sensitive. Similarly, the insensitive explosive PBX 9502 was mechanically damaged using the same two techniques. Since PBX 9502 does not undergo a solid - solid phase transition but does undergo irreversible or "rachet" growth when thermally cycled, thermal damage to PBX 9502 was induced by this procedure. As for LX-04, the thermally damaged PBX 9502 demonstrated a greater shock sensitivity than mechanically damaged PBX 9502. The Ignition and Growth reactive flow model calculated the increased sensitivities by igniting more damaged LX-04 and PBX 9502 near the shock front based on the measured densities (porosities) of the damaged charges.

INTRODUCTION

The results presented in this paper are derived from an extended effort to understand the shock initiation of damaged explosives. Recently, the main goal of this project was to characterize the effect that damage has on the safety of an Insensitive High Explosive (IHE). During the course of its lifetime, a large high explosive charge may be damaged mechanically or thermally. This damage can change the sensitivity and performance of the charge. The shock sensitivity of thermally damaged PBX 9502 charges is being determined in this research project.

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A shock initiation experiment was heated to 190°C and then cooled to ambient temperature to characterize the effect of thermal damage on the in-situ pressure gauge data, run-distance-to-detonation behavior, and Ignition and Growth modeling parameters. A 101 mm diameter propellant driven gas gun was utilized to initiate the explosive sample with manganin piezoresistive pressure gauge packages placed between sample slices. The shock sensitivity of the PBX 9502 heated to 190°C and fired at ambient temperature had a similar shock sensitivity to what would be expected when heating PBX 9502 to approximately 90°C. Ignition and Growth modeling parameters were obtained with a reasonable fit to the experimental data by decreasing the initial density of the sample to a value estimated to be caused by the damage mechanism.

Shock sensitivity data is desired to determine the relative safety under shock and the changes of sensitivity after the material becomes damaged extends this knowledge. The explosives PBX 9502 and LX-17 (92.5% TATB and 7.5% Kel-F by weight) are insensitive high explosives (IHE) that have been shock initiated at a variety of temperatures [1-5]. Most recently, a study of damaged IHE was conducted by heating PBX 9502 to 190°C and then cooling back to ambient before performing the experiment. The run-distance-to-detonation is obtained, as well as in-situ pressure gauge records to compare with the Ignition and Growth modeling results and previous heated shots.

EXPERIMENTAL PROCEDURE

The shock initiation experiments were designed and performed using the 101 mm diameter propellant driven gas gun at Lawrence Livermore National Laboratory (LLNL). Figure 1 shows a schematic of the typical experiment detail that was used. The projectile consisted of a composite sabot with a micarta tube and polycarbonate end caps (Mod II) or a one-piece polycarbonate design (Door Knob) with a flyer plate on the impact surface. As seen in Figure 1, the target includes a 5 mm aluminum buffer plate with a heater and thin plate behind it for good thermal conductivity. The explosive disks are then stacked with another thin plate, heater, and thicker rear plate for good thermal conductivity and to hold the material in place. The flyer, buffer, and end cap plates were made from aluminum (6061-T6). The explosive consisted of thin disks (90 mm diameter

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by 2mm, 3mm or 5 mm thick) with the gauge packages inserted in between. The total explosive thickness was 30 mm, and the thin or thick disks were stacked preferentially to place the thin disks in the region where detonation is expected. Figure 2 shows photographs of a typical experiment assembly and assembled experiment.

Manganin piezoresistive foil pressure gauges [6,7] were placed within the explosive sample and 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). As shown in Figure 1, PZT Crystal pins were used to measure the projectile velocity and tilt (planarity of impact). During the experiment, oscilloscopes measure the gauge voltage traces over time that are converted to pressure traces over time by using the hysteresis corrected calibration curve published elsewhere. Stretching of foil gauges is a concern, since as the gauge stretches it causes a resistance change in the foil that appears as a fictitious pressure increase. This stretching occurs later in time when the rarefaction waves from the outer edges reach the gauge locations.

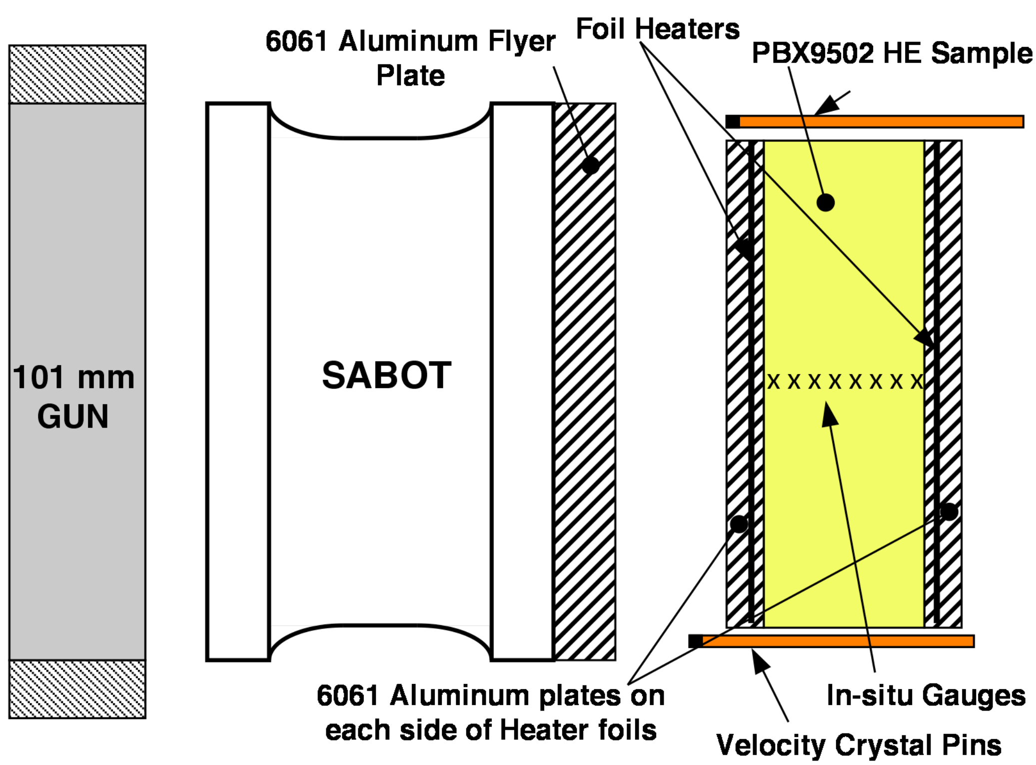

Figure 1. Schematic of a typical heated PBX 9502 gun experiment.

