PRESSURE WAVE MEASUREMENTS DURING THERMAL EXPLOSION OF HMX-BASED HIGH EXPLOSIVES

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Five different experiments on the violence of thermal explosion in HMX-based explosives were performed. Three experiments thermally exploded PBX 9501 (HMX/Estane/BDNPA-F; 95/2.5/2.5 wt %) donor charges, while two others thermally exploded LX-04 (HMX/Viton A; 85/15 wt %). These donor charges were encased in 304 stainless steel. The transmitted two-dimensional pressure waves were measured by gauges embedded in acceptor cylinders of Teflon, PBX 9501, or LX-04 that were in contact with the donors' steel case. A fifth experiment measured the pressures in an acceptor charge of PBX 9501 that had a 100 mm stand-off from the top of the steel case of the thermally exploded PBX 9501 donor charge. Reactive flow hydrodynamic modeling using a deflagration velocity of approximately 500 m/s reproduced the pressure gauge records for both the in contact and stand off experiments that used PBX 9501 donors and acceptors.

INTRODUCTION

A better understanding of thermal explosion is needed for safe handling, transportation, and storage of explosive devices. Questions exist on the level of violence of these events as a function of confinement and thermal heating rates. Experimental measurements of the violence of thermal explosion events of known sizes, confinements, and thermal histories are essential for developing and calibrating reactive flow computer models for calculating events that are impossible to measure experimentally. The measured accelerations of metal cases from thermal explosions are also needed to assess whether the resulting flying fragments can shock initiate violent reaction or detonation in a neighboring explosive item.

The current experiments were heated at rate of 5.7 ° C until 170 ° C was reached, then at a rate of 1° C per minute until reaction occurred. Another set of experiments[1] heated these same explosives at a rate of 1° C per hour. These different heating rates bound many of the safety scenarios of interest. The ability to model these two different experiments will provide confidence in predictions without requiring experimental validation in all circumstances. In this paper, pressure gauge measurements are used for the first time to quantitatively determine the level of violence in a cook-off experiment. Carbon resistor pressure gauges are used to measure low-pressure ramp waves with pulse widths greater than 1.5 μs. Carbon resistor gauges have been successfully used in two-dimensional shock wave experiments where time resolution and accuracy were sacrificed for survival of the gauge.[2-6] The calibration of the carbon resistor gauge has been reported by numerous researchers.[2,3,7,8]

EXPERIMENTAL PROCEDURES

Five different thermal explosion experiments were done using PBX 9501 or LX-04 donor charges confined by 304 stainless steel plates.

The donor charge confinement assembly design has been kept constant for all experiments. The PBX 9501 donor discs were isostatically pressed to 1.82 g/cc (98.1% TMD), and one LX-04 donor was isostatically pressed to 1.86 g/cc (98.5% TMD), while the other donor was hand packed to a density of 1.05 g/cc (55.6% TMD) using the same pressing powder lot as used for the isostatically pressed LX-04 donor. The explosive acceptor discs were machined out of the same isostatically pressed billets as the donor charges. The acceptors were in contact with the donor system's top steel plate for four of these experiments. Experiment TEXT VII had the acceptor charge separated from the donor steel case top by 100 mm. This experiment was designed to measure the pressure induced by the impact of the steel case after acceleration to its terminal velocity by the cook-off event that occurred in the steel encased PBX 9501 donor charge. The assembled experiments were placed inside a large steel expendable cylinder to protect the firing chamber walls.

The pressure ramp waves generated in all experiments were measured by carbon resistor pressure gauges placed in machined grooves in the acceptor at various locations. The resistor gauge is a standard 1/8 W, 470 Ω carbon composition resistor made by Allen-Bradley Corporation. It is a 1.6 mm diameter by 4 mm long cylindrical resistor. It has a peak pressure accuracy of ± 15% for pressures less than 4 GPa and a temporal resolution of 1.5 μs based on 4.5 wave transits through the resistor to reach the host material's equilibrium pressure state.

Manganin foil pressure gauges were also placed in the acceptors just in case the explosive reaction in the acceptor built to a detonation. Detonation pressures are typically 20-40 GPa, which is above the carbon resistor gauge operating range. Manganin foil gauges are well established for measurement of one-dimensional shock wave pressures[9-11] from 2.0 to 40 GPa and have also been shown to be temperature insensitive.[9,12] For this investigation, manganin records need corrections for large lateral strain,[13] because the flow is multi-dimensional. The manganin gauge data is not presented here, because all reactions created sub-detonation pressures in these experiments, and the recording times for the manganin gauges were less than the measured pressure ramp waves rise-times.

