UCRL-CONF-214667

Initiation of Heated PBX-9501 Explosive When Exposed to Dynamic Loading

P. A. Urtiew, K. S. Vandersall, C. M. Tarver, F. Garcia

August 17, 2005

Disclaimer

INITIATION OF HEATED PBX-9501 EXPLOSIVE WHEN EXPOSED TO DYNAMIC LOADING

Paul A. Urtiew, Kevin S. Vandersall, Craig M. Tarver and Frank Garcia

Energetic Materials Center
Lawrence Livermore National Laboratory
P.O.Box 808, L-282, Livermore, CA 94550

Abstract. Shock initiation experiments on the heated PBX9501 explosive (95% HMX, 2.5% estane, and 2.5% nitro-plasticizer by weight) were performed at temperatures 150˚C and 180˚C to obtain in-situ pressure gauge data. A 101 mm diameter propellant driven gas gun was utilized to initiate the PBX9501 explosive and manganin piezo-resistive pressure gauge packages were placed between sample slices to measure time resolved local pressure histories. The run-distance-to-detonation points on the Pop-plot for these experiments showed the sensitivity of the heated material to shock loading. This work shows that heated PBX-9501 is more shock sensitive than it is at ambient conditions. Proper Ignition and Growth modeling parameters were obtained to fit the experimental data. This parameter set will allow accurate code predictions to be calculated for safety scenarios involving PBX9501 explosives at temperatures close to those at which experiments were performed.

INTRODUCTION

A considerable interest exist in studying safety aspects of exposing heated energetic materials to dynamic loading conditions. Of particular interest are the HMX (octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine) based explosives such as the commonly used PBX 9501 (95% HMX, 2.5% estane, and 2.5% nitroplasticizer by weight) and LX-04 (85 % octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazine (HMX) with 15 % Viton binder) when they are exposed to elevated temperatures prior to their dynamic loading such as a shock wave. The work on LX-04 has been described earlier in several publications [1-3] with the latest overview still in press [4]. Prior studies on PBX-9501 include wedge tests [5], embedded particle velocity gauges [6-8], and VISAR at low input shock pressures [9,10], and embedded manganin gauges [11,12] at both ambient and elevated temperature. In this paper an attempt was made to extend the heating temperature to that beyond the polymorphic phase transformation of HMX from β to δ phase and show how shock sensitivity of PBX-9501 is affected by this increase in temperature.

EXPERIMENT

Shock initiation experiments were performed on the explosive PBX 9501 using the 101 mm diameter propellant driven gas gun at Lawrence Livermore National Laboratory (LLNL), which allows close control of the projectile velocity and of the loading pressure imposed on the energetic materials (EM) target.

The target assembly, shown in Fig. 1, consisted of several discs of different thickness. Gauge packages containing manganin pressure gauges were embedded between individual discs. The gauges were armored with thin (125 μm) Teflon insulation on both sides to prevent shorting of the gauges in a conductive medium when the material becomes reactive. Other details of the manganin pressure gauges were described in our previous publications [13-17]. For better control of the impact pressure a thin buffer plate of the same material as the impact plate is placed in front of the target assembly for symmetrical impact. Also included in the target assembly are six tilt pins placed around the periphery of the target flush with the impact surface to measure tilt of the impact plate as it strikes the target, and two velocity pins sticking out some known distance from the target to measure velocity of the impact plate just before it strikes the target.

During the heated experiments nichrome foil spiral heaters were placed on both sides of the target separated by a thin aluminum disc for better heat distribution into the material under study. In this case gauge packages also contained thermocouples (TC) for better monitoring of the target temperature distribution during the heating cycle. The heating rate of the target was usually held constant initially at 3˚C/min until about10˚C below the desired temperature. Then it was changed to 1˚C/min until the final desired temperature is reached where it was held as long as necessary before the gun was fired.

Figure 2 illustrates the temperature record during the heating cycle of the experiment to the temperature of 150˚C with traces representing the records of thermocouples at various locations within the target assembly.

EXPERIMENTAL RECORDS

Following are the types of pressure records obtained from the gun experiments on shock initiation of PBX-9501 explosive heated to different initial temperatures. Figure 3 shows the pressure records of shock loaded PBX-9501 initially at ambient temperature impacted by an aluminum flyer at a velocity of 0.697 mm/μs yielding an impact pressure of 3.3 GPa. Figures 4 and 5 illustrate the pressure records for the same explosive initially at 52 and 50 degrees Centigrade impacted by an aluminum flyer at 0.8 and 0.64 mm/μs respectively generating corresponding pressures of 3.9 and 2.95 GPa. Figures 6 and 7 show pressure records when PBX-9501 was initially heated to 150˚C and impacted by an aluminum flyer at velocities 0.73 and 0.55 mm/μs yielding impact pressures of 3.0 and 2.1 GPa respectively.