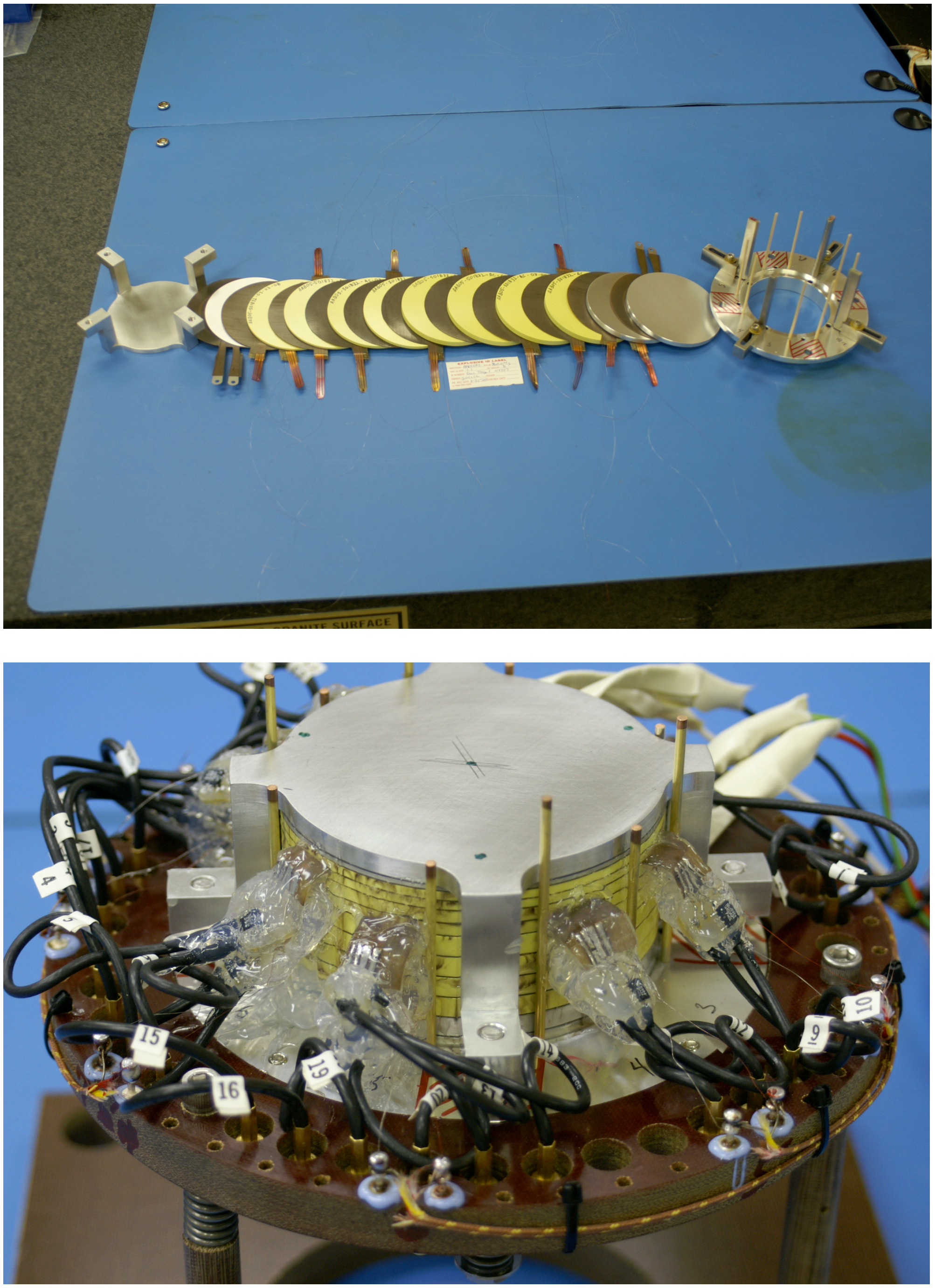

Figure 2. Photographs of a typical heated PBX 9502 gun experiment before and after assembly.

Ignition and Growth Modeling

The Ignition and Growth reactive flow model [8] uses two Jones-Wilkins-Lee (JWL) equations of state, in the form:

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

where p is pressure, V is relative volume, T is temperature, ω is the Gruneisen coefficient, C_V is the average heat capacity, and A, B, R_1 and R_2 are constants. Table 1.0 contains the material parameters and reaction rate parameters for the damaged PBX 9502 material at 25˚C. The reaction rate equation is:

$$dF/dt = \underbrace{I(1-F)^b(\rho/\rho_0 - 1 - a)^x}_{0<F<F_{Ig\max}} + \underbrace{G_1(1-F)^c F^d p^y}_{0<F<F_{G_1\max}} + \underbrace{G_2(1-F)^e F^g p^z}_{F_{G_2\min}<F<1} \quad (2)$$

where F is the fraction reacted, t is time in μs, ρ is the current density, ρ_o is the initial density, p is pressure in Mbars, and I, G_1, G_2, a, b, c, d, e, g, x, y, and z are constants.

Table 1.0 Ignition & Growth parameters used for damaged PBX 9502 modeling at ambient temperature (25°C).