The donor assembly was made up of a 12.4 mm thick 304 stainless steel top plate fastened to the 12.4 mm bottom 304 steel plate with several "grade-8" hardened steel bolts tightened to 95 N-m (70 ft-lbs). The 90 mm by 25 mm thick disk of explosive was radially constrained by a 304 stainless steel ring with wall thickness of 34.5 mm. The ring height and diameter were slightly greater than the explosive at room temperature to allow the explosive and metal container to come into contact when the explosive reached 150 º C. A 3 mm thick aluminum or copper plate was placed between the front steel plate and explosive to distribute the heat faster and more uniformly across the explosive/metal interface than would a steel plate alone. The aluminum or copper plate also served as a gasket for a pressure seal, since both steel interfaces had knife edges machined in them. The flat nichrome spiral ribbon heater of outer diameter of 66 mm, width 2.5 mm and thickness 0.1 mm laminated inside two 0.25 mm thick sheets of Teflon was placed between the steel cover plate and aluminum or copper plate at the top and bottom.

Two type K thermocouples from RDF Corporation are in this heater package to monitor temperature and control the heating rate of the heaters. The temperature measuring system is accurate to ±4°C. No thermocouples were placed internal to the steel encased PBX 9501 or LX-04 to allow simple pressure seal designs for this steel fixture. The heater controllers were programmed for the heating rates. A computer using a LABVIEW program collected the thermocouple data every 10 seconds. For all experiments, the heat was delivered to the donor at a rate of 5.7 °C a minute until the thermocouples at the heater package recorded 170 ° C. The heaters overshot a few degrees for about 7 minutes, and then the temperature came back to 170 ° C for about 30 minutes. Then the heating rate in the heater package was set at 1° C/min until the explosive thermally reacted.

Acceptor stacked discs with in-situ pressure gauges at various distances from the front impact face were built differently for each explosive cook-off experiment and will be described separately. The carbon resistor gauges were placed in machined grooves in the acceptor disc surfaces, which means that the center of this gauge is 0.8 mm from the acceptor disc interface.

The manganin gauges and thermocouples were laminated between two 0.13 mm thick Teflon insulating sheets and placed between the acceptors' machined discs. The TEXT IV acceptor was made of Teflon and was in contact with the top steel plate of the donor. It had carbon resistor gauges, manganin gauges and type K thermocouples at explosive interfaces placed 19 and 25 mm from the donor's top steel plate. No carbon resistor gauge was placed right at the top steel plate/explosive interface, because this gauge is temperature sensitive. Gauge layouts and heater packages are all similar to that shown for TEXT VI in Figure 1. For TEXT VI the manganin, carbon resistor gauges, and thermocouples were placed at interface depths of 10, 25, 40, 55, and 70 mm from the donor's steel top plate. A 10 mm thick Teflon disc is placed between the steel top plate of the confined donor system and the acceptor to provide thermal insulation for the acceptor charge. This insures that the acceptor charge does not overheat and cook-off. A second benefit is to keep the temperature lower on the carbon resistor gauges, because pressure calibrations at temperatures other than room temperature have not been done. The schematic drawing for TEXT VI is shown in Figure 2.

TEXT VII is shown in Figure 3 with the 79 mm diameter PBX 9501 acceptor placed at a 100 mm standoff from the top steel plate of the donor. The manganin and carbon resistor gauges were placed at the interfaces of the acceptor discs at 0, 8, 16, 24, and 32 mm from the front face of the acceptor HE. The acceptor was sitting on a 9.3 mm thick 304 stainless steel plate placed 100 mm from donor's steel top plate.