Experiments at higher initial temperature turned out very noisy due to the polymorphous transformation of HMX from a β to δ phase. This phase change has lead to a density increase of the samples, creating new voids and a loss of integrity of the target assembly, causing noisy performance of the gauges. The evidence of HMX phase transformation is illustrated in the temperature records taken during heating of explosive to the temperature of 180˚C shown in Fig. 8. Here, the phase transition can easily be observed to start at above 170˚C and last for more than 30 minutes. Thus, due to the severity of the environment, the pressure records of heated PBX-9501, just as they were in LX-04, are quite noisy and will not be shown here. However, the pertinent information for such experiment was retrieved from these records by looking at each trace separately.

The relative shock sensitivity of PBX-9501 at various initial temperatures is illustrated on the "Pop Plot" [18] shown in Fig. 9. The "Pop Plot" represents a plot of run distance to detonation as a function of impact pressure in a log-log space. The closer the points are to the origin of the plot the more sensitive the explosive is to pressure impact. Included in the Pop Plot are the results of previous studies by the Los Alamos group as well as our present work with the results previously published by the LLNL group. The data of both groups agree very well for all published results. The data point for PBX-9501 heated to 180˚C with large error bars is also in a good agreement with the data of another HMX based explosive, LX-04, heated to 190˚C.

REACTIVE FLOW MODELING

Since not all shock initiation scenarios can be experimentally tested, the Ignition and Growth reactive flow hydrodynamic computer code model of shock initiation and detonation has been developed based on the embedded gauge experiments discussed above to predict the results for such scenarios [19].

The Ignition and Growth reactive flow model uses two Jones-Wilkins-Lee (JWL) equations of state, one for the un-reacted explosive and another one for the reaction products, in the form:

where p is pressure in Megabars, V is relative volume, T is temperature, w is the Gruneisen coefficient, C_V is the average heat capacity, and A, B, R_1 and R_2 are constants. The equations of state are fitted to the available shock Hugoniot data. Table 1 contains the modeling parameters for these experiments.

Table I. Ignition and Growth modeling parameters for PBX 9501 at 150˚C.

UNREACTED JWL	PRODUCT JWL
A=7320 Mbar	A=16.689 Mbar
B=-0.065278 Mbar	B=0.5969 Mbar
R_1=14.1	R_1=5.9
R_2=1.41	R_2=2.1
ω=0.8867	ω=0.45
C_V=2.7806x10^{-5} Mbar/K	C_V=1.0x10^{-5} Mbar/K
T_0 = 423ºK	E_0=0.102 Mbar
Shear Modulus=0.0352 Mbar	-
Yield Strength=0.002 Mbar	-

The reaction rate equation is:

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

where F is the fraction reacted, t is time in ms, ρ is the current density in g/cm^3, ρ_0 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. This reaction rate law models the three stages of reaction generally observed during shock initiation of solid explosives.

Reaction rate constants used in this modeling are listed in Table 2.

Table II. Reaction rate constants.

REACTION RATES	
a=0	x=20.0
b=0.667	y=2.0
c=0.277	z=2.0
d=0.667	F_{igmax}=0.3
e=0.333	F_{G1max}=0.5
g=1.0	F_{G2min} =0.5
I=1.4x10^{11} µs^{-1}	G_1=190 Mbar^{-2}µs^{-1}
-	G_2=400 Mbar^{-2}µs^{-1}

The Grueneisen parameters used for the inert materials are listed in Table 3.

Table III. Grueneisen parameters for inert materials.

INERT	ρ_0 (g/cc)	C (km/s)	S_1	S_2	S_3	γ_0	a
6061-T6 Al	2.703	5.24	1.4	0.0	0.0	1.97	0.48
Teflon	2.15	1.68	1.123	3.98	-5.8	0.59	0.0

The Ignition and Growth simulation of the shock initiation of PBX 9501 at 25, 50 and 150°C are illustrated in Figs. 10 - 12 respectively. From these figures it is quite evident that the Ignition and Growth model simulates experimental records quite well and can be reliably used to calculate safety scenarios involving PBX-9501 explosive at temperatures from ambient to 180°C. While most of the modeling constants remain unchanged, only few of them require a change depending on the temperature. These constants are shown in Table 4.

Table IV. Ignition and Growth parameter changes for 25°C, 50°C and 150°C PBX 9501

To (°C)	Density (g/cm^3)	Unreacted B (Mbar)	G1(Mbar$^{-2}\mu$s^{-1})
25	1.83	-0.052654	130.0
50	1.82	-0.055179	130.0
150	1.762	-0.065278	190.0

SUMMARY

Previously published shock initiation experiments on the explosive PBX-9501 were reviewed and extended to initial temperature of 180°C. The use of the Ignition and Growth model for the explosive works well and can be used to calculate safety scenarios involving this explosive for the range of temperatures between ambient and 180°C.

ACKNOWLEDGEMENTS

California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

REFERENCES

1. P. A. Urtiew, C. M. Tarver, J. W. Forbes, and F. Garcia, "Shock Sensitivity of LX-04 at Elevated Temperatures," *Shock Compression of Condensed Matter-1997,* S. C. Schmidt, D. P. Dandekar, and J. W. Forbes, eds., AIP Conference Proc. 429, Amherst, MA, 2000, pp. 727 - 730.

