RECEIVED BY TIC JUN 23 1972

CONF-720811--2

PRESSURE FIELD IN A SHOCK-COMPRESSED HIGH EXPLOSIVE*

J. E. Kennedy

Sandia Laboratories, Albuquerque, New Mexico 87115

ABSTRACT

Pressure histories have been measured at the impacted face and the downstream face of shocked PBX-9404 explosive samples, and they indicate pressure growth with time due to chemical energy release. A real-time correlation is noted between the traces at the two faces. A simple model of the development of the pressure field is suggested by this correlation, and is examined by comparison with the data. This comparison reveals the development behind the shock front of a pressure hump which tends to overtake the front as the shock wave builds toward detonation. Since the support of the shock front is an important factor in shock initiation of explosives, reactions continuing well after shock front passage may contribute significantly to the shock wave buildup toward detonation

*

This work was supported by the U. S. Atomic Energy Commission.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

24

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

-2-
INTRODUCTION

Instrumentation techniques capable of making time-resolved stress or particle-velocity measurements at a given material plane have only recently been applied to the problem of shock initiation of solid explosives. These measurements have revealed the occurrence of substantial chemical energy release well behind the shock front in pressed TNT,^{1/} pressed PETN,^{2/} and PBX-9404.^{3,4,5/} In the work reported here, we have extended the pressure range of measurements beyond that reported previously for PBX-9404.^{5/} We express the results of these experiments in a manner intended to show the development of these continuing reactions during the shock initiation process.

This paper briefly describes our instrumented impact experiments, which were conducted using a light gas gun. The features of observed stress histories at the impacted face of the explosive sample and at its opposite face (denoted the downstream face) are discussed and compared. The emphasis in this paper is on the development of protracted pressure excursions over a period of one to two microseconds after shock wave arrival. Risettime limitations in our experiments precluded complete observation of the structure of the front of the shock wave.

Some of our experiments suggest a simple model for the description of the growth of pressure with time after shock front passage. When the prediction of this model is compared with the collective results of our experiments, we find that some features of the model are in reasonable agreement with observations, but more complex behavior is indicated after shock front passage through the explosive.

EXPERIMENTS

The PBX-9404 explosive material used in this work had a density of $1.835 \pm .005 \text{ g/cm}^3$. Shock initiation experiments were conducted by impacting PBX-9404 discs with gun-driven quartz stress gauges.^{5,6/} In a few experiments, a material of high shock impedance, such as copper or sapphire (single-crystal Al_2O_3 , Z-cut), was used as a facing on this quartz impact gauge, as shown in Fig. 1. Another stress gauge assembly, involving either a quartz crystal^{5/} or a Manganin wire sensor, was attached to the downstream face of the explosive in each experiment to measure the transmitted-pressure history. A Plexiglas buffer disc was inserted between the explosive and the downstream quartz gauge in most experiments, for reasons discussed in Ref. 5.

All pressure history measurements were made in regions unaffected by rarefactions entering laterally or from the rear surface of the impactor. The time resolution of our measurements was typically limited to 40 nanoseconds due to slight deviations from flatness in the assemblies and in the impacts.

The impact pressures and durations of load application were sufficient to lead toward the development of detonation at some downstream plane within the target explosive.^{7/} In each case, however, our explosive sample thickness was less than that required for the reaction to grow to high order detonation.^{8/} Thus, the pressure history measurements were taken at various conditions in zones of buildup toward detonation. A gradual but substantial increase in pressure with time was observed at a given face of the explosive sample in most experiments. Such an excursion represents chemical energy release.

Our principal interest in these experiments was to observe the development of the shock wave in the explosive as it grew toward detonation. The stress histories measured by the impact gauge are precisely those experienced at this interface; no correction is required for interaction of the wave with the gauge. For the downstream face of the explosive, we have estimated the stress history of the wave incident on the downstream face of the explosive before its interaction with the gauge. Whenever the wave had to travel through materials interposed between the explosive face and the gauge, the shock interactions occurring at interfaces were unfolded by assuming that unloading or reloading occurred along paths that were mirror images of the P-u shock Hugoniot of each material, as described in Ref. 5. Distortion of the shock wave shape as it passed through an inert material (i. e. the tendency to steepen gradual pressure rises toward abrupt shocks) was also unfolded by accounting for the variation in sound speed with stress in the intervening material.^{9/} The explosive material was assumed to possess a Hugoniot given by Craig.^{10/} In data treatment no account was taken of changes in the mechanical properties of the explosive due to chemical reaction.