UNREACTED JWL	PRODUCT JWL	REACTION RATES	
A=632.07 Mbar	A=13.454 Mbar	a=0.214	x=7.0
B=-0.04472 Mbar	B=0.6727Mbar	b=0.667	y=1.0
R_1=11.3	R_1=6.2	c=0.667	z=3.0
R_2=1.13	R_2=2.2	d=0.111	F_{igmax}=0.5
ω=0.8938	ω=0.50	e=0.333	F_{G1max}=0.5
C_V=2.487x10^{-5} Mbar/K	C_V=1.0x10^{-5} Mbar/K	g=1.0	F_{G2min} =0.0
Shear Modulus=0.017 Mbar	E_o=0.069 Mbar	I= 4.4x10^6 μs^{-1}	G_1=0.6 Mbar^{-2}μs^{-1}
Yield Strength=0.002 Mbar	-	-	G_2=400 Mbar^{-2}μs^{-1}
T_o = 298ºK, ρ_0=1.840 g/cm^3			

Pressure must be equilibrated between the two phases, and temperature equilibrium is also assumed. Sufficient mesh density must be used so that the calculations have converged. The only changes to the model needed for a damaged LX-04 are the initial density ρ_o and the fraction of explosive ignited (F_{igmax}). Table 1.1

below contains the required values to perform the calculations. The damaged LX-04 density was changed to 1.715 g/cm^3 and the damaged LX-04 maximum fraction Ignited was changed to 0.10.

Table 1.1. Ignition & Growth parameters used for LX-04 modeling at ambient temperature (25°C).

UNREACTED JWL	PRODUCT JWL	REACTION RATES	
A=9522.0 Mbar	A=15.3516 Mbar	a=0.0794	x=4.0
B=-0.05944 Mbar	B=0.6004Mbar	b=0.667	y=2.0
R_1=14.1	R_1=5.9	c=0.667	z=3.0
R_2=1.41	R_2=2.1	d=0.667	F_{igmax}=0.02
ω=0.8867	ω=0.45	e=0.333	F_{G1max}=0.5
C_V=2.7806x10^{-5} Mbar/K	C_V=1.0x10^{-5} Mbar/K	g=1.0	F_{G2min} =0.5
Shear Modulus=0.0474 Mbar	E_o=0.095 Mbar	I=2.0 x 10^4 μs^{-1}	G_1=220 Mbar^{-2}μs^{-1}
Yield Strength=0.002 Mbar	-	-	G_2=320 Mbar^{-2}μs^{-1}
T_o = 298ºK, ρ_0=1.868 g/cm^3			

RESULTS AND DISCUSSION

The details from our most recent experiment 4757 on PBX 9502 are presented in Table 2. The details include the pretest condition, impact velocity, materials used, input pressure and run-distance-to-detonation. The heating profile in Figure 3 shows that the target was heated to 190°C followed by an hour soak and then cooling for about 16 hours before the shot was fired.

Table 2. Summary of PBX 9502 gun experiment 4757

SHOT	PRETEST CODITION	IMPACT VELOCITY (km/s)	SABOT TYPE	FLYER PLATE	IMPACT PLATE	INPUT PRESSURE (GPa)	RUN TO DET (mm)
4757	25°C after heating to 190°C	1.490	DK	Al 6061	Al 6061	8.3	11

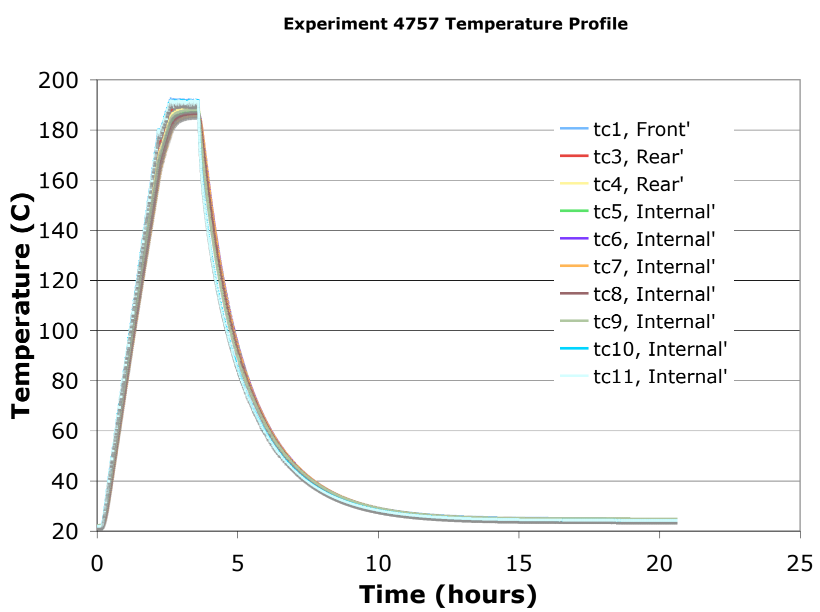

Figure 3. Temperature profile of the PBX 9502 target heated to 190°C, soaked for 1 hour, and then cooled to ambient temperature for about 16 hours before shooting.

Run distance to detonation versus shock pressure ("Pop-Plot") data on PBX 9502 and LX-17 at a variety of temperatures is shown in Figure 4 below with experiment 4757 plotted. Since the data point falls between data sets at 75°C and 120°C, the resulting shock sensitivity is roughly the same as material heated to approximately 90°C.

