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Title: ELECTROMAGNETIC GAUGE MEASUREMENTS OF SHOCK INITIATING PBX9501 AND PBX9502 EXPLOSIVES

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Electromagnetic Gauge Measurements of Shock Initiating PBX9501 and PBX9502 Explosives

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We have used an embedded electromagnetic particle velocity gauge technique to measure the shock initiation behavior in PBX9501 and PBX9502 explosives. Experiments have been conducted in which up to twelve separate measurements have been made in a single experiment which 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, thus providing a position-time trajectory of the wave front as it moves through the explosive sample. This provides similar data to that obtained in a traditional wedge test and is used to determine the position and time that the wave attains detonation. Data on both explosives show evidence of heterogeneous initiation (growth in the front) and homogeneous initiation (growth behind the front) with the PBX9502 showing more Heterogeneous behavior and the PBX9501 showing more homogeneous behavior.

INTRODUCTION

Shock initiation processes can be measured by in-situ gauging techniques which track the reactive wave growth as a function of time and depth. Experiments of this kind are usually done using a light gas gun to provide a well characterized input to the explosive sample. Using this technique, pressure or particle velocity measurements can be made at several Lagrangian positions during the initiation process.

These waveforms represent valuable information relating to the homogeneous/heterogeneous nature of the reactive buildup process.[1] They are also valuable to those simulating the initiation process with reactive modeling, since they provide data to calibrate the models. Because of the large amount of data obtained from a single experiment, as described in this paper, it provides a particular challenge to any global reaction rate model.

Measurements at several Lagrangian positions in a single experiment have been carried out at a number of different laboratories in the past. For example, in-situ magnetic particle velocity gauges have been used at Los Alamos National Laboratory (LANL)[2-3] since 1980 and similar experiments were done at SRI[4] and Lawrence Livermore National Laboratories (LLNL)[5] during the same time frame. In-situ manganin pressure gauges have been used at LLNL[6-7] for a number of years and are now being used in several other places. These studies have led to information about the reaction rates (from Lagrange analysis[8]) and refinements in the global reaction rate models, and the specific parameters used for a particular explosive material, employed by the reactive wave codes.[6,7,9]

In this paper we describe recent measurements made in shock initiated PBX9501 and PBX9502 explosives in which measurements of the particle velocity at up to 12 Lagrangian positions are made in a single experiment. The particle velocity waveforms track the reactive wave growth all the way from the initial input shock, through the build-up process, to very nearly a full detonation. In addition to the particle velocity gauges, another gauge (called a "shock tracker") provides information about the wave front position as a function of time, the same information obtained in a traditional explosive wedge experiment. Using this data, the position and time the reactive wave achieves detonation can be determined. A new method of analyzing this information is discussed.

EXPERIMENTAL TECHNIQUE

MAGNETIC GAUGE METHOD

Magnetic gauging was used first in Russia and described in 1960 by Zaitsev et al.[10] They used a loop gauge to measure particle velocity in explosively driven shock experiments. Although a number of researchers in the U. S. tried this technique, it was not used extensively until the technique was developed further on gas guns at

Physics International and Washington State University, largely under the direction of Fowles and coworkers[11-12] during the 1970's.

The gauge is based on a simple physics principle: when a conductor in a closed loop moves in a magnetic field, a voltage is induced in the circuit because part of the loop cuts magnetic field lines as it moves. Output voltage depends on the magnetic field strength, the length of the conductor which is cutting the field lines, and the velocity it is moving. This can be written as $E = Blv$ where E is the voltage, B is the magnetic field strength, l is the length of the conductor cutting the field lines, and v is conductor velocity. In the experiments B and l are measured before the experiment and E, as a function of time, is recorded during the experiment. From this the conductor velocity (v) as a function of time can be determined. If one assumes that the conductor moves with the material it is embedded in, then v is the mass or particle velocity of the sample material at that particular Lagrangian position.

In solid samples we have found that the gauges accurately measure the particle velocity. In liquid samples, there are two-dimensional effects that develop as the shock interacts with the gauge membrane/liquid interface. Errors up to 10 % in particle velocity can result depending on the impedance mismatch between the liquid and the gauge membrane.[13]

The magnetic gauge technique in use at LANL was developed by Vorthman and Wackerle[2-3] in the early 1980s and now includes a number of refinements which have been implemented over the years. A typical gauge configuration is shown in Figure 1. It includes 10 particle velocity gauges and a "shock tracker" in the center of the package.