EXPERIMENTAL RESULTS

Stress histories for the impact face and the downstream face of impacted PBX-9404 samples are presented on Fig. 2. These traces illustrate features, some mechanical and some chemical in origin, which characterize the shock response and shock wave growth in PBX-9404.

The pair of traces in Fig. 2a are the impact and downstream face stress histories from a single experiment plotted in real time, and thus are separated by the transit time through the explosive. Figures 2b and 2c illustrate representative impact face and downstream face stress histories. The traces in Fig. 2 are typical of our results in that:

- (1) the shock pressure plateau is higher at the downstream face than at the impact face, indicating that the shock grows in strength as it travels through the explosive, and
- (2) the pressure rises at a faster rate when the pressure level is higher, for both impact face and downstream face records.

The experimental conditions for the shots depicted in Figs. 2 and 3 are listed in Table I.

Shock Front Structure

The planar impact of two elastic slabs will result in the introduction of a step-function stress wave into each. Deviations from squareness in the waveform, as sensed at either the impact or the downstream face of a slab, may be interpreted to indicate particular properties of the material. Typical waveforms of this type recorded in PBX-9404 are displayed in Fig. 2.

The downstream-face records exhibit some rounding near the wave front, which appears to become more extensive for greater sample thicknesses and lower stress levels. This increased dispersion cannot be attributed to the presence of the Plexiglas buffer. It resembles a wave-transmission property of viscoelastic or composite materials. In the downstream record for Shot 559 (shown in Fig. 2c) in which the buffer was omitted, a precursor jump is noted before a constant pressure

level is reached. Note that this precursor, seen also in a duplicate experiment, was completely missed in trace 656D (Fig. 3), a similar experiment except for the addition of the Plexiglas buffer. In Shot 656 the precursor was overtaken by the higher pressure portions of the wave during transit through the Plexiglas. Precursors in lower-amplitude waves transmitted through TNT have been reported by Wasley and Walker.^{11/} Such precursors may indicate a region of reverse curvature (where $\partial^2 P / \partial u^2 < 0$) in the Hugoniot.

The impact-face records sometimes exhibit a stress peak followed very shortly by relaxation (as in Fig. 2b, Shot 614), which also is characteristic of viscoelastic materials. While such a peak might alternatively be attributed to exothermic reaction at the shock front, this is not believed to be correct because similar behavior has been observed in mock explosive material (nonreactive).

Pressure Excursions

Pressure histories measured at both the impact and the downstream faces of the explosive in each individual experiment were compared by plotting both versus time relative to the instant of impact, t_1 , as illustrated in Fig. 2a. When the shock transit time through a thin (2-4 mm) explosive sample was less than the impact gauge lifetime, there was a time interval during which pressure histories were being observed at both explosive faces simultaneously. Figure 3 illustrates the results of two impact conditions at which a pair of experiments were fired on samples of different thicknesses. Over the common recording intervals, pressure histories at both faces were quite similar over a time interval spanning about 1 μ sec and pressures ranging from 20 to 40 kbar.

-1-

If the pressure were indeed identical at a given time for any thickness of sample, as these experimental data suggest, this would imply that pressure is independent of position in the shock-compressed explosive, and is dependent only on time. Let us then assume this simplified model of the pressure field in the explosive, and develop a basis on which we may compare it with all of our experimental data.

PRESSURE FIELD HYPOTHESIS

The physical model suggested above on the basis of the observations in Fig. 3 is that of a growing square wave pressure field. This field consists of a uniform pressure distribution at all points behind a shock front at which the pressure grows with time and propagation distance. Figure 4 presents a sketch of this hypothesis.