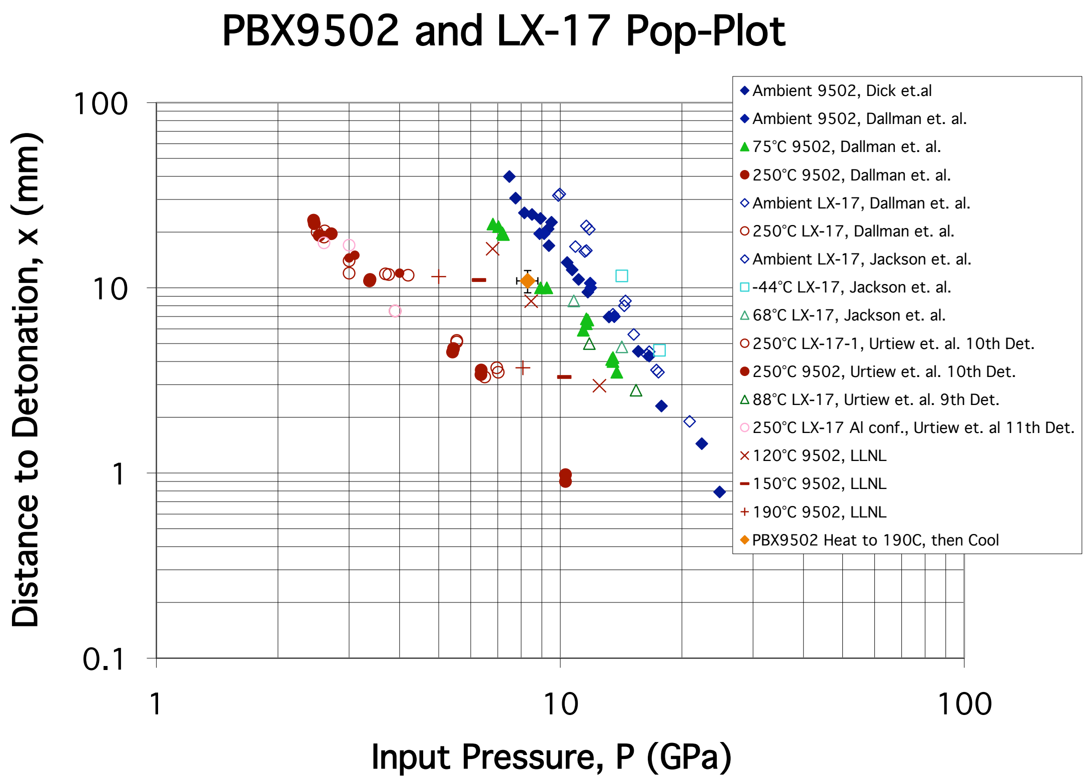

Figure 4. Pop-Plot for PBX 9502 Heated Gun experiments with prior data.

For computer model validation, the modeling was performed before the experiment was conducted. The PBX 9502 ignition and growth parameters were utilized to create simulated gauge records using an approximated density and the input pressure from an earlier experiment at 190°C with an experiment input pressure of 8.1 GPa. The modeling runs using ALE3D and LS-DYNA are shown in Figures 5 and 6, respectively. The reaction rate parameters are the same as the ambient temperature, except that the ignition rate is increased to ignite more TATB, because the damaged density is lower and thus

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more hot spots (ignition sites) will be created. These modeling results compare well with the experimental pressure histories shown in Figure 7.

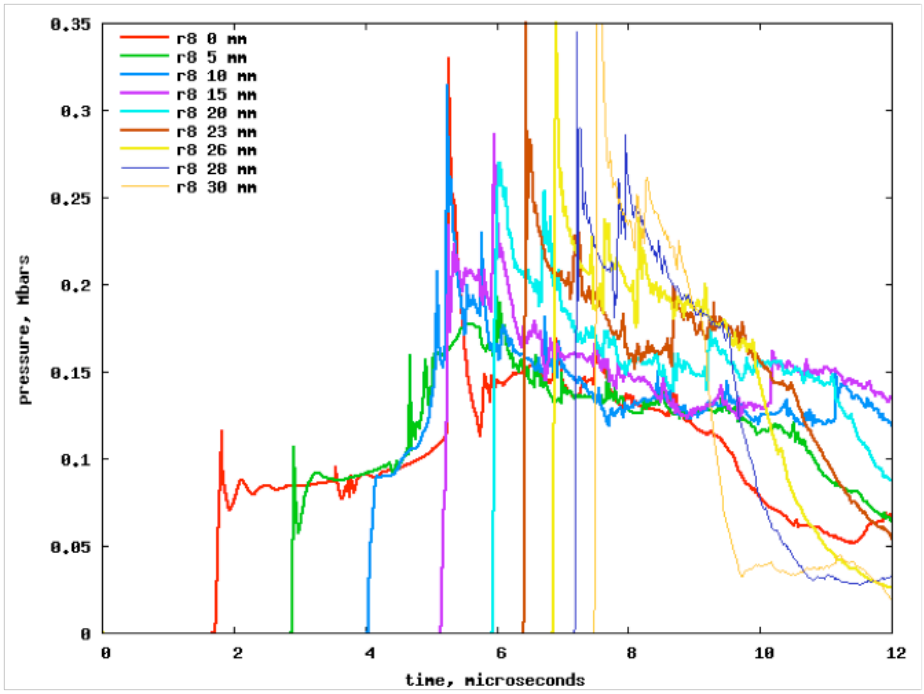

Figure 5. Simulated gauge records for the PBX 9502 experiment before the experiment was performed using ALE3D.

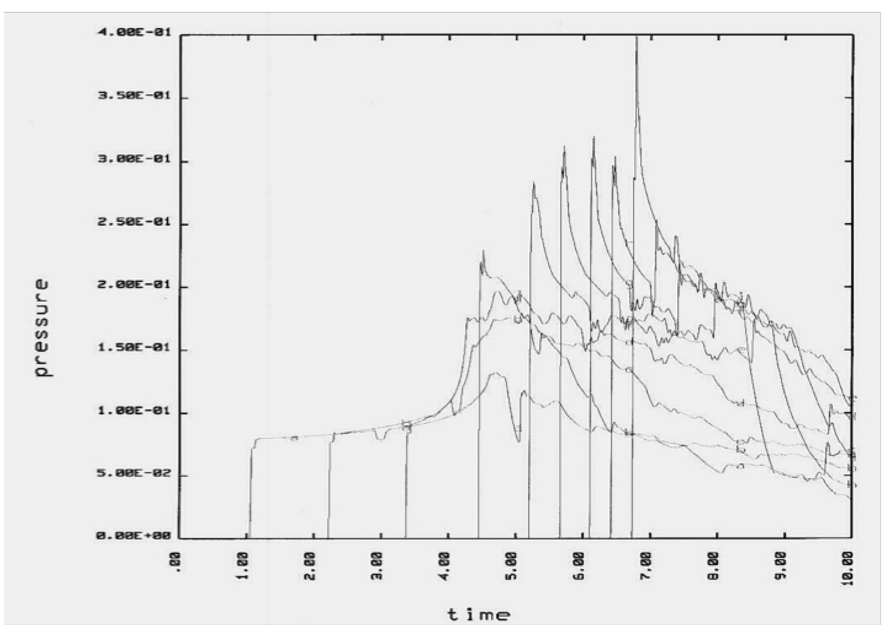

Figure 6. Simulated gauge records for the PBX 9502 experiment before the experiment was performed using LS-DYNA.