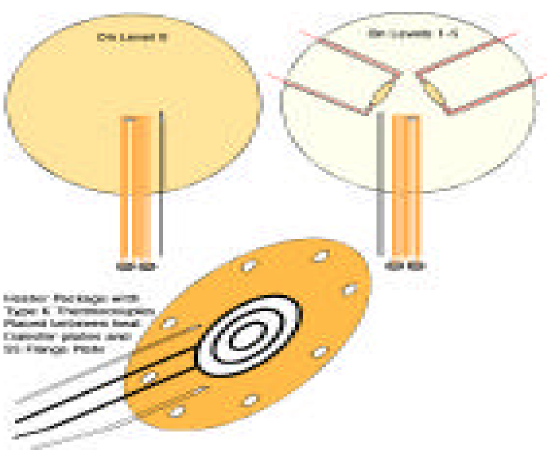


FIGURE 1. TEXT VI GAUGE AND HEATER PACKAGES

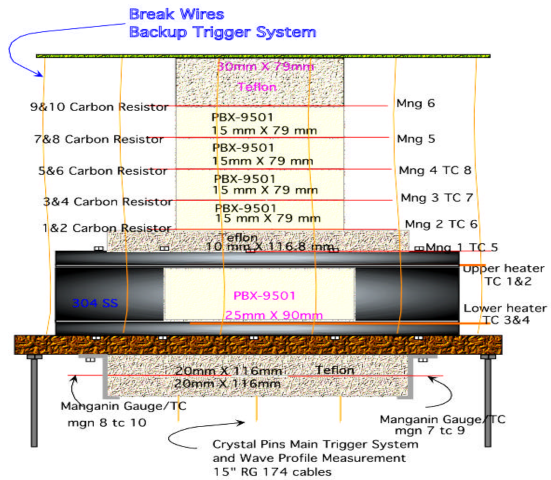


FIGURE 2. SCHEMATIC FOR TEXT VI

TEXT VIII is similar to TEXT VI except it has a LX-04 acceptor with manganin, carbon resistor gauges, and thermocouples placed at interfaces at 10, 25, 40, 55, and 70 mm in the 79 mm diameter LX-04 cylinder. A 10 mm thick by 116 mm diameter Teflon disc is placed between the steel top plate of the confined donor system to provide thermal insulation for the acceptor charge and carbon resistor gauges.

The TEXT IX acceptor was made of Teflon and was in contact with the top steel plate of the donor. It only had carbon resistor gauges and type K thermocouples at Teflon disc interfaces 20 and 28 mm from the donor's top steel plate. The first acceptor Teflon disc was 116 mm diameter by 20 mm thick, while the second Teflon disc was 79 mm diameter and 8 mm thick.

The triggering of the power supplies and the digitizers is a critical feature of this experiment. For the primary triggering system and to measure the wave arrival times at the bottom steel plate surface, a series of thirteen PZT pins were held in a Teflon disc and placed against the bottom steel plate of all donor assemblies. The pins were in a cross pattern with one pin at the center and each pin being 13.7 mm center to center distance apart. These pins can be seen just below the acceptor in Figure 2 and 3. The thirteen PZT pins were all summed so that any one of them would trigger the digitizers and the power supply for the manganin gauge. A back-up break wire trigger system designed for the STEX cook-off experiments[1] was also used. This system provided a trigger pulse from a circuit if any of the wires break. These break wires were also summed so the first one to break would trigger the digitizers and power supplies. The modern Tektronix TDS digitizer continuously records data until a trigger signal stops it. The digitizer then captures events ahead and behind the trigger signal at amounts determined by the chosen settings. This gives some necessary flexibility in performing these cook-off experiments, because there is always uncertainty as to when and where the trigger signal will originate. To measure the time of arrival of the accelerated top steel plate at the acceptor in TEXT VII, another cross pattern of 13 PZT arrival pins was used. Five pins were placed 15 mm in front surface and eight were placed 25 mm in front of the front steel acceptor plate. The placement of these pins within the acceptor can be seen in Figure 3.