The shock tracker is a particle velocity gauge in which the length of the active element changes as the wave progresses over the gauge (see center gauge in Figure 1). Since the length is changing, the voltage output is high when the conductor is relatively long and low when it is short. These changes in voltage can be correlated with the shock position so that a time-distance diagram of the shock as it progresses through the sample can be plotted. If a transition to detonation occurs during the measuring time of the shock tracker, the shock-to-detonation transition can be determined.[14] John Vorthman first conceived the idea of a shock tracker during the 1980s. It was not used at that time due to recording difficulties, which have now been overcome.

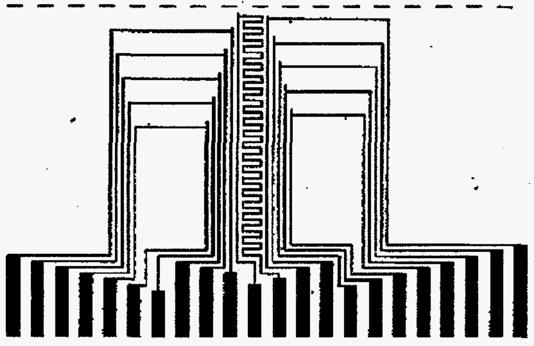


FIGURE 1. LANL MAGNETIC GAUGE MEMBRANE WITH 10 GAUGE ELEMENTS AND A SHOCK TRACKER

A "stirrup" gauge is a single element particle velocity gauge in the shape of a stirrup with long side leads and an active element 10 mm long. It is mounted in a plane parallel to the impact surface and provides a particle velocity measurement at that surface. In our experiments, stirrup gauges are usually mounted on the front of the sample so they provide a measurement of the input shock characteristics. They are also sometimes used to measure the particle velocity at the interface between a thin cylinder of explosive on the front of the experiment and the larger explosive sample containing the multiple gauge membrane behind it. It has been possible to make measurements at twelve different Lagrangian positions on a single experiment when two stirrup gauges are used in conjunction with an embedded multiple gauge.

EXPLOSIVE EXPERIMENT DESIGN

In solid high explosive experiments, the sample is machined with a bottom and top shape so that the gauge membrane can be glued at an angle (typically 30 degrees with respect to the shock plane) as shown in Figure 2. With this angle, the 10 active elements are at depths of approximately 0.5 through 5.0 mm into the explosive on 0.5 mm intervals. A stirrup gauge is mounted on the front of the sample, parallel to the shock plane, providing a measurement of the input wave. The explosive sample is typically 50 mm diameter by about 25 mm thick.

The explosive sample is then mounted to a target plate with the active gauge elements are carefully positioned and marked. The target plate is placed in the gun target chamber so that it is between the pole pieces of a large electromagnet and it is positioned so the gauge ends are perpendicular to the field lines as shown in Figure 3. When the gauge ends are perpendicular to the field lines, the gauge leads are automatically situated so they don't cut the field lines as they move; otherwise the lead movement would add to the measured voltage signal causing it to be in error.