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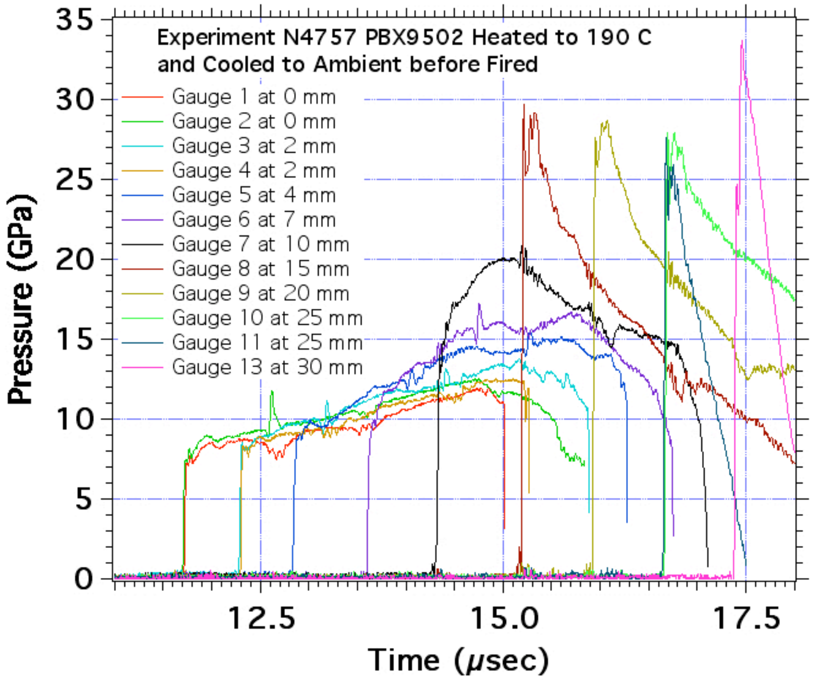

Figure 7. Experimental gauge records from experiment 4757.

While detonation depends only on the average initial density of the solid explosive, shock initiation depends strongly on the initial porosity, temperature, and explosive particle grain size. Shock initiation is governed by the creation of "hot spots" formed under shock compression. Damaged explosive charges have higher porosities than pristine charges, and therefore more "hot spots" are formed when the pores are collapsed by the shock front. At higher initial temperatures, these "hot spots" also grow faster into the surrounding explosive particles than they do at ambient temperatures. This effect has been quantitatively measured with embedded pressure and/or particle velocity gauges and calculated using the Ignition and Growth reactive flow model for several explosives, including LX-04.

To quantitatively determine the increased shock sensitivity of LX-04 damaged by different mechanisms, three 101 mm gas gun experiments were fired at comparable impact velocities to achieve similar run-distances-to-detonation using damaged LX-04 targets containing embedded manganin pressure gauges. In this study, LX-04 charges with embedded manganin gauges in the geometry shown in Figure 8 were damaged thermally, mechanical, and simulated by cutting the disks into slices. One LX-04 target

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was heated to 190˚C to allow the beta to delta phase transition to occur and then cooled to ambient temperature. Another LX-04 target was mechanically damaged to simulate low level, long time duration damage mechanisms, and the third target was machined into wedge shaped parts and then loosely reassembled to simulate the presence of a smaller number of relatively large cracks.

The heating and cooling curve for the thermally damaged LX-04 shot is shown in Figures 9 and 10. Figure 9 shows the heating and heat soak portion of the thermal profile. An endotherm indicating the beta to delta HMX solid state phase transition can be seen in the embedded thermocouple traces. The shot was fired after about 18 hours after the heaters were turned off.

Figures 11 - 13 show the measured pressure versus time histories at the embedded gauge locations for the three gas gun experiments. The thermally damaged LX-04 target reacts nearly as rapidly as previous LX-04 targets shocked at 190˚C, indicating that the increased porosity caused by thermal expansion and the beta to delta phase transition dominates the shock sensitivity of thermally damaged LX-04. The two "mechanically" damaged LX-04 targets exhibited slightly increased shock sensitivity compared to pristine LX-04, as determined by previous embedded gauge experiments on pristine LX-04. Figure 14 shows the measured shock sensitivities of the damaged LX-04 targets compared to ambient temperature and preheated LX-04 targets in terms of run distances to detonation versus shock pressure ("Pop Plots").

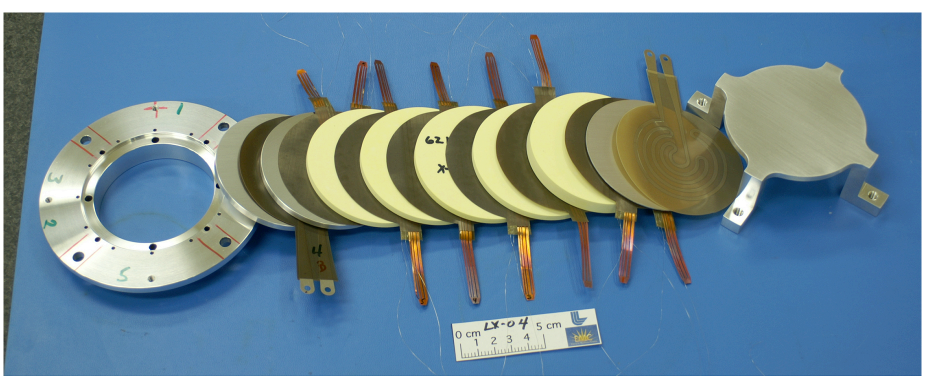

Figure 8. Stack-up of LX-04 and gauges for the shock initiation experiments.