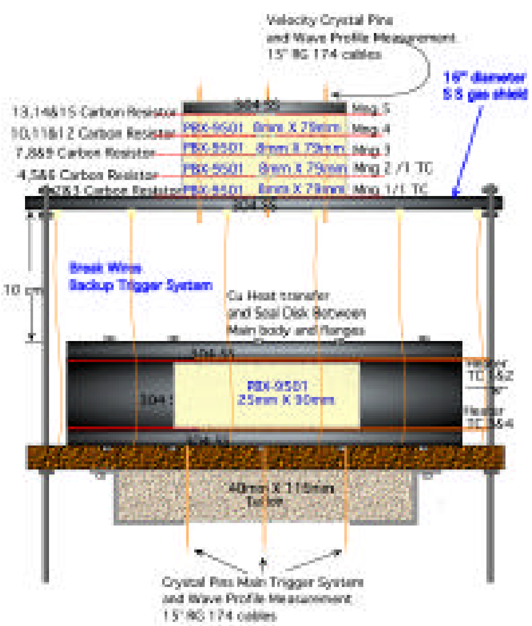


FIGURE 3. SCHEMATIC OF TEXT VII

Carbon resistor and manganin foil gauges require a constant current source to allow direct correlation of the measured voltage change to resistance change. The change in resistance has been calibrated as a function of pressure for both of these gauges at room temperature. The constant current allows conversion of measured voltage signals directly to pressure. The constant current power supply for the carbon resistor gauges is always turned on sending 18 mA through the 470 Ω resistors. The constant current pulse for the manganin gauges was provided by a Dynasen CK2-50/0.050-300 power supply that gave the gauge a constant current of 30-50 A.

RESULTS

Table 1 gives a general summary of results for these experiments. A high-pressure ramp wave was measured in TEXT IV by carbon resistor gauges with peak pressure near 0.43 GPa at a depth of 19 mm and 0.35 GPa at a depth of 25 mm into the Teflon acceptor. The carbon resistor gauges appear to have broken just after reaching peak pressures. The analysis of pin arrival times with their location for TEXT IV indicates that the reaction started slightly off center. The phase velocity across the steel surface where the PZT pins were located gave a velocity of about 1 mm/µs. This subsonic phase velocity shows that a deflagration occurred and not an instantaneous thermal explosion of the entire donor. The measured pressure pulses are also consistent with deflagration wave formation.

The carbon resistor pressure gauge results (without temperature corrections) for TEXT VI are shown in Figure 4. A ramp wave with a peak pressure of about 1.2 GPa exists at the first gauge level in the acceptor. Some variation in gauge pressure exists for gauges on the same plane, which is likely due to the ramp wave not being symmetric as it propagates into the acceptor. The ramp pressure wave decays very rapidly as it moves up the acceptor charge and the rise time of the ramp lengthens. This decay is faster than observed in the Teflon acceptor of TEXT IV, because PBX 9501 is a stiffer material with faster release wave velocities. It is clear from the gauge records that the wave did not build toward violent reaction or detonation, which would be a much more severe safety issue. In fact, the peak pressures decay exponentially.

Figure 5 gives the temperature time profiles for the five thermocouples that behaved well for TEXT VI. Their locations are given in Figure 2. These show that rapid explosion occurred when the thermocouples at the heater package of the donor system reached 209 °C. The initial heating rate was 5.7 °C per minute up to 170 °C at the metal surface of the donor. Then the temperature at this surface was held at 170 °C for 35 minutes to allow for the donor to be somewhat uniform in temperature. The temperatures in the acceptor did increase but at much lower magnitude and

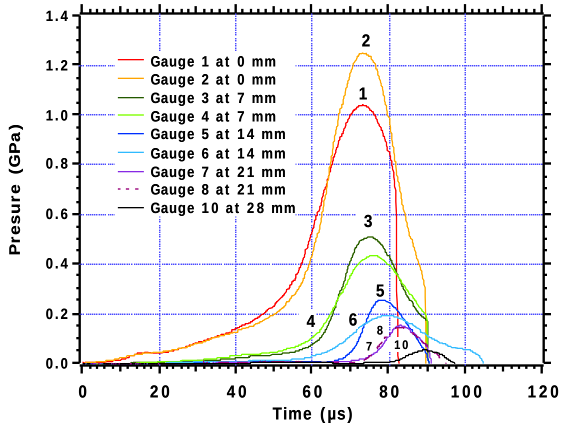
TABLE 1. GENERAL SUMMARY OF EXPERIMENTS

Shot number	Donor material	Acceptor	Heater package Temperature at Ignition (°C)	Results
TEXT IV	295 g PBX 9501 with initial density of 1.82 g/cc	Teflon cylinder in contact with donor assembly	208	Pressure ramp of 0.4 GPa peak with 100's μs rise time
TEXT V	Teflon	Teflon	N/A	Temperature profile measured inside the Teflon donor
TEXT VI	295 g PBX 9501 with initial density of 1.82 g/cc	PBX 9501 cylinder in contact with donor assembly	209	Pressure ramp of 1.2 GPa peak with 100's μs rise time
TEXT VII	295 g PBX 9501 with initial density of 1.82 g/cc	PBX 9501 cylinder stood off by 100 mm	208	Pressure ramp wave with peak 1.0 GPa with 100's μs rise time from the impact of a warped plate traveling at 0.55 mm/μs
TEXT VIII	301 g LX-04 with initial density 1.86 g/cc	LX-04 cylinder in contact with donor assembly	220	No pressure wave was measured in acceptor from a non-violent reaction in donor
TEXT IX	176 g LX-04 pressing powder packed to a density of 1.05 g/cc	Teflon cylinder in contact with donor assembly	232	Pressure ramp wave with peak 0.8 GPa with 20 μs rise time