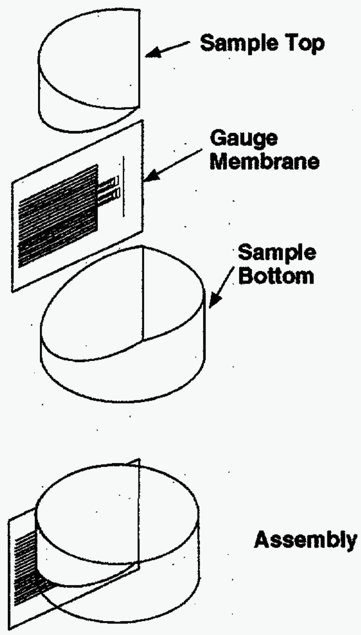


FIGURE 2. DETAILS OF THE EXPLOSIVE SAMPLE MAGNETIC GAUGE INSTALLATION

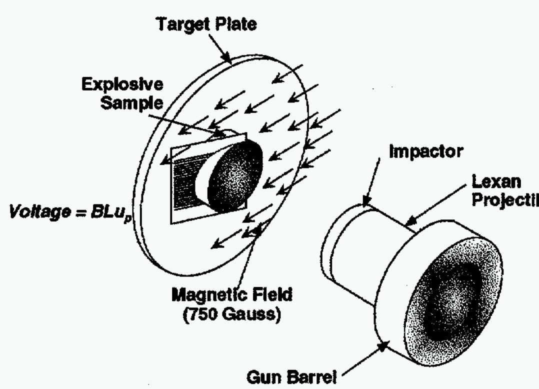


FIGURE 3. EXPLOSIVE SAMPLE INSTALLED IN GUN TARGET CHAMBER AND MAGNETIC FIELD

GUN AND EXPLOSIVE CONSIDERATIONS

PBX9501 is an HMX-based explosive composed of 95% HMX, 2.5% energetic binder, and 2.5% plasticiser (Estane). It is pressed to about 98.5% of theoretical maximum density (TMD) and can be machined quite easily. It is sensitive enough that it can be initiated on a single-stage gas gun so in our experiments, all the PBX9501 shots were done on our 72-mm bore single-stage gun. This bore allowed experiments of 50 mm diameter to be conducted. Multicrystalline sapphire (pressed to a high density and marketed commercially as Vistal) impactors were used. The electromagnet in this gun produces a magnetic field of about 750 gauss in the region of the experiment.

PBX9502 is a TATB based explosive composed of 95% TATB and 5% Kel-F binder. Typically it is pressed to about 98% of TMD and can be machined quite easily. It is very insensitive and can not be initiated with our single-stage gun on the time scales necessary for one-dimensional experiments. Because of this it was necessary to use our gas-driven two-stage gun[15] to obtain the necessary projectile velocity to initiate it. This gun has a launch tube bore diameter of 50 mm so it was necessary to cut down the size of the magnetic gauge and the explosive sample by about 20%. This means the magnetic gauge depths vary 0.5 to 4 mm and the diameter of the explosive sample is 43 mm rather than 50 mm. A Kel-F impactor was used so it was necessary to have a projectile velocity near 3 mm/μs to initiate the PBX9502. The electromagnet on this gun produces a magnetic field of about 1000 gauss.

EXPERIMENTAL RESULTS

PBX9501 PARTICLE VELOCITY WAVEFORMS

A number of experiments have been completed on PBX9501 at several different input shock levels from about 3.1 to 5.2 GPa. In this paper, which concentrates on the technique and method of measurement, we only show a few results. Figure 4 shows the wavefroms from an experiment in which PBX9501 was impacted by a Vistal impactor at a velocity of 0.586 mm/μs producing an input to the explosive of 3.4 GPa. There are eleven waveforms from gauges that were at depths of 0 to 5 mm into the explosive; the first one was from the stirrup gauge on the front of the explosive and the remaining ten from the multiple embedded gauge. Input particle velocity was about 0.52 mm/μs and this grew to over 1.0 mm/μs at the last Lagragian depth of about 5 mm. This indicates that significant reaction occurred during the gauge measurements.

Particle velocity waveforms from a similar experiment but with a higher input pressure are shown in Figures 5 (a) and (b). In these experiments, the PBX9501 input was 5.2 GPa and it caused the material to initiate fast enough that it very nearly reached a detonation by the time the wave had traversed the last gauge at a position about 5 mm into the explosive. The gauges measured reliably even when there was a great deal of reaction in the wave. Figure 5(a) shows the profiles in a 3-D plot which provides a good picture of the wave as it evolves. Figure 5(b) shows the same data in 2-D to make it easier to see the particle velocity magnitude of each of the waveforms. The first waveform is from the stirrup gauge