2. C. M. Tarver, J. W. Forbes, P. A. Urtiew, and F. Garcia, "Shock Sensitivity of LX-04 at 150°C," *Shock Compression of Condensed Matter-1999,* M. D. Furnish, L. C. Chhabildas, and R. S. Hixon, eds., AIP Conference Proc. 515, Snowbird, UT, 2000, pp. 891 – 894

3. Paul A. Urtiew, Jerry W. Forbes, Craig M. Tarver, Kevin S. Vandersall, Frank Garcia, Daniel W. Greenwood, Peter C. Hsu, Jon L. Maienschein, "Shock Sensitivity of LX-04 Containing Delta Phase HMX at Elevated Temperatures," *Shock Compression of Condensed Matter - 2003*, M.D. Furnish, Y.M. Gupta and J.W. Forbes eds., AIP Conference Proc. 706, Portland OR, 2004, pp. 1053-1056.

4. Paul A. Urtiew and Craig M. Tarver, " Shock Initiation of Energetic Materials at Different Initial Temperatures", *Fizika Goreniya i Vzryva* , (in press).

5. LASL Explosive Property Data, Terry R. Gibbs and Alphonse Popolato, Editors, University of California Press, pp. 353-358, 1980.

6. Sheffield, S. A., Gustavsen, R. L., Hill, L. G., and Alcon, R.R., "Electromagnetic Gauge Measurements of Shock Initiating PBX9501 and PBX 9502 Explosives", *Eleventh International Detonation Symposium,* ONR 33300-5, Snowmass, CO*,* 1998, pp. 451-458.

7. Sheffield, S. A., Gustavsen, R. L., and Alcon, R. R., "In Situ Magnetic Gauging Technique Used at LANL – Method and Shock Information Obtained" *Shock Compression of Condensed Matter-1999*, M. D. Furnish, L. C. Chhabildas, and R. S. Hixson, eds., AIP Conference Proc. 505, Snowbird, UT, 2000, pp. 1043-1048.

8. R. L. Gustavsen, S. A. Sheffield, R. R. Alcon, and L. G. Hill, "Shock Initiation of New and Aged PBX 9501", *Proceedings of the 12th International Symposium on Detonation*, ONR 333-05-2, San Diego, CA, 2002, pp 530-537.

9. Dick, J. J., "Stress-Strain Response of PBX 9591 below 1 GPA from Embedded Magnetic Gauge Data Using Lagrangean Analysis", *Shock Compression of Condensed Matter-1999*, Furnish, M. D Chhabildas, L. C., and Hixson, R. S.,eds., AIP   Conference Proceedings 505, Snowbird, UT, 2000, pp. 683-686.

10. Dick, J, J., Martinez, A. R., and Hixson, R. S., "Plane Impact Response of PBX9501 Below 2 GPa", *Eleventh International Detonation Symposium,* ONR 33300-5, Snowmass, CO*,* 1998, pp. 317-324.

11. C. M. Tarver, J. W. Forbes, F. Garcia and P.A. Urtiew, "Manganin Gauge and reactive Flow Moeling Study of the Shock Initiation of PBX 9501", *Shock Compression of Condensed Matter-1999,* M. D. Furnish, L. C. Chhabildas, and R. S. Hixon, eds., AIP Conference Proc. 620, Atlanta, GA, 2000, pp. 1043 – 1046.

12. Kevin S. Vandersall, Craig M. Tarver, Frank Garcia and Paul A. Urtiew, "Shock Initiation Experiments on PBX9501 Explosive at 150˚C for Ignition and Growth Modeling", presented at the *Shock Compression of Condensed Matter Conference – 2005*, Baltimore MD, July 31 to August 5, 2005

13. P. A. Urtiew, J. W. Forbes, C. M. Tarver, and F. Garcia, "Calibration of Manganin Pressure Gauges at 250˚C, *Shock Compression of Condensed Matter-1999,* M. D. Furnish, L. C. Chhabildas, and R. S. Hixon, eds., AIP Conference Proc. 515, Snowbird, UT, 2000, pp. 1019 – 1022.

14. P. A. Urtiew, L. M. Erickson, B. Hayes, and N. L. Parker, "Pressure and Particle Velocity Measurements in Solids Subjected to Dynamic Loading," *Combustion, Explosion and Shock Waves* **22**, 597 – 614 (1986).

15. P. A. Urtiew, T. M. Cook, J. L. Maienschein, and C. M. Tarver, "Shock Sensitivity of IHE at Elevated Temperatures," *Tenth International Detonation Symposium,* ONR 33395-12, Boston, MA, 1993, pp. 139 -147.

16. P. A. Urtiew, C. M. Tarver, J. L. Maienschein, and W. C. Tao, "Effect of Confinement and Thermal Cycling on the Shock Initiation of LX-17," *Combustion and Flame* **105**, 43 – 53 (1996).

17. J. W. Forbes, C. M. Tarver, P. A. Urtiew, and F. Garcia, "The Effects of Confinement and Temperature on the Shock Sensitivity of Solid Explosives," *Eleventh International Detonation Symposium*, ONR 33300-5, Snowmass, CO, 1998, pp.147 -152.