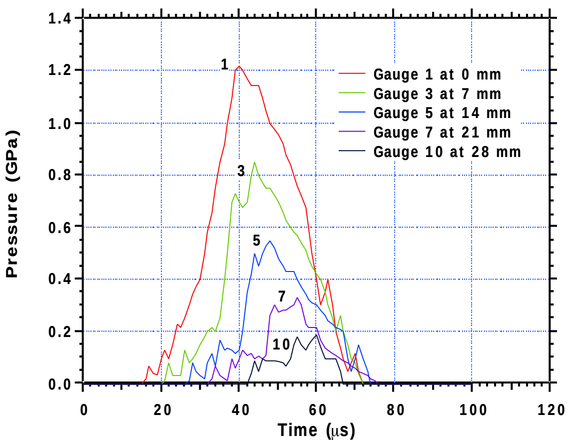
rate. However, these acceptor temperatures are high enough that calibration of the carbon resistor gauge at these temperatures is needed to improve the accuracy of these measurements. Note that TEXT V measured the temperature inside a Teflon donor assembly with thermocouples at various depths using the same heating rates as used in the explosive experiments, so thermal histories of explosive donors can be calculated for future work.

The heating history provided by the thermocouple outputs for TEXT VII went to 170 °C at a rate of 5.7 °C a minute. The controllers then allowed the heaters to overshoot to 175°C for 7 minutes and then brought the temperature back to 170 °C for 30 minutes. The heating rate at the heater package then went to 1°C/min until the temperature at the steel plate reached 210°C and the PBX 9501 donor exploded. Thermocouples 5 & 6 were located at the interface between the acceptor's steel plate and the first PBX 9501 disc. The thermocouples in the acceptor charge showed only a few degree temperature rise during this experiment, as was expected based on heat transfer calculations.

The data from the trigger and arrival time pins at the bottom of TEXT VII donor assembly indicates that a reaction pressure wave started near the center of the charge and the wave swept out from the center across the bottom steel plate. The pins near the center reported a rapid phase velocity of about 1.8 mm/μs, whereas the velocity from the center to outer pins registered phase velocities approximately 1 mm/μs. This suggests that the reaction bulged the center of the steel plate triggering center pins. The reaction then spread radially outward from the center to the outer pins that registered phase velocities of 1 mm/μs. This suggests that the plate section just above the reaction front pushed into the pins.



A.



B.

FIGURE 4. (A) EXPERIMENTAL AND (B) CALCULATED PRESSURE RESULTS FOR TEXT VI

Figure 6 gives the measured contours of the flying donor top steel plate just before impacting the steel plate that confined the acceptor charge. These contours were determined from the plate's velocity and arrival times at the array of pins protruding from the acceptor. The plate was traveling at an average velocity of 0.55 ± 0.04 mm/μs. Based on the limited pin data, the flying plate had a oblate spheroid shape (i.e., the shape of the back of a door knob).

The carbon resistor gauge records for TEXT VII are given in Figure 7. The ramp wave's peak pressure decays rapidly as the wave travels through the acceptor. The pressure wave has a peak of 1.0 GPa at the first PBX 9501 acceptor disc, decreasing to 0.4 GPa after a 32 mm run distance into the PBX 9501acceptor. The ramp wave in these records with structure later in time is due to the three-dimensional loading of the warped flyer plate. This pressure amplitude did not cause significant reaction in the PBX 9501 acceptor charge.

The results for TEXT VIII are very qualitative since no pressure wave was measured. A standard video (60 Hz) of the event showed that the bolts broke at 220 °C causing the assembly to become airborne a few inches, which pushed the acceptor aside. The LX-04 donor had flames coming out of one side. The acceptor was recovered intact with gauges still functional.