To examine this model in its simplest form, let us further assume that a shock which is introduced into the explosive material at any point along the locus of the shock front curve will grow as a function of time and distance in accordance with the locus. This amounts to the assumption that buildup of a shock front toward detonation occurs along a single curve which may be entered at any point, and further that the pressure at all points behind the shock front is equal to that at the shock front at all times.

Notice that at any given material position in the explosive, this hypothesis predicts that the pressure should rise with time. This feature has been observed in our experiments, which measure pressure histories at given material planes, over a wide range of pressures.

This simple model clearly does not include provision for the stress relaxation and possible precursor behavior which has been observed at

the shock front. It is intended only as a proposed description of the gross behavior of the pressure field, particularly at times well after shock front passage.

Time Basis

In order to quantitatively compare our experimental data with implications of this pressure field hypothesis, we must develop a unified time basis in terms of which all pressure histories can be expressed. In analyzing shock initiation data, Ramsay and Popolato^{8/} have suggested an empirical correlation which involves the parameters of interest here. They found that θ_i and X_i , the time and distance (respectively) of shock wave travel from the instant of loading until establishment of detonation at the shock front, are related; in addition, the input shock front pressure P_i , is related to X_i (hereafter called distance to detonation) for several high explosives including PBX-9404. The form of the relation $P_i(X_i)$ is

$$\ln X_i = k_1 + k_2 \ln P_i \quad , \quad (1)$$

where k_1 and k_2 are constants.^{12/} Their time correlation is expressed in terms of Δt_e , excess transit time to detonation, which is defined as

$$\Delta t_e \equiv \theta_i - X_i/D \quad , \quad (2)$$

where D is detonation velocity. Note that X_i/D is the time that would have been required for steady detonation to traverse the observed run distance to detonation, X_i . The correlation is

$$\ln X_i = k_3 + k_4 \ln \Delta t_e \quad , \quad (3)$$

where k_3 and k_4 are constants.^{12/}

the shock front. It is intended only as a proposed description of the gross behavior of the pressure field, particularly at times well after shock front passage.

Time Basis

In order to quantitatively compare our experimental data with implications of this pressure field hypothesis, we must develop a unified time basis in terms of which all pressure histories can be expressed. In analyzing shock initiation data, Ramsay and Popolato^{8/} have suggested an empirical correlation which involves the parameters of interest here. They found that θ_i and X_i , the time and distance (respectively) of shock wave travel from the instant of loading until establishment of detonation at the shock front, are related; in addition, the input shock front pressure P_i , is related to X_i (hereafter called distance to detonation) for several high explosives including PBX-9404. The form of the relation $P_i(X_i)$ is

$$\ln X_i = k_1 + k_2 \ln P_i \quad , \quad (1)$$

where k_1 and k_2 are constants.^{12/} Their time correlation is expressed in terms of Δt_e , excess transit time to detonation, which is defined as

$$\Delta t_e \equiv \theta_i - X_i/D \quad , \quad (2)$$

where D is detonation velocity. Note that X_i/D is the time that would have been required for steady detonation to traverse the observed run distance to detonation, X_i . The correlation is

$$\ln X_i = k_3 + k_4 \ln \Delta t_e \quad , \quad (3)$$

where k_3 and k_4 are constants.^{12/}

We shall now extend the correlations given in Eq. (1) and (3) beyond that intended by Ramsay and Popolato. Consider P , θ , and X to be continuous variables instead of single-valued parameters associated with impact conditions. Equations (1) and (3) can be generalized by dropping the subscript i 's and these equations then represent $P(X)$ and $\Delta t_e(X)$ relations. Eliminating X between Eqs. (1) and (3), so modified, yields

$$\ln \Delta t_e = k_5 + k_6 \ln P \quad . \quad (4)$$

Equation (2) defining Δt_e can be rearranged into the form $\theta = X/D + \Delta t_e$ and substitution of Eqs. (4) and (6) into this relation leads to the result

$$\theta = [\exp(k_1 + k_2 \ln P)]/D$$

$$= \exp(k_5 + k_6 \ln P) \quad (5)$$

correlating pressure and time to detonation.