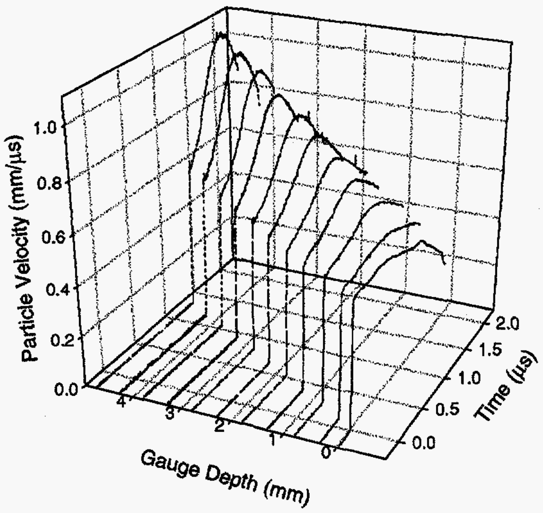
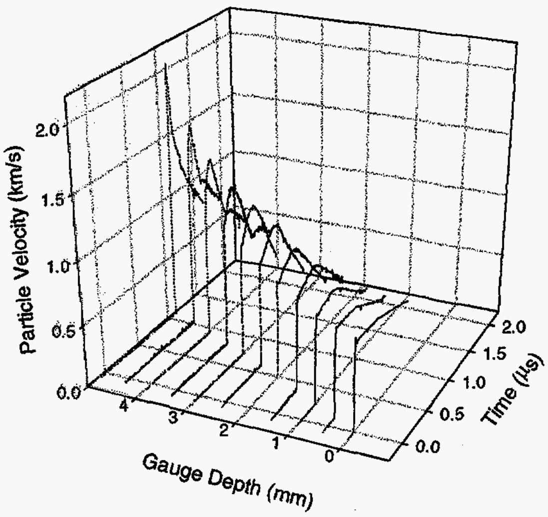


FIGURE 4. PARTICLE VELOCITY WAVEFORMS FROM PBX9501 EXPERIMENT WITH A 3.4 GPA INPUT

(a)



(b)

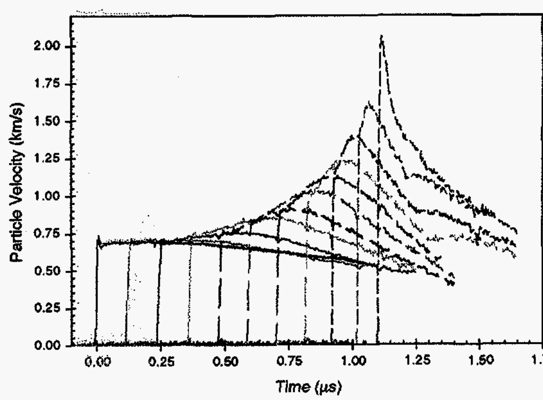


FIGURE 5. PARTICLE VELOCITY WAVEFORMS FROM PBX9501 EXPERIMENT WITH A 5.2 GPA INPUT

on the front of the sample and the remaining ten gauges are from the multiple embedded gauge.

PBX9501 SHOCK TRACKER DATA

The output from the shock tracker measurement for the experiment shown in Figure 5 is shown on Figure 6. Note that the output goes up and down as the wave passes over each change in length. The transition to detonation makes a rather large perturbation on the data. It has been our experience that this perturbation does not significantly hinder the interpretation of the position-time information.

As indicated earlier, the shock tracker is a particle velocity gauge in which the active length changes, in the case of this experiment, every 0.25 mm into the explosive. This means there are 20 shock tracker position-time measurements in the same regime as the 10 gauges and each gauge provides an additional position-time measurement, i.e., there are 30 position-time measurements up to a depth of 5 mm. In addition, as can be seen in Figure 1, the shock tracker gauge continues on past the last gauge to the end of the gauge region. This provides another approximately 20 position-time measurements in the next 5 mm of depth and allows a measurement of the wave front changes after it passes the last gauge. If a transition to detonation occurs while the shock tracker is still measuring, the wave front changes are tracked. Since a detonation proceeds after the transition, a measurement of the detonation velocity is also possible.

The early part of the shock tracker data can be used to provide the unreacted shock velocity for the explosive. With the input particle velocity and this measurement, an unreacted Hugoniot point can be determined.

The position-time plot for the experiment with waveforms shown in Figure 5 and the shock tracker waveform shown in Figure 6 is shown in Figure 7. Lines have been drawn through the data indicating the unreacted shock velocity (initial slope) and the detonation velocity (final slope). The depth and time of the transition to detonation will be discussed later.