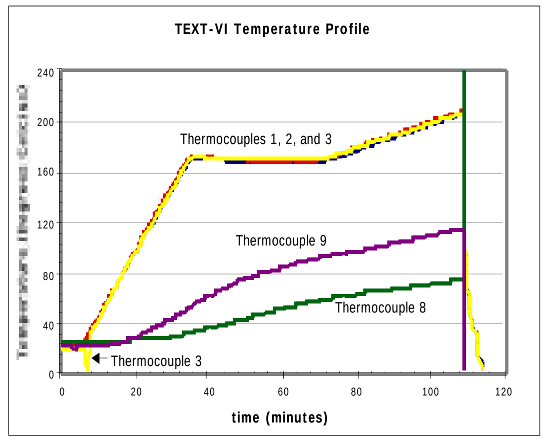


FIGURE 5. TEMPERATURE PROFILES OF VARIOUS THERMOCOUPLES AT VARIOUS LOCATIONS IN THE TEXT VI TARGET

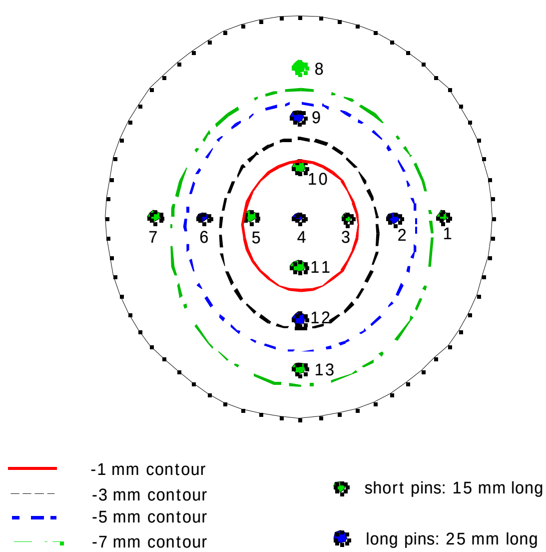
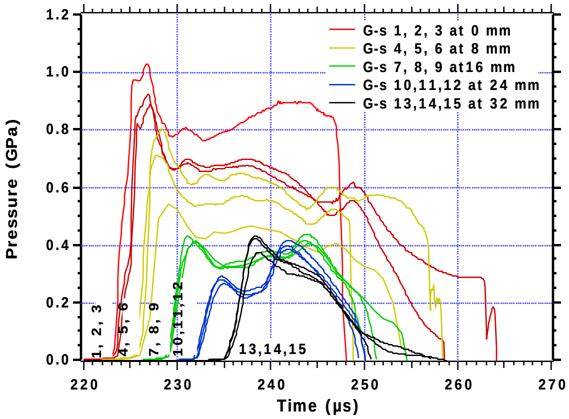
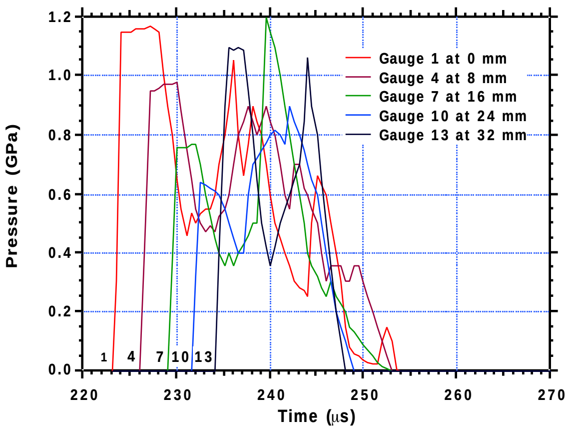


FIGURE 6. TEXT VII FLYER PLATE CONTOUR AS MEASURED BY ARRIVAL PINS IN FRONT OF ACCEPTOR



A.



B.

FIGURE 7. (A) MEASURED AND (B) CALCULATED PRESSURES FOR TEXT VII EXPERIMENT.

TEXT IX donor was LX-04 pressing powder hand packed to a density of 1.05 g/cm^3. The gauges in the Teflon acceptor at 20 mm depth gave a pressure ramp wave with peak 0.8 GPa with 20 µs rise time. This ramp wave was not symmetric since gauges at 28 mm depth in the Teflon gave stresses from 0.4 to 0.7 GPa with the highest value at the center gauge. The rapid reaction occurred when the thermocouples in the heater package reached 132°C.