Time to detonation, θ , is a decreasing quantity as time, t , elapses during an experiment, and it may be defined as a continuous variable for a given experiment as follows:

$$\theta - \theta_i \equiv -(t - t_i) \quad . \quad (6)$$

Pressure Field Development

In Fig. 5 the Ramsay-Popolato correlation is drawn for PBX-9404 in terms of the variables P and θ . This curve corresponds to the locus of shock-front pressures sketched in Fig. 4, except that the time parameter is time to detonation instead of elapsed time of shock wave travel. The nonlinear correspondence between time to detonation and run distance to detonation is also shown in Fig. 5. Time to detonation

(rather than run distance to detonation) is plotted as the abscissa because this permits direct comparison of our pressure-time measurements with the Ramsay-Popolato correlation.

Figure 5 also contains pressure history data from 21 experimental measurements (13 impact face and 8 downstream face waveforms from a total of 13 experiments). To provide the most direct comparison of the data with the curve, we chose θ_i for each experiment by matching the initial pressure jump observed at the impact face of the explosive to the Ramsay-Popolato curve. The entire impact face history was then plotted on an elapsed time basis, as experimentally measured. The downstream face history was offset from θ_i by the measured transit time through the sample.

If the Ramsay-Popolato (R-P) curve were indeed the single curve followed by any shock wave building toward detonation, and if the growing square wave hypothesis were true, then our data ought to track along that curve. In Fig. 5 we see that the impact face waveforms tend to follow along the R-P curve, deviating by less than 20% in amplitude except for some stress relaxation dips which exceed that difference. The initial pressure jump on each downstream face waveform (terminated with "x" in Fig. 5) is approximately in accord with the R-P curve, but the tails of the downstream traces then consistently swing above the curve.

As the initial pressure jump is increased, the downstream trace tails begin to depart from the R-P curve at shorter times after shock front passage and the magnitude of the slope of the tail increases. For the highest pressure downstream face record shown, there is a maximum in the pressure which is believed to be a real occurrence.

DISCUSSION

In this discussion let us ignore viscoelastic effects noted earlier. Regarding the major features of pressure field growth, the following picture emerges from this study for 1.835 g/cm^3 PBX-9404. In the range from 20 to 50 kbar, the shock front pressure grows with time in approximate accord with a Ramsay-Popolato curve plotted in terms of time to detonation. The pressure history at the impact face also grows with time in correspondence with the R-P curve. In these regards the growing square wave model applies.

As the shock pressure increases from 20 toward 50 kbar, however, the downstream face traces exhibit increasingly earlier and higher pressure excursions (tails). This indicates that (1) a pressure hump develops behind the shock front and (2) this hump is of high amplitude and closer to the shock front as the shock pressure becomes higher. While only the upward slope of the pressure hump is evident in the traces for $t > 1 \text{ } \mu\text{sec}$, the peak and a downward sloping portion of the hump were observed at $t < 1 \text{ } \mu\text{sec}$ (depicted also in Shot 822 trace in Fig. 2c). At a time still closer to the time of establishment of detonation, the pressure distribution behind the increasingly strong shock front falls off with time (see Fig. 2c, Shot 833, not depicted in Fig. 5).

The pressure hump thus appears to grow in amplitude and to overtake the front as the shock front pressure rises from about 20 kbar to about 200 kbar. Since the pressure hump develops during propagation

over a wide range of impact pressures but is not seen at the impact face, the shock wave development cannot be viewed as a self-similar process

The development of a clear pressure hump closely following the shock front at a run distance to detonation (X) of about one-half centimeter serves to explain an interesting observation by Craig and Marshall^{11/} regarding the acceleration of Plexiglas driven by shocked (but not detonating) PBX-9404. They noted an abrupt increase in the sustained acceleration of Plexiglas at and below a value of X equal to 0.6 cm in the explosive. The pressure hump we observe could be expected to propagate a pulse into the Plexiglas which would contribute significantly to its acceleration.