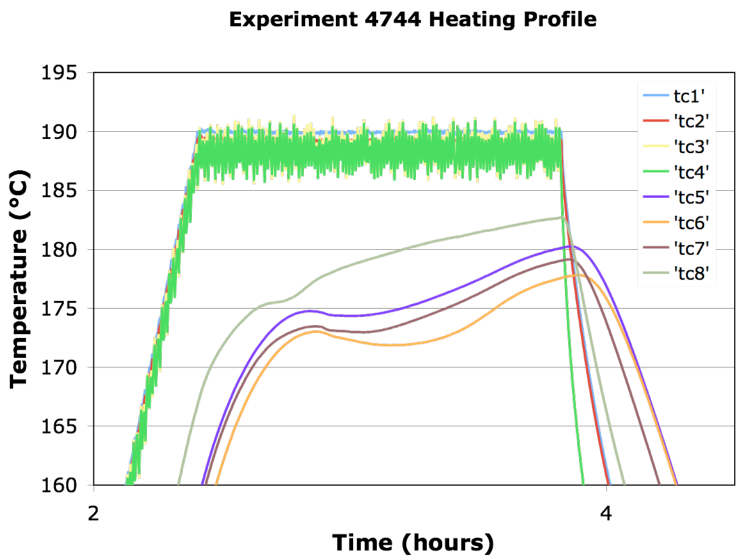

Figure 9. Heating and cooling curves for thermally damaged LX-04 (showing the beta to delta HMX phase transition).

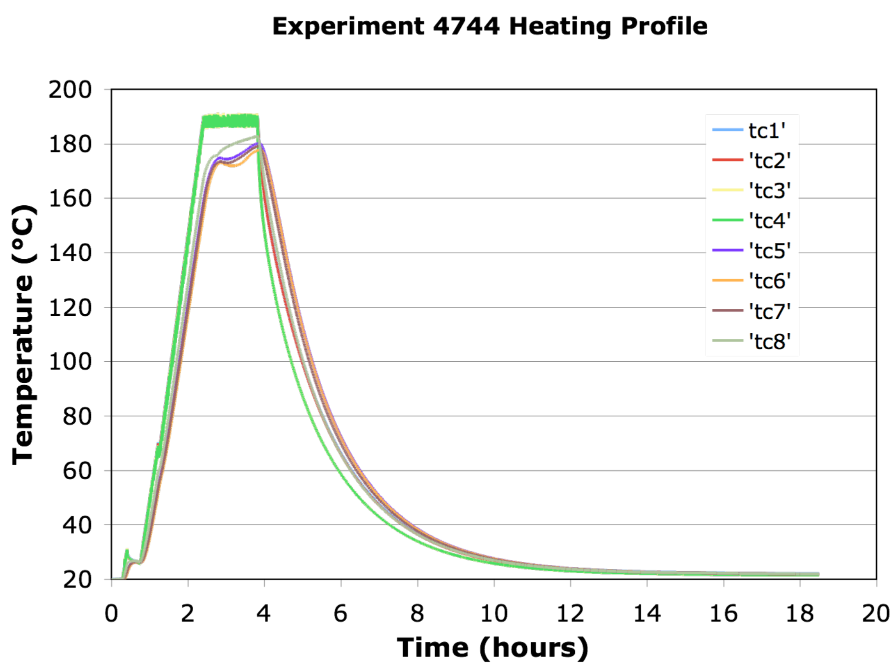

Figure 10. Complete heating and cooling curve for thermally damaged LX-04.

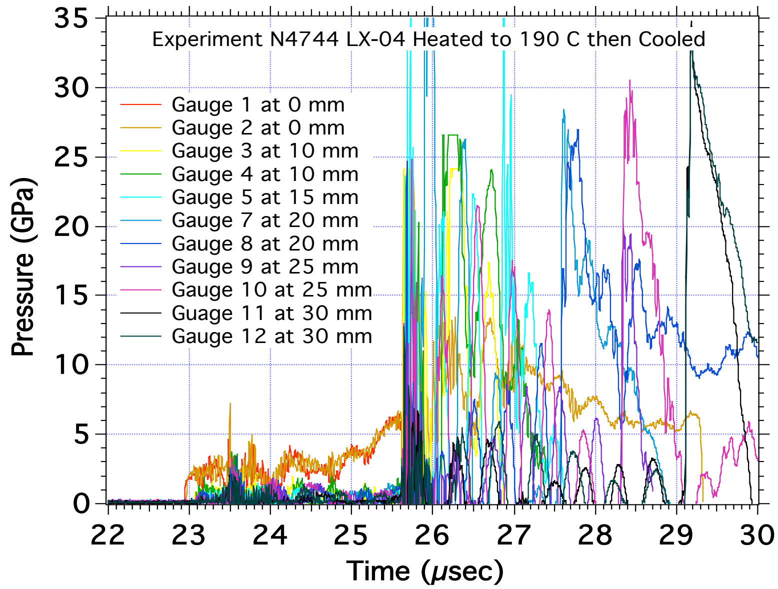

Figure 11. Pressure histories measured in thermally damaged LX-04.

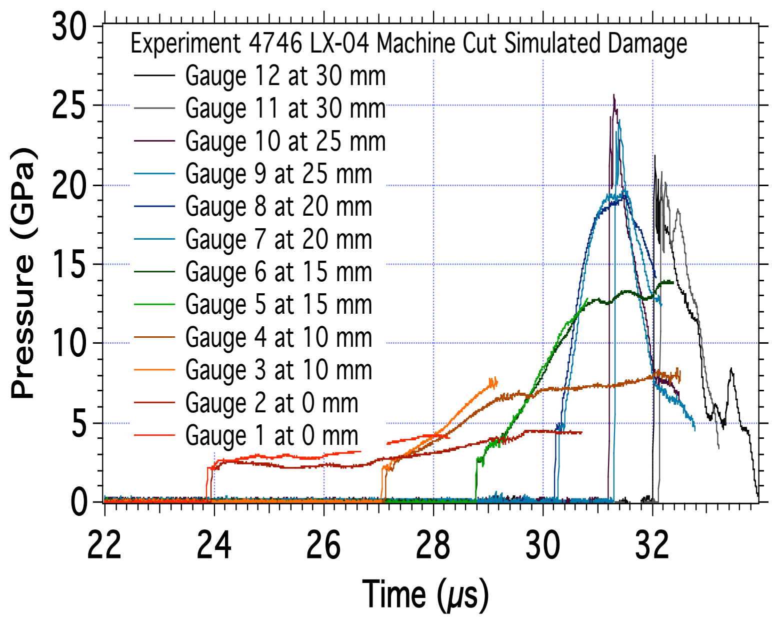

Figure 12. Measured pressure histories for machine cut simulated damage in LX-04.