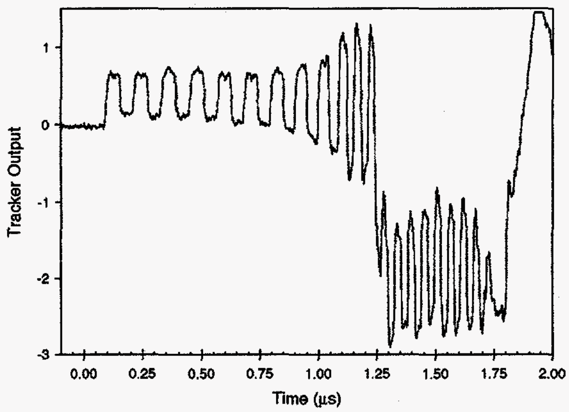


FIGURE 6. SHOCK TRACKER GAUGE OUTPUT FROM PBX9501 EXPERIMENT WITH A 5.2 GPA INPUT

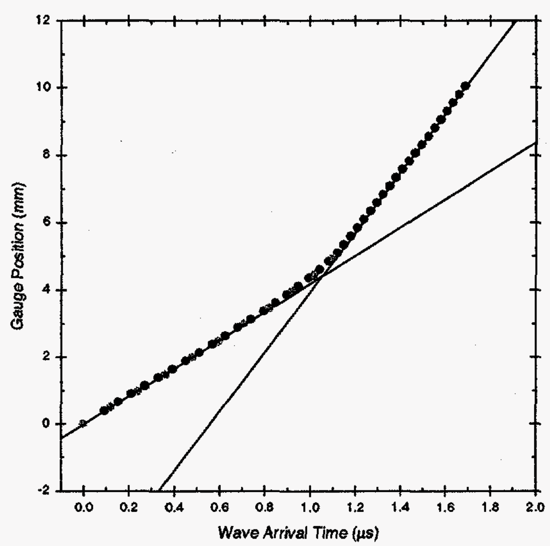


FIGURE 7. POSITION-TIME PLOT OF SHOCK TRACKER AND GAUGE ARRIVAL TIME DATA PBX9501 EXPERIMENT WITH A 5.2GPA INPUT

PBX9502 PARTICLE VELOCITY WAVEFORMS

Because it was necessary to shock the PBX9502 much harder to make it initiate during the time scales of a magnetic gauge measurement, all the work on PBX9502 had to be done on a two-stage gun as indicated earlier. A number of problems associated with projectile tilt, measuring the projectile velocity, and projectile integrity

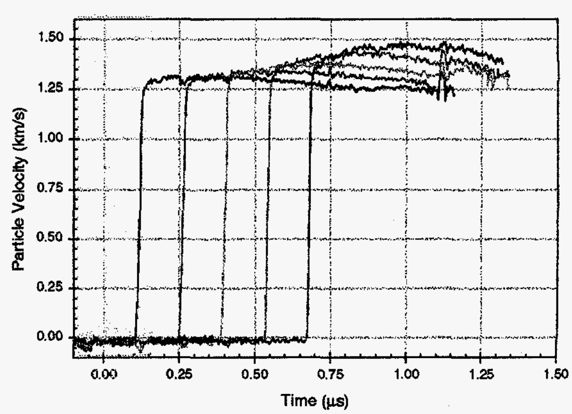


FIGURE 8. PARTICLE VELOCITY WAVEFORMS FROM PBX9502 EXPERIMENT WITH A 13.5 GPA INPUT

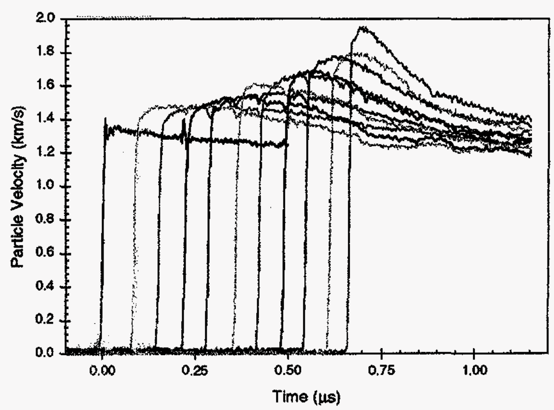


FIGURE 9. PARTICLE VELOCITY WAVEFORMS FROM PBX9502 EXPERIMENT WITH A 15.4 GPA INPUT

were encountered during the course of preparing for the PBX9502 experiments. As a result, only a relatively few experiments have been successfully completed.

Particle velocity waveforms from an experiment in which the input was 13.5 GPa are shown in Figure 8. Only five are shown because the data from the other five gauges were spurious, probably due to projectile damage prior to projectile impact on the explosive sample. The waveforms evolve due to the reaction but, even at this rather high input, the reactive wave growth was minimal.