18. J. B. Ramsay and A. Popolato, "Analysis of Shock Wave and Initiation Data for Solid Explosives", *Fouth Symposium (International) on Detonation,* ACR-126 Office of Naval Research, White Oak, MD, 1965, pp. 233 - 238.

19. C. M. Tarver, J. O. Hallquist, and L. M. Erickson, "Modeling Short Pulse Duration Shock Initiation of Solid Explosives," *Eighth Symposium (International) on Detonation,* Naval Surface Weapons Center NSWC MP86-194, Albuquerque, NM, 1985, pp. 951 - 961.

FIGURE CAPTIONS

Figure 1   Experimental set-up used to study initiation process in heterogeneous solid explosives. It depicts a moment as the projectile with an impactor leaves the gun barrel just before striking the target assembly. The target assembly is fitted with manganin pressure gauges and thermocouples at various depth of the target and with pins ahead of the target to measure the impact velocity and the tilt of the impact.

Figure 2   Pressure histories in hot 150 C LX-04 impacted by an aluminum flyer at 0.701 km/s.

Figure 3   Pressure histories in ambient PBX-9501 impacted by an aluminum flyer with a velocity of 0.607 mm/µs.

Figure 4   Pressure histories in PBX-9501 heated to 52°C and impacted by an aluminum flyer with a velocity of 0.8005 mm/µs.

Figure 5   Pressure histories in PBX-9501 heated to 50°C and impacted by an aluminum flyer with a velocity of 0.649 mm/µs.

Figure 6   Pressure histories in PBX-9501 heated to 150°C and impacted by an aluminum flyer with a velocity of 0.73 mm/µs.

Figure 7   Pressure histories in PBX-9501 heated to 150°C and impacted by an aluminum flyer with a velocity of 0.55 mm/µs.

Figure 8   Thermal traces at various depth of the target during the heating process to the desired temperature of 190 C. The figure shows a distinct evidence of the b to d phase transition process in HMX occurring above 175 C.

Figure 9   "Pop Plot" for PBX-9501 at various initial temperatures demonstrating its sensitivity to impact pressure.

Figure 10   Experimental (solid) and calculated (dashed) pressure profiles in ambient PBX-9501 impacted by an aluminum flyer with a velocity of 0.607 mm/µs.

Figure 11   Experimental (solid) and calculated (dashed) pressure profiles in heated to 50°C PBX-9501 impacted by an aluminum flyer with a velocity of 0.649 mm/µs.