REACTIVE FLOW MODELING OF TEXT VI AND TEXT VII EXPERIMENTS

The experimental geometries of TEXT VI and TEXT VII were modeled using the DYNA2D hydrodynamic computer code. Initially, the PBX 9501 donor charge was assumed to detonate, which resulted in pressures much greater than those measured in the PBX 9501 acceptors. This was also found to be true for a calculation assuming a constant volume explosion of the entire donor charge. To realistically model TEXT VI and TEXT VII, the PBX 9501 was assumed to deflagrate with pressure dependent rates using the DYNABURN option of the code. DYNABURN is an outgrowth of the Ignition and Growth reactive flow model for shock initiation and detonation wave propagation in solid explosives.[14] A small initial pressure and/or fraction reacted initializes DYNABURN in the elements where the reaction is known or assumed to begin. A subsonic deflagration wave is then propagated using the pressure and particle geometry dependent growth of reaction terms of the Ignition and Growth model. DYNABURN has been used to model air bag propellants, internal ballistics of guns, explosive and propellant deflagration, and other violence of thermal explosion experiments.[15]

The Ignition and Growth reactive flow model uses two Jones-Wilkins-Lee (JWL) equations of state in the temperature dependent form:

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

where p is pressure in Megabars, V is relative volume, T is temperature, ω is the Gruneisen coefficient, Cv 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 in the DYNABURN option is:

$$dF/dt = G_1(1-F)^c(F+a)^d(p+b)^y + G_2(1-F)^e F^g p^z \qquad (2)$$

$$0<F<F_{G1max} \qquad F_{G2min}<F<1$$

where F is the fraction reacted and a, b, c, d, e, g, y, and z are constants. The usual PBX 9501 JWL equations of state were used in these calculations.[16] The constants c, d, e, and g were set equal to 2/3 to model spherical particles. The pressure exponents y and z were set equal to one to simulate a linear dependence of deflagration rate on pressure. The reaction rate coefficients G_1 and G_2 were adjusted to yield an overall deflagration rate of approximately 500 m/s. In both calculations, the deflagration wave was assumed to start along the entire bottom surface of the donor PBX 9501 charges and then propagate upward toward the acceptor charges. In the model, this was accomplished by setting b = 0.005 Mbars in Eq. (2) for each of the zones along the bottom of the PBX 9501 donor charge.

In the TEXT VI calculation, a pressure ramp wave is transmitted to the in-contact PBX 9501 acceptor. The peak magnitude and rise-times of these pressure ramp waves are similar to the experimental measurements. The calculated decay of the peak pressure as the ramp wave moves deeper into the PBX 9501 acceptor is also in good agreement. Figure 4B shows the calculated pressure histories in the PBX 9501 acceptor at the embedded gauge depths. The calculated peak pressures agree well with those measured with carbon resistor gauges. Since a simple elastic-plastic model was used for PBX 9501, the calculated compression times are shorter than those observed experimentally, and the measured early low-pressure ramp wave was not accurately simulated. The calculated pressure histories decay rapidly as they propagate through the PBX 9501 and do not evolve into shock waves that could cause any significant reaction.

The same modeling approach was used for the PBX 9501 cook-off for TEXT VII. In this case, the hydrodynamic code calculated the donor's top steel plate accelerating across the stand-off distance following the deflagration process. The calculations showed that the donor's top steel plate reached its terminal velocity of 0.51 mm/µs in less than the 100 mm experimental stand-off distance. This calculated velocity is within the uncertainty of the experimental measurement, 0.55 +/- 0.04 mm/µs. Figure 7B shows the resulting calculated pressure histories in the PBX 9501 acceptor charge at the 0, 8, 16, 24, and 32 mm depths where the carbon resistor gauges were located. The calculated pressures and rise times are in better agreement with the shock waves created by the flyer plate impact with PBX 9501 in TEXT VII than the ramp waves created in the in-contact experiment TEXT VI. The Ignition & Growth PBX 9501 reactive flow model normalized to LLNL and LANL embedded gauge records for shock initiation[16] predicts that these pressure waves do not cause significant reaction and thus no buildup to violent reaction in the acceptor charge.

The general agreement between these calculated records and the carbon gauge records in Figures 4 and 7 show that these resistor gauges are recording the peak pressures and pulse durations with an accuracy of at least 20%. The attenuation of the peak pressures are faster in the experiments than in the calculations, and the pressure releases in the calculations is faster than in the gauge records. Further experimentation and more sophisticated reactive flow modeling are required to address these differences. Part of the difference is likely due the carbon resistor gauges hysteresis upon the release of pressure.