A second PBX9502 experiment was recently completed with an input of 15.4 GPa. The gauge depths ranged from 0 to 3.8 mm into the explosive. Particle velocity waveforms from this shot are shown in Figure 9. A considerable amount of reactive wave growth is

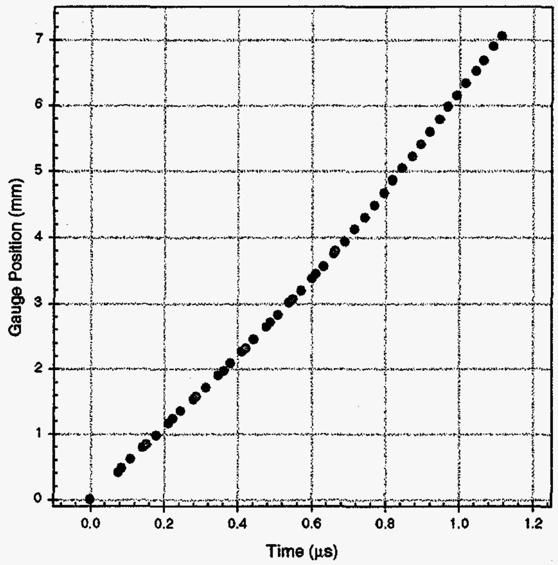


FIGURE 10. POSITION-TIME PLOT OF SHOCK TRACKER AND GAUGE ARRIVAL TIME DATA PBX9502 EXPERIMENT WITH A 15.4 GPA INPUT

apparent. The first waveform in time is from the stirrup gauge and has a curious shape. The other ten waveforms are from the embedded multiple gauges. The wave grew to a detonation less than a mm beyond the last gauge.

The shock tracker measurement from this experiment was quite good and the position-time data from it and the particle velocity gauges are shown in Figure 10. For this experiment the input shock, a gradual transition, and detonation are apparent in the figure. A discussion of the analysis of this experiment will be given in the discussion section.

DISCUSSION AND SUMMARY

The reactive particle velocity waveforms and the position-time plot from the shock tracker provide valuable information relating to the growth of the wave from the input shock to a detonation. From these we can obtain information about the nature of the reactive process. The two ends of the spectrum are homogeneous initiation and heterogeneous initiation. In homogeneous initiation, a reactive wave develops well behind the shock front, strengthens and may even grow to a super detonation. Eventually it overtakes the initial shock which remains at the initial input shock strength. The overtake is abrupt and an overdriven detonation is produced that eventually settles down to a steady detonation.[16,1] In heterogeneous initiation, wave growth occurs in the shock front which gradually accelerates until it reaches a steady detonation.[17,1]

Most high-density explosives exhibit a combination of homogeneous and heterogeneous reactive wave growth, i.e., there is some growth in the wave front but there is also a reactive wave that develops behind the front, builds, and eventually overtakes the front. This behavior is clear in the PBX9501 particle velocity waveforms shown in Figure 5. The input wave is shown to be flat topped with some reaction taking place after a few hundred nanoseconds that slows down the impactor, i.e., the interface particle velocity decreases. The other profiles show a reactive wave growing behind the front and some growth in the front. By the time the wave has reached the last gauge, the wave behind the front has overtaken the front. A detonation was produced about 0.4 mm after the last gauge.

This can be contrasted to the growth in the PBX9502. Figure 9 shows particle velocity waveforms in which a substantial amount of growth occurs. The shapes of all the waveforms are quite different from those in the PBX9501 in that they are more rounded on top. In addition, there is considerable growth in the front and a small amount of growth behind the front. The waveforms indicate that PBX9502 is more heterogeneous and less homogeneous in terms of its wave growth than PBX9501. The position-time plots shown in Figure 7 for the PBX9501 and Figure 10 for the PBX9502 agree with this. The wave front for PBX9501 accelerates very slowly and there is an abrupt change in the slope when it turns over to detonation while the similar plot for PBX9502 shows a rather gradual acceleration and a much less abrupt change.