Figure 12   Experimental (solid) and calculated (dashed) pressure profiles in heated to 150°C PBX-9501 impacted by an aluminum flyer with a velocity of 0.55 mm/µs.
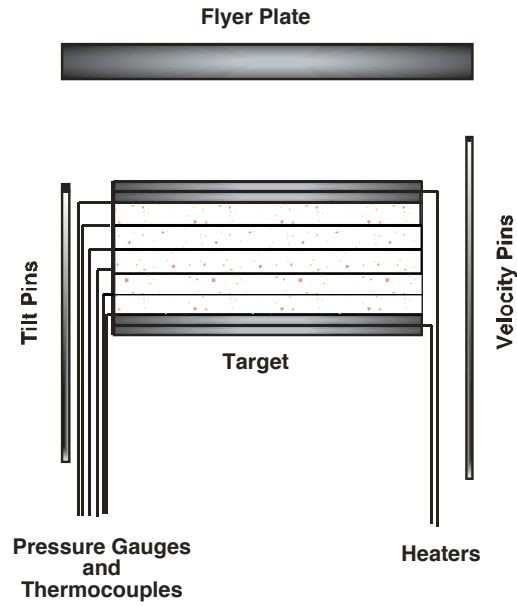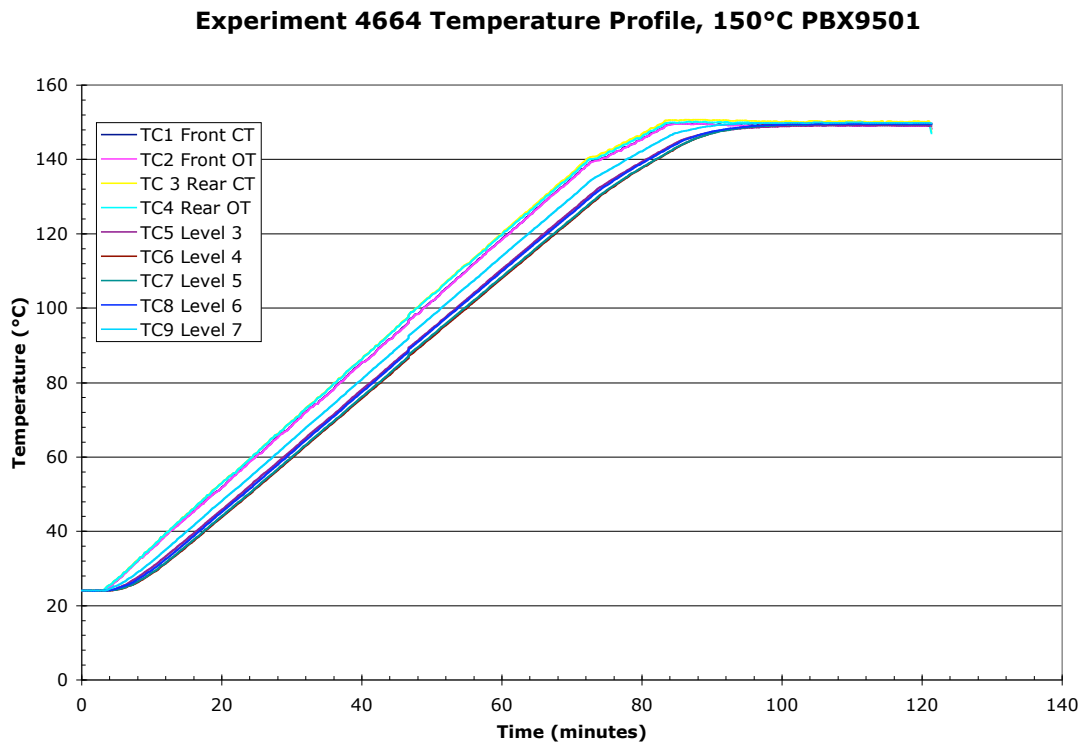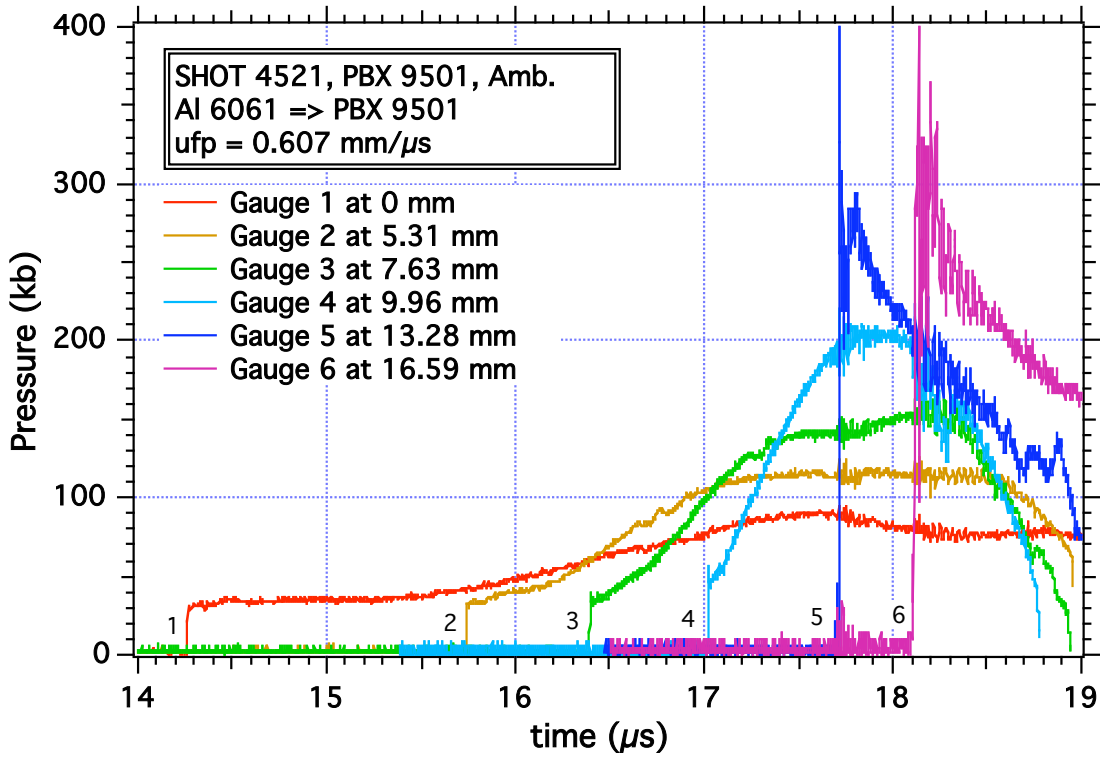
Figure 1