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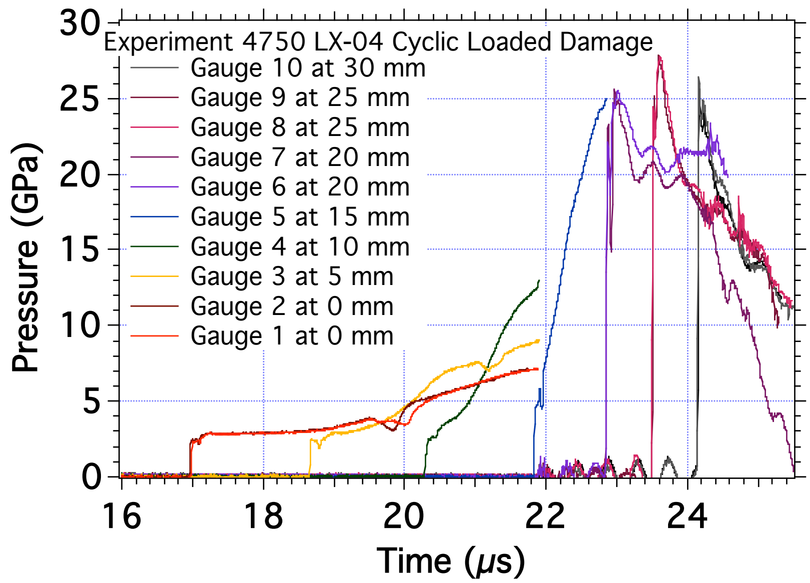

Figure 13. Measured pressure histories in mechanically damaged LX-04.

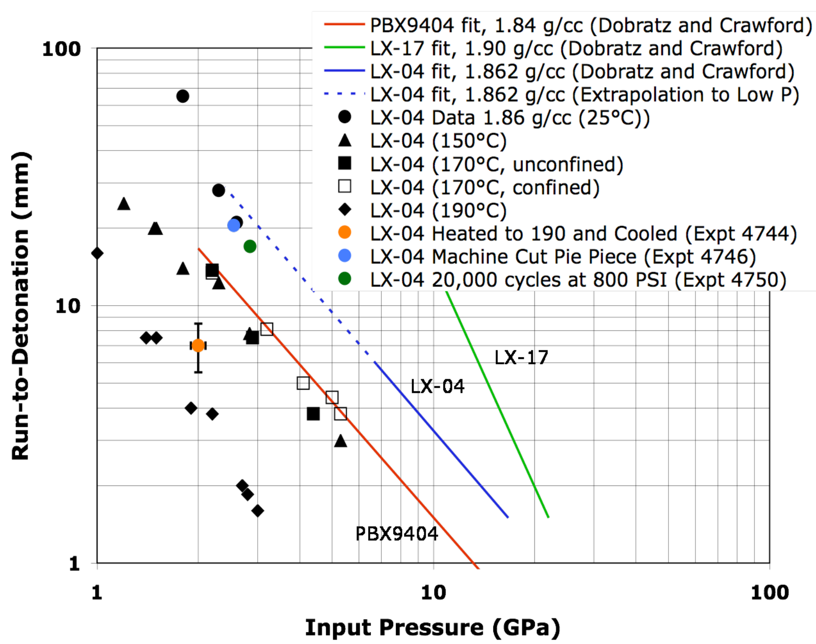

Figure 14. Pop Plots for pristine and damaged LX-04 relative to LX-17 and PBX 9404.

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Table 3. Summary of LX-04 “damaged” experiments

SHOT	MAT’L	TEMP.	DENSITY	IMPACT VELOCITY	SABOT	FLYER PLATE	IMPACT PLATE	INPUT PRESSURE	RUN TO DET
4744	LX-04	25°C	1.76 g/cc	0.654 km/s	Mod II	Al-6061	Al-6061	2.0 GPa	7 mm
4746	LX-04	25°C	1.86 g/cc	0.896 km/s	Mod II	Teflon	Teflon	2.55 GPa	20.5 mm
4750	LX-04	25°C	1.86 g/cc	0.951 km/s	Mod II	Teflon	Teflon	2.85 GPa	17 mm

Figures 15 – 17 contain the calculated pressure verses time histories for the three damaged LX-04 targets. The thermally damaged experiment was modeled using the density measured for the appropriate degree of cooling (1.75 g/cm^3), thus more LX-04 was ignited in hot spots formed by shock compression (approximately 8%). Then the growth of reaction was calculated using the reaction rate for ambient LX-04, because the hot spot reaction was progressing in LX-04 shocked at ambient temperature. The mechanically damaged LX-04 charge had a measured density of 1.831 g/cm^3, which implies 4% voids. Thus the ignition term in the Ignition and Growth model assumed that approximately 4% of the LX-04 was ignited by shock compression. Similarly, for the simulated damage LX-04 charge, the measured density was 1.85 g/cm^3, which is about 3% porous, and thus 3% of the LX-04 was ignited when that experiment was calculated. The rest of the LX-04 Ignition and Growth parameters were assumed to be the same as pristine LX-04. Comparing Figures 11 – 13 with Figures 15 – 17 shows that the calculations agree very well with the experiments, indicating that the ignition assumptions used in the modeling of the damaged charges were reasonable.