The shape of the pressure field must be an important factor in the shock initiation process. Gittings^{12/} has shown that, when shock pulses of quite limited duration are introduced into explosives, greatly increased pressure levels are required to achieve initiation of detonation. This shows that a relief of the pressure has a quenching effect upon the reaction.

Results for Other Explosives

We have performed a limited number of experiments similar to those described above on lower density charges of PBX-9404 (1.70 g/cm^3).^{13/} This material exhibits greater sensitivity due to its greater porosity, but the behavior pattern appears to be generally similar to that for 1.835 g/cm^3 PBX-9404. Pressure histories tend to follow the Ramsay-Popolato curve for this material^{13/} within the range of our measurements, i.e. up to $\sim 50 \text{ kbar}$.

Dremin^{15/} has sketched pressure-distance profiles for the shock initiation of pressed TNT, based on time resolved measurements of particle velocity histories after shock front passage. At low pressure levels he sketches a nearly square profile behind the front, which evolves to develop a pressure hump behind the front at higher pressure levels, and then to a sharp shock front at still higher levels.

Thus it appears that the mode of behavior noted for PBX-9404 may be generic for a class of polycrystalline heterogeneous high explosives.

Computer Model

Mader has developed a computer model^{16/} of the shock initiation process in heterogeneous explosives which assumes a pressure spike at the shock front due to prompt partial reaction of the explosive. We have not seen clear evidence of this spike.

In considering details of the pressure field behind the front in view of these experimental results, Mader has recently incorporated a temperature-dependent description for the continuing reaction which occurs behind the front.^{17/} The computational model thus provides for continuous energy release throughout the charge, and can be made to approximate features of the "growing square wave" pressure field as well as to reproduce results of related experiments^{4/} involving chemical energy release well behind the front.

CONCLUSIONS

The growing square wave model of shock wave growth toward detonation has been a useful hypothesis through which to examine the structure of the pressure field, but our experimental data indicate that the reaction development is more complex than that simple model. Over a range of pressures from 20 to 50 kbar in 1.835 g/cm^3 PBX-9404, the pressure at the shock front indeed tends to grow in accordance with the model, assuming the Ramsay-Popolato curve to be the locus of shock front pressure growth. An important additional feature noted from the data is the development, well behind the front, of a pressure hump which steepens as the shock front pressure increases. The hump overtook the shock front in our experiments at some pressure between 50 and 235 kbar.

Mechanical behavior resembling viscoelastic effects have also been noted in our measured pressure histories, particularly at pressures in the vicinity of 20 kbar.

ACKNOWLEDGEMENTS

This effort has benefited from interaction with staff members of the Los Alamos Scientific Laboratory: B. G. Craig measured the shock response of 1.7 g/cm^3 PBX-9404, C. L. Mader performed timely computations, and A. Popolato provided the explosive material which was used. B. G. Craig, G. E. Duvall of Washington State University, and L. W. Davison of Sandia made helpful suggestions regarding data interpretation. At Sandia K. W. Schuler and J. W. Nunziato were consulted regarding viscoelastic properties of the Plexiglas buffer and of the explosive material. L. M. Lee provided Manganin wire gauge calibration information. The experiments were assembled and conducted by O. B. Crump Jr.