Figure 2

Figure 3
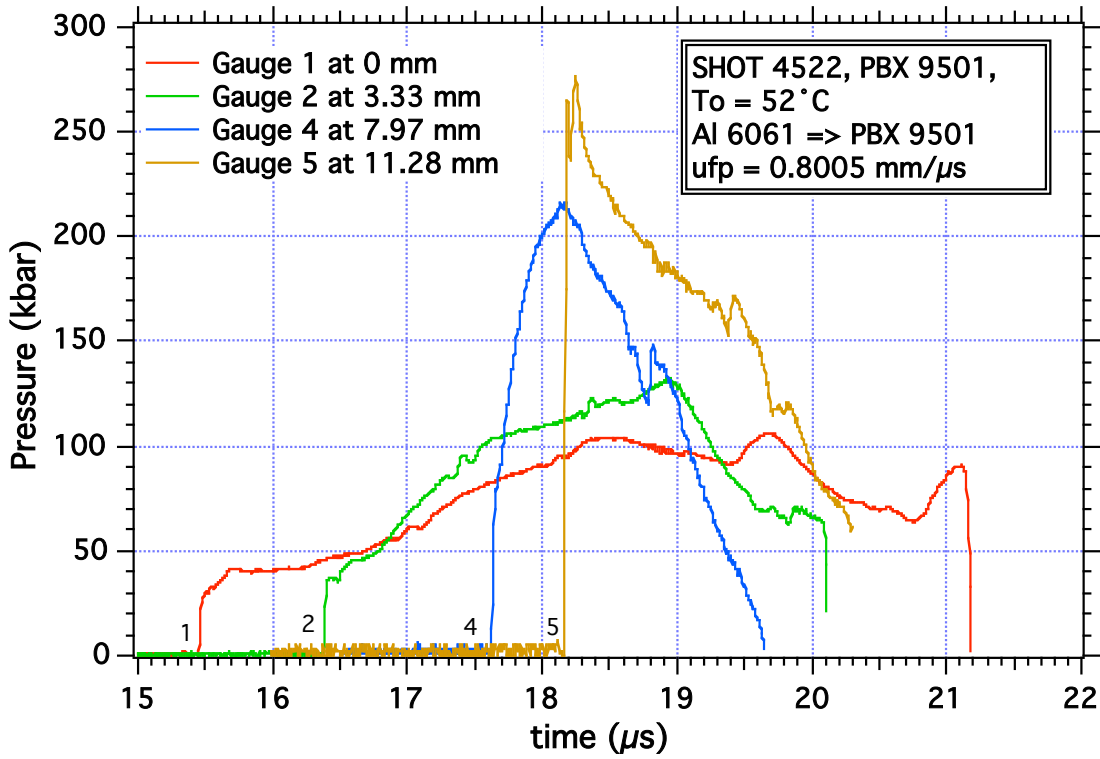
Figure 4
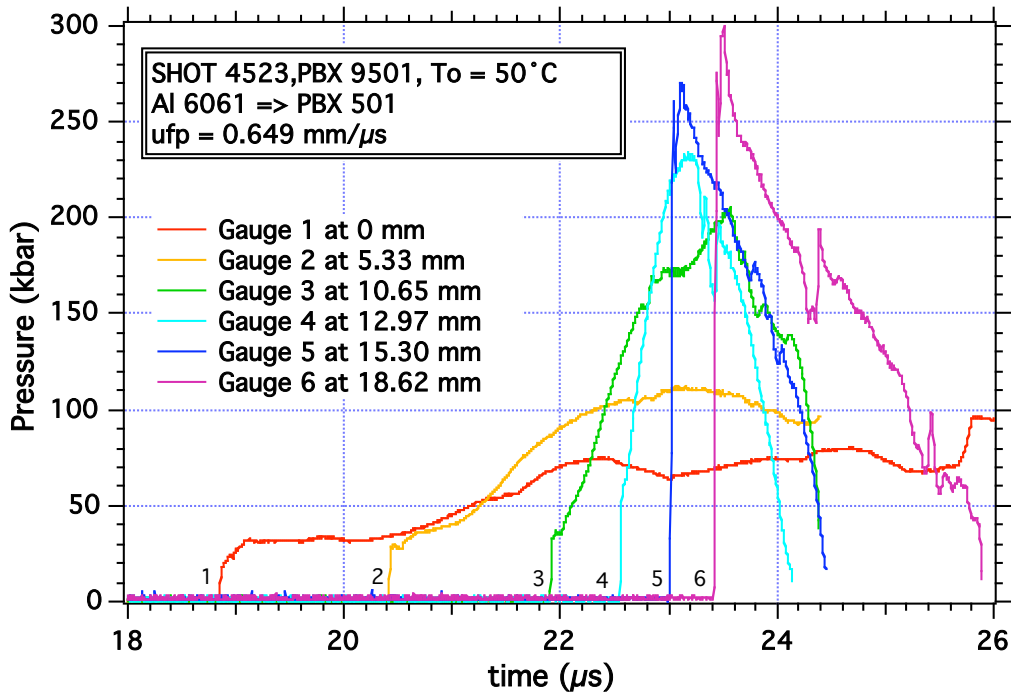
Figure 5