The first waveform in Figure 9 is from the stirrup gauge and has a curious shape. It can be compared to the first gauge on the PBX9501 experiment shown in Figure 5 which has the shape expected. The reason for this difference is unknown at this time but there is a kink in the PBX9502 unreacted Hugoniot[18] which has not been explained. One thought is that there may be an instantaneous and equilibrium Hugoniot state associated with the extension of the lower Hugoniot and the upper Hugoniot, respectively. If this were the case and whatever was causing the kink had a rate which allowed the magnetic gauge to track it, the shapes observed may be giving us hints about what is causing the kink.

Other magnetic gauge measurements have been made in PBX9502[8,19] but the data are not directly comparable to this data because of the input shock was not constant or the sample temperature was higher than ambient. However, some of the rounded wave behavior is seen in the waveforms.

The data from the shock trackers were analyzed using a new method recently developed which uses an analytic acceleration function of the form dU/dt = a(U), where U is the shock velocity, as the shock fitting scheme. The motivation for such a function is 1) it incorporates all the shock trajectory information in the domain between the initial shock and the detonation shock, 2) it is the initiation behavior embedded in the extended detonation shock dynamic models and is useful in their calibration, and 3) our experience to date suggests that the peak acceleration is an important parameter in classifying initiation behavior. The chosen expression for a(U) works only for heterogeneous initiation behavior and is typically a rational polynomial. This model will be discussed in a future paper.

Using this method for the PBX9501 data shown in Fig. 7, the time and distance to detonation were found to be 1.15 μs and 5.6 mm, respectively. A linear fit to the initial slope gives an unreacted shock velocity of 4.19 mm/μs and the detonation velocity is measured at 8.8 mm/μs.

The same analysis for the PBX9502 data shown in Fig. 10 gave the time and distance to detonation to be 0.76 μs and 4.4 mm, respectively. A linear fit to the initial slope gives an unreacted shock velocity of 5.30 mm/μs and the detonation velocity is measured to be 7.52 mm/μs.

These measurements compare favorably to that recorded in other studies on these materials. More experiments will have to be completed to determine how accurate this technique is relative to other techniques. However, preliminary data on the shots that we have completed to date indicates it is more accurate than data from explosively driven wedge experiments. This would be expected since the input shock is planar and well known in gun experiments.

It is clear that the multiple magnetic gauge technique described in this paper provides a rich harvest of data from each experiment, more than can be obtained by any other experimental method. Information is obtained about unreacted states, reactive wave evolution, reactive wave front acceleration, the transition to a detonation, and the detonation state all in a single experiment. This kind of information will be very helpful to people modeling the behavior of these materials.

ACKNOWLEDGEMENTS

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REFERENCES

1. Sheffield, S. A., Engelke, Ray, and Alcon, R. R., "In-Situ Study of the Chemically Driven Flow Fields in Initiating Homogeneous and Heterogeneous Nitromethane Explosives", in *Proceedings of Ninth Symposium (International) on Detonation*, Office of the Chief of Naval Research Report OCNR 113291-7, 1989, pp. 39-49; see also Engelke, Ray, and Sheffield, S. A., Chapter 7, "Initiation and Propagation of Detonation in Condensed-Phase High Explosives," in High-Pressure Shock Compression of Solids III, Eds. Davison, Lee, Shahinpoor, Mohsen, Springer-Verlag,New York Inc., 1998.

2. Vorthman, J. E., "Facilities for the Study of Shock Induced Decomposition of High Explosives", in *Shock Waves in Condensed Matter – 1981*, Eds., Nellis, W. J., Seaman, L., and Graham, R. A., AIP Conference Proceedings No. 78, American Institute of Physics, New York, 1982, p. 680.

3. Vorthman, J. E., and Wackerle, Jerry, "Multiple-Wave Effects on Explosive Decomposition Rates", in *Shock Waves in Condensed Matter – 1983*, Eds., Asay, J. R., Graham, R. A., and Straub, G. K., Elsevier Science Publishers B. V., 1984, p. 613.

4. Cowperthwate, M., and Rosenberg, J. T., "Lagrange Gage Studies in Ideal and Non-Ideal Explosives," in *Proceedings of the Seventh Symposium (International) on Detonation*, Naval Surface Warfare Center Report NSWC MP 82-334, pp. 1072-1083.

5. Erickson, L. M., Johnson, C. B., Parker, N. L., Vantine, H. C., Weingart, R. C., and Lee, R. S., "The Electromagnetic Velocity Gauge: Use of Multiple Gauges, Time Response, and Flow Perturbations," in *Proceedings of the Seventh Symposium (International) on Detonation*, Naval Surface Warfare Center Report NSWC MP 82-334, pp. 1062-1071.