REFERENCES

1. Dremine, A. N., and Koldunov, S. A., "Initiation of Detonation by Shock Waves in Cast and Pelletized TNT," UCRL Translation 10408 from Vzyryvnoye delo 63, 37 (1967).
2. Stirpe, D., Johnson, J. O. and Wackerle, Jr., "Shock Initiation of XTX-8003 and Pressed PETN," Los Alamos Rept. LA-DC-10970 (1969).
3. PBX-9404 is a plastic-bonded explosive, 94% HMX, 3% nitrocellulose (12% N), and 3% tris β -chloroethyl phosphate by weight.
4. Craig, B. G., and Marshall, E. F., Preprints, Fifth Symposium (Int'l.) on Detonation, ONR Rept. DR-163 (1970).
5. Kennedy, J. E., *ibid.*
6. Ingram, G. E., and Graham, R. A., *ibid.*
7. Trott, B. D., and Jung, R. G., *ibid.*
8. Ramsay, J. B., and Popolato, A., Proc. Fourth Symp. (Int'l.) on Detonation, ONR ACR-126, 233 (1965).
9. Schuler, K. W., Preprints, Fifth Symp. (Int'l.) on Detonation, ONR Rept. DR-163 (1970) and private communication (1972).
10. Craig, B. G., private communication (1970).
11. Wasley, R. J., and Walker, F. E., J. Appl. Phys. 40, 2639 (1969).
12. Values of constants were derived from data in Ref. 8. Values of k_5 and k_6 were derived from values of k_1 , k_2 , k_3 and k_4 .
 $k_1 = -5.499637$; $k_2 = -1.568639$; $k_3 = -0.242593$; and $k_4 = 0.739835$,
for 1.83 g/cm^3 PBX-9404.
13. Gittings, E. F., Proc. Fourth Symp. (Int'l.) on Detonation, ONR ACR-126, 373 (1965).
14. Craig, B. G. private communication (1972) regarding shock Hugoniot and Ramsay-Popolato correlation constants (see Ref. 12) for 1.7 g/cm^3 PBX-9404.

15. Dremine, A. N., private communication (1967) cited in Detonics of High Explosives (p. 94), by C. H. Johansson and P. A. Persson, Academic Press, N. Y. (1970).
16. Mader, C. L. and Gage, W. R., "Fortran SIN," Los Alamos Rept. LA-3720 (1967).
17. Mader, C. L., "An Empirical Temperature Dependent Dremine Burn Model," Los Alamos Rept. to be published.

TABLE I

Conditions for Experiments Illustrated in Figs. 2 and 3

Shot	Impact Velocity, mm/ μ sec	Impactor Thickness, cm	Impactor Material	PBX-9404 Thickness, cm	Target Gauge Material
658	0.661	0.954	Quartz	0.400	Quartz
614	0.394	0.637	Quartz	0.200	None
643	0.451	0.954	Quartz	0.600	Quartz
822	0.612	0.634	Sapphire	0.401	Manganin*
659	0.506	0.846	Quartz	0.200	Quartz [#]
833	0.884	0.631	Sapphire	0.202	Manganin*
644	0.620	0.954	Quartz	0.200	Quartz
647	0.633	0.954	Quartz	0.400	Quartz
656	0.525	0.847	Quartz	0.200	Quartz

Note: 3 mm Plexiglas buffer was between explosive and quartz target gauge except when marked #.

* Pulsar Instruments (Redwood City, CA) Model 741M, with 3-mil Manganin wire element cast in C-7 epoxy matrix. No Plexiglas buffer used.

FIGURE CAPTIONS

- Figure 1 PROJECTILE AND TARGET ASSEMBLY FOR IMPACT EXPERIMENTS.
- Figure 2 STRESS HISTORIES AT SURFACES OF EXPLOSIVE SAMPLES.
Numbers on traces denote shot (see Table I); I and D denote impact face and downstream face record, respectively. *Trace for Shot 833 was offset by 75 kbar for convenience.
- Figure 3 REAL-TIME HISTORIES WITH OVERLAPPING OBSERVATION TIMES.
Numbers on traces denote shot. I and D denote impact face and downstream face records, respectively. Quartz impacted explosive at 0.62 mm/ μ sec in (a) and at 0.52 mm/ μ sec in (b).
- Figure 4 GROWING SQUARE WAVE PRESSURE FIELD HYPOTHESIS. Pressure distributions are shown at times t_i , where $t_4 > t_3 > t_2 > t_1$. Detonation is attained in plane D.
- Figure 5 COMPARISON OF HYPOTHESIS WITH DATA FROM TWENTY-FOUR MEASUREMENTS. "X" at tip of a stress history trace identifies it as a downstream face record.

Figure 1 - Kennedy

Figure 2 - Kennedy

(a) Real-Time Histories, Shot 658

(b) Impact-Face Traces

(c) Downstream-Face Traces

Figure 3 - Kennedy

Figure 4 - Kennedy

Figure 5 - Kennedy