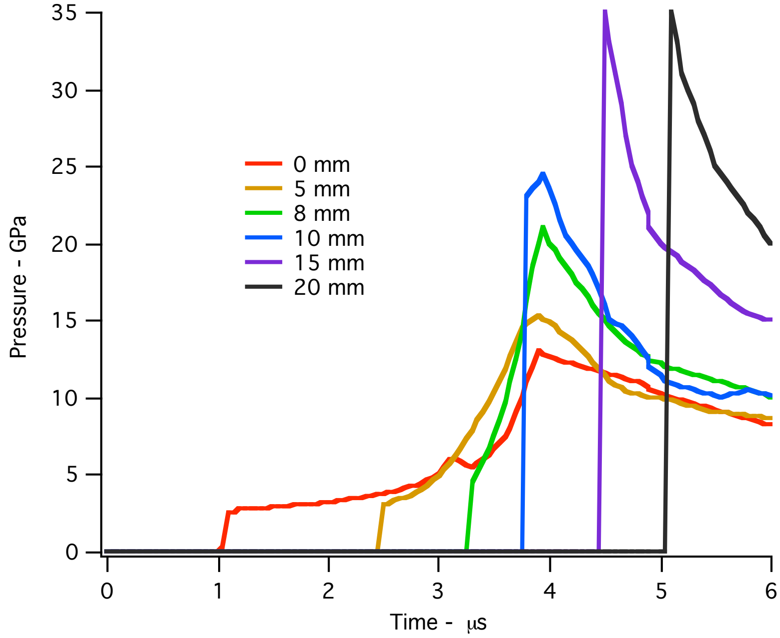

Figure 15. Calculated pressure histories for the thermally LX-04 experiment

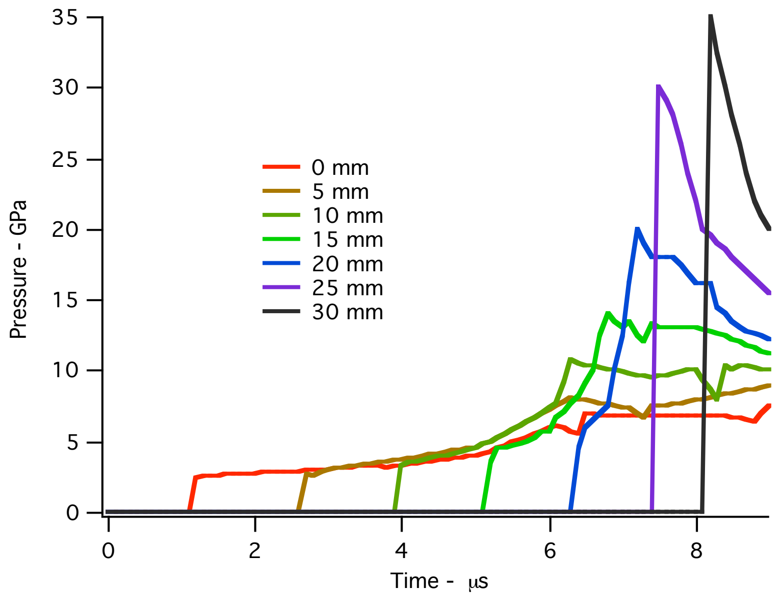

Figure 16. Calculated pressure histories for the simulated damage LX-04 test.

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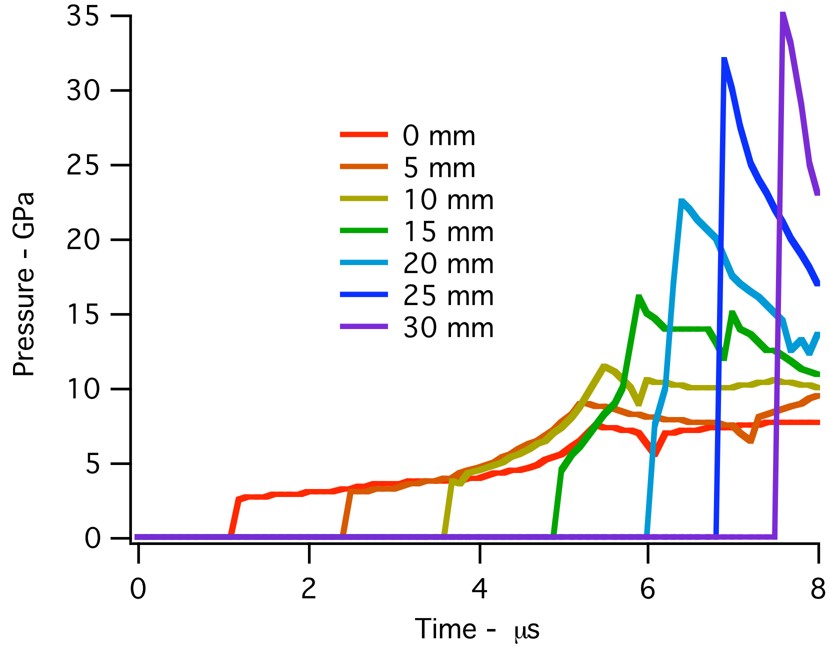

Figure 17. Calculated pressure histories for the mechanically damaged LX-04 test.

SUMMARY

A shock initiation experiment on the explosive PBX 9502 (95% TATB and 5% Kel-F by weight) heated to 190°C and cooled to room temperature was performed to obtain in-situ pressure gauge data and Ignition and Growth modeling parameters. The run-distance-to-detonation points on the Pop-plot for these experiments and in-situ gauge records showed the damaged material has approximately the same shock sensitivity of material heated to roughly 90°C. The Ignition and Growth modeling also support these conclusions. Future experimental and modeling work is needed extend the Pop plots into safety regime (lower pressure and longer run to detonation distances) and to better establish the effect that damage has on the insensitive high explosive (IHE) when heating at different temperatures.

Material damage was defined in three different ways (simulated, thermal and mechanical) for the study of the LX-04, a more shock sensitive HMX-based explosive. The large scale testing showed that simulated and mechanical damage produced slight increases in shock sensitivity in LX-04. In contrast, the thermally damaged LX-04 did exhibit greatly increased shock sensitivity.

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