6. Urtiew, P. A., Cook, T. M., Maienschein, J. L., and Tarver, C. M., "Shock Sensitivity of IHE at Elevated Temperatures", in *Proceedings of the Tenth International Symposium on Detonation*, Office of Naval Research Report ONR 33395-12, 1993, pp. 139-147.

7. Urtiew, P. A., Tarver, C. M., and Simpson, R. L., "Shock Initiation of 2,4-dinitroimidazole (2,4-DNI)", in *Shock Compression of Condensed Matter – 1995*, Eds. Schmidt, S. C. and Tao, W. C., American Institute of Physics (AIP) Conference Proceedings 370, AIP Press, 1996, pp. 887-890.

8. Forest, C. A., Wackerle, J., Dick, J. J., Sheffield, S. A., and Pettit, D. R., "Lagrangian Analysis of MIV Gauge Experiments on PBX9502 Using the Mass-Displacement Moment Function", in *Proceedings of Ninth Symposium (International) on Detonation*, Office of the Chief of Naval Research Report OCNR 113291-7, 1989, pp. 683-692.

9. Vorthman, J., Andrews, G., and Wackerle, J., "Reaction Rates from Electromagnetic Gauge Data", in *Proceedings of the Eighth Symposium (International) on Detonation*, Naval Surface Weapons Center Report NSWC MP 86-194, 1985, pp. 99-110.

10. Zaitsev, V. M., Pokhil, P. F., and Shvedov, K.K., DAN SSSR, **132**, 1960, p. 1339.

11. Young, C., Fowles, R., and Swift, R. P., in *Shock Waves and the Mechanical Properties of Solids,* Eds., Burke, J. J., and Weiss, V., Syracuse University Press, 1971, p. 203.

12. Koller, L. R., Generation and Measurement of Simultaneous Compression-Shear Waves in Arkansas Novaculite, PhD. Thesis at Washington State University working under R. Fowles, 1978.

13. Gustavsen, R. L, and Sheffield, S. A., "Response of Inclined Electromagnetic Particle Velocity Gauges in Shocked Liquids," in *High Pressure Science and Technology -- 1993*, Eds. Schmidt, S. C., Shaner, J. W., Samara, G. A., and Ross, M., American Institute of Physics AIP Conference Proceedings 309, 1994, Part 2, p. 1703.

14. Alcon, R. R., and Mulford, R. N., "Shock Tracker Configuration of In-Material Gauge", in *Shock Compression of Condensed Matter – 1995*, Eds. Schmidt, S. C., Tao, W. C., American Institute of Physics (AIP) Conference Proceedings 370, AIP Press, 1996, pp. 1057-1060.

15. Alcon, R. R., Sheffield, S. A., Martinez, A. R., and Gustavsen, R. L., "Magnetic Gauge Instrumentation on the LANL Gas-Driven Two-Stage Gun," in Shock Compression of Condensed Matter – 1997, Eds., Schmidt, S. C., Dandekar, D. P., and Forbes, J. W., American Institute of Physics (AIP) Conference Proceedings 429, AIP Press, 1998, pp. 845-848.

16. Campbell, A. W., Davis, W. C., and Travis, J. R., "Shock Initiation of Detonation in Liquid Explosives," Phys. Fluids Vol. 4, No. 4, 1961,pp. 498-510.

17. Campbell, A. W., Davis, W. C., Ramsay, J. B., and Travis, J. R., "Shock Initiation of Solid Explosives, " Phys. Fluids Vol. 4, No. 4, 1961, pp. 511-521.

18. Dick, J. J., Forest, C. A., Ramsay, J. B., and Seitz, W. L., "The Hugoniot and Shock Sensitivity of a Plastic-Bonded TATB Explosive PBX9502," J. Appl. Phys. Vol. 63, No. 10, 1988, pp. 4881-4888.

19. Mulford, R. N., and Alcon, R. R., "Shock Initiation of PBX-9502 at Elevated Temperatures", in *Shock Compression of Condensed Matter – 1995*, Eds. Schmidt, S. C., and Tao, W. C., American Institute of Physics (AIP) Conference Proceedings 370, AIP Press, 1996, pp. 855-858.