No significant pressure was calculated from the cook-off of the LX-04 donor in TEXT VIII. The calculated time to thermal explosion in TEXT VIII using the LX-04 multimaterial, multistep chemical kinetic decomposition model of Tarver and Tran[17] was 7677 seconds. This is in good agreement with the experimental time of 7380 seconds, considering that the temperature measuring system has an uncertainty of 4 ˚C and the thermocouples were not embedded in the LX-04 donor.

LX-04 at densities near TMD has never exhibited the rapid deflagration wave velocities of several hundred meters per second (often called deconsolidated burning) that PBX explosives containing over 90% HMX have demonstrated in the strand burner[18], diamond anvil cell[19], and simulated crack experiments.[20] LX-04 deflagration velocities of less than 100 m/s resulted in no significant pressures being delivered to the acceptor charge in TEXT VIII simulations. If the deflagration velocity of LX-04 remained relatively slow (tens of meters per second or less) following thermal explosion, then it is not surprising that TEXT VIII and previous LX-04 thermal explosions[1,15] were not violent and no measurable pressures were generated in the TEXT VIII acceptor. The porous LX-04 pressing powder cook-off experiment TEXT IX has not yet been modeled.

SUMMARY AND CONCLUSIONS

Carbon resistor pressure gauges have been used successfully in two-dimensional shock wave experiments in which time resolution and accuracy were sacrificed for survival of the gauges. The carbon resistor pressure gauge results (without temperature corrections) in adjacent PBX 9501 or Teflon acceptors for the experiments show ramp waves with peak pressures of 1 GPa magnitude and rise times of hundreds of microseconds. These experiments used PBX 9501 donors. The ramp pressure wave decays very rapidly as it moves through the acceptor charge and the rise time of the ramp shortens. The ramp wave in the acceptors did not build into a detonation wave for any experiment.

In TEXT VI, the pressure ramp wave is transmitted to the in-contact PBX 9501 acceptor. The calculated peak magnitude and rise-times of these pressure ramp waves are in good agreement with the experimental measurements. The calculated decay of the peak pressure is also in good agreement.

In TEXT VII the gauged PBX 9501 acceptor was at a standoff distance of 100 mm from the donor's steel cover plate. A multi-dimensional ramp pressure wave was transmitted to the PBX 9501 acceptor from the impact of the curved steel plate accelerated over the 100 mm stand-off distance by the thermal explosion of a confined PBX 9501 donor system. The peak pressure in the PBX 9501 acceptor was 1.0 GPa decreasing to 0.4 GPa at a 32 mm run distance. This ramp wave showed more complex features than the other experiments. It is believed that this extra structure is due to the three-dimensional loading from the tilted and curved flyer plate impact. The measured pressures are strong enough to scatter burning materials around, but will not cause build-up to detonation in the accepter under these experimental conditions. The DYNA2D modeling of this experiment yielded results that are in fair agreement with the experiment. This indicates that 3-D flow effects are not much different than 2-D flow effects.

The Ignition and Growth reactive flow model for the shock initiation of PBX 9501, which has been normalized to a great deal of experimental data from LLNL and LANL[17], predicts no significant exothermic reaction in this PBX 9501 acceptor charge. Therefore, the model results imply that no shock initiation and subsequent buildup to detonation will occur in this type of thermal explosion test. This is consistent with the results of previous experiments on PBX's containing 85 - 95% HMX.[1,15]

In TEXT VIII no pressure waves were measured in the acceptor when the donor reacted. In fact, the acceptor was recovered intact with useable gauges. Flame was observed emitting from the donor. This mild reaction result for LX-04 is consistent with STEX test results[1] where the heating rate was 1 °C/hr. Results of TEXT IX showed that porosity was important in the cook-off of LX-04 pressing powder with density of 1.05 g/cm^3. This experiment did show peak pressures of 0.8 GPa at a distance of 20 mm depth in a Teflon acceptor. The rise time of the ramp wave to its peak value was 20 µs.

Future work in this area will include additional experiments with different heating rates, material porosities and levels of confinement. Calibration of carbon resistor gauges will be done for multi-dimensional flow and for initial temperatures up to 100 °C. The coupled thermal/hydrodynamic code ALE3D will be used to calculate these and future experiments using more sophisticated models.

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