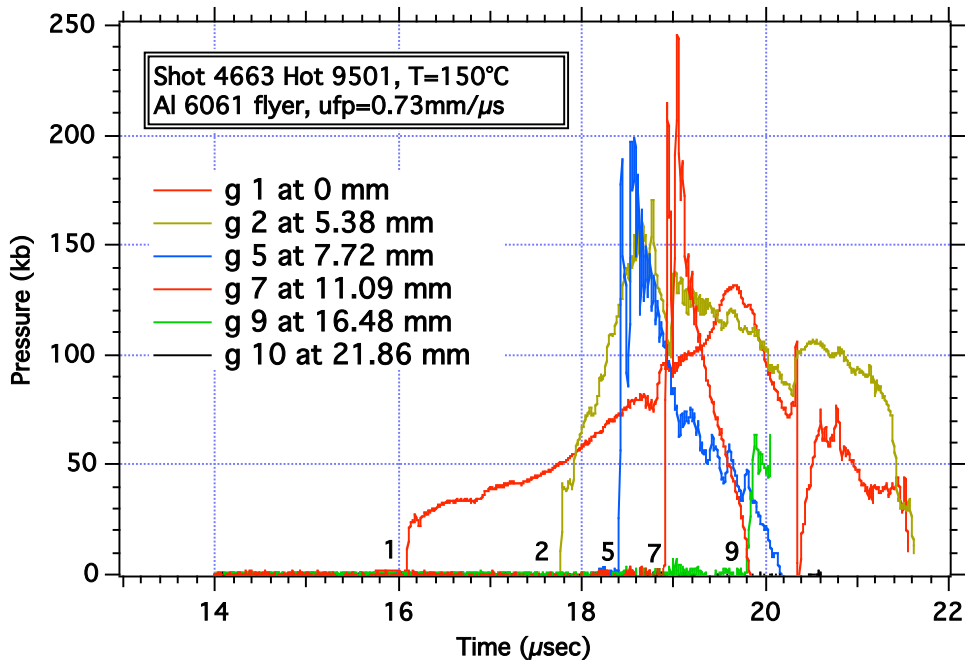
Figure 6
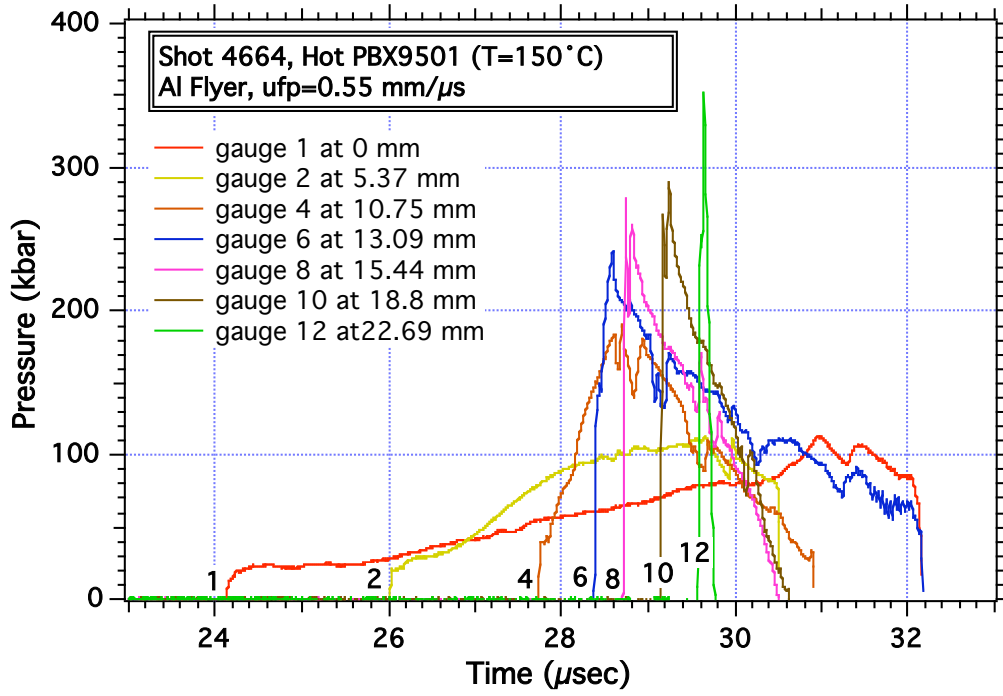
Figure 7
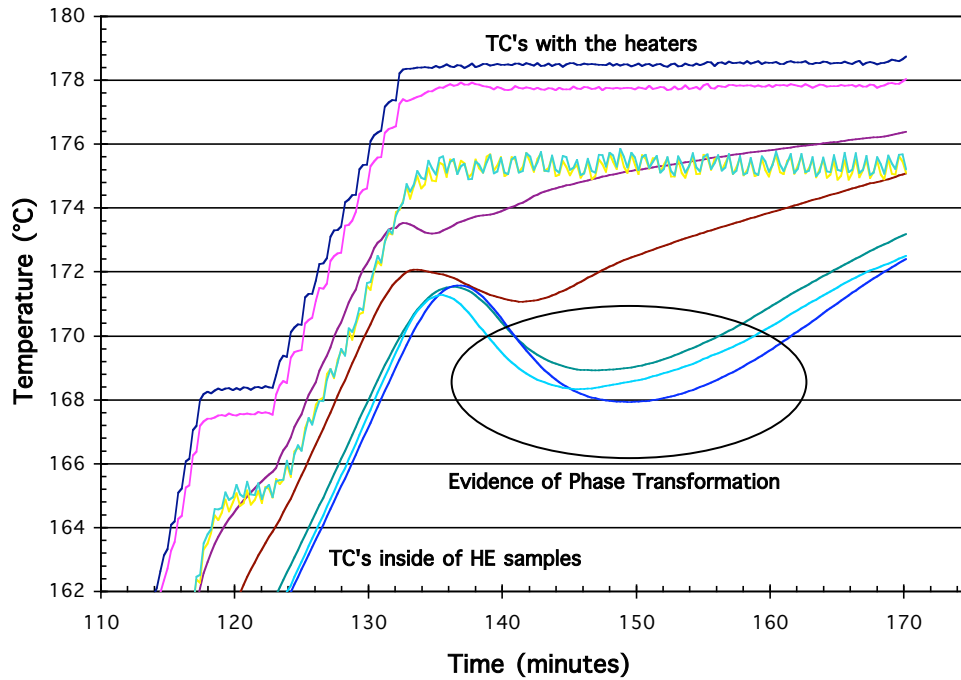
Figure 8
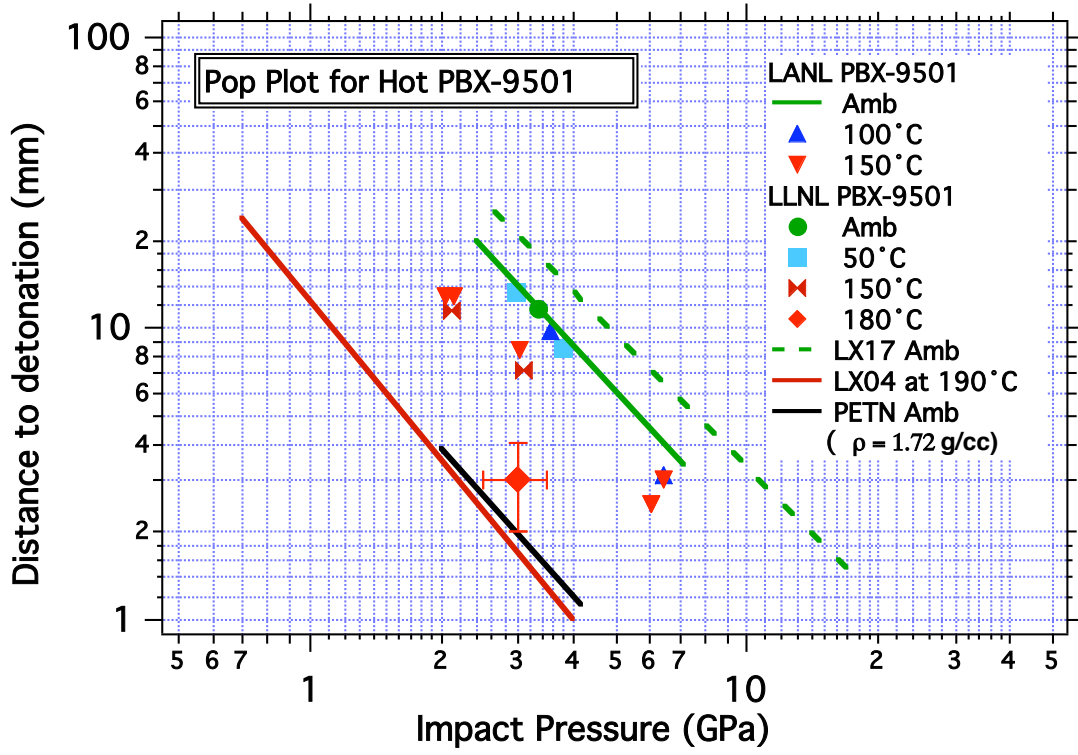
Figure 9
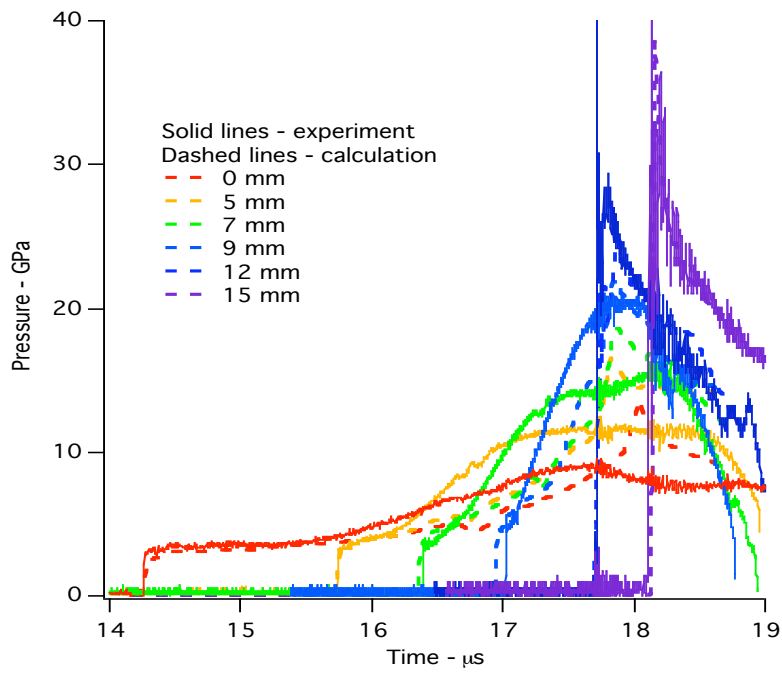
Figure 10

Figure 11

Figure 12

14