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INTRODUCTION

An established detonation may be considered as a shock wave supported by a chemical reaction in such a manner that the average propagation rate of shock (and reaction) is independent of time. This phenomenon has been described in a one-dimensional steady flow model by Chapman (1) and Jouguet (2). Their model assumed infinitely rapid chemical reaction and assumed that the detonation velocity was equal to the sum of the particle velocity and speed of sound in the shocked state.

Zel'dovitch (3), von Neumann (4) and Doring (5) extended the model to include finite reaction rates but maintained the assumption of a one-dimensional steady flow. These one-dimensional models are quite useful in predicting detonation pressures and velocities for common military explosives and are the basis for nearly all calculational schemes used today for explosive performance prediction.

In spite of their widespread utility, the one-dimensional steady detonation models have been shown to be incorrect. Reactive gasdynamic studies made in recent years (6,7) have shown all gaseous detonations to contain finite amplitude transverse waves which interact with the main detonation front to produce traveling Mach stems. Thus, gaseous detonations are, in general, three dimensional nonsteady flows, and a "plane" detonation propagating in a time-average steady manner is actually a complex multifront detonation which is highly nonsteady within the period of one cell length. The lead shock decays from beginning to end of the cell. Collision of transverse waves at the beginning of each cell regenerates the original strength of the lead shock (see Figures 1, 2). This oscillatory behavior can be quite periodic or irregular, depending upon the chemical kinetics and other factors of the system. A gaseous detonation fails when conditions are such that collision of transverse waves fails to cause explosion of the shocked gas (8).

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Nearly all studies of structure and stability of detonations have been made with gaseous systems due to the ease with which shock tube experiments can be made. Little work has been done with solid explosives. In fact, because of the gasdynamic or fluid dynamic nature of the transverse wave mechanism and because of the intrinsic physical heterogeneity of solid explosives, it has long been believed that regular transverse wave systems would not occur in solid explosive systems.

The objective of this study was to develope a technique applicable to the solid phase, and determine what similarities and differences exist between the two phenomenologies. The value of such a goal is clear; it would be particularly helpful to be able to apply the gas phase phenomenology to treatments of the more difficult solid phase.

EXPERIMENTAL APPARATUS AND PROCEDURES

An approach analogous to that developed for studying transverse waves in detonating liquid explosives (9) was only partially successful in the study of solid explosives. The greater pressures developed in the detonation of the solids caused severe distortion and breakup of the metal witness plates. Thus, an optical approach was utilized. The experimental setup is shown schematically in Figures 3, 4.

Advantage is taken of the fact that shocked argon is an excellent light source. The intensity of the emitted light is a function of the strength of the shock waves. Thus, a time exposure of the shocked argon reveals the trajectories of high pressure regions as they move through the gas. Since propane produces negligible light intensity in the pressure regions of interest, the argon layer is surrounded with a layer of propane. This provides sharp cutoffs and permits good resolution of the transverse wave trajectories. By changing the thickness of the argon layer, considerable control over the degree of structural detail obtained could be exercised. Typically, argon layer thicknesses of ~2 mm were used to observe fine structure. Thicknesses ~1 cm were used for gross structure.

In all of the experiments, the explosive samples were detonated using a BRL 66 mm explosive plane wave generator buffered with a 9.52 mm Al plate. This produced a pressure of ~ 140 Kbar in the receptor explosive. Sample explosive dimensions varied; however, in all cases square cylindrical or rectangular cylindrical geometry was maintained. Several explosive compositions were investigated, but the majority of experiments were performed upon cast and pressed TNT. The density of the cast TNT used was 1.62 g/cc.

Recording of the transverse wave trajectories was by means of the apparatus shown in Figure 4. The 90-600 dichroic mirror was chosen in order to record the emitted light in the blue spectral region, corresponding to wavelengths of ~ 4800 Angstroms. This choice

permitted the recording of light emitted from the shocked argon while spurious signals from explosive products and air shocks were mostly eliminated. The use of the neutral density filter permitted wide flexibility in argon layer thicknesses.

RESULTS AND DISCUSSION

The most important result of all the experiments is that, over a wide range of conditions, oscillatory behavior in the form of transverse waves occurred. These transverse wave patterns were affected by a variety of factors, including the dimensions of the charge, confinement, particle size, loading density, and whether the charge was cast or pressed. Each of these results will be considered individually.

The fact that highly regular transverse wave systems were observed in detonating solid explosives deserves special attention. Frey (10) has shown theoretically that oscillatory behavior occurs when a delay in the heat release behind the shock front occurs. Cases with a uniform heat release rate or where the rate of heat release decreases with distance from the front do not exhibit oscillatory behavior (see Fig. 5).

Shock initiation studies have shown two mechanisms of heat release to occur. One of these, a homogeneous mechanism, always leads to a heat release rate similar to that of type A in Fig. 5, and oscillatory behavior can occur. In the case of a heterogeneous mechanism, however, the situation is more complicated. Heat release occurs via a grain burning mechanism. Two models of grain burning have been proposed (11, 12). In one of these, reaction occurs at the surface of the explosive grains and the grains burn from the outside in. The total heat release rate is very strongly a function of the surface area of the grains. As the grains burn, the available surface area decreases, and type B behavior obtains. Boyar proposed that reaction begins at "hotspots" in between grains and the hotspots burn outward. This results in type A behavior. It is important to note that the presence of transverse waves in heterogeneous explosives provides strong support for Boyar's mechanism.

All published transverse wave studies to date of gas phase systems using shock tubes have used essentially rigid wall confinement. Thus, in these systems, transverse waves are reflected from the walls as shock waves. The reflected shock waves intersect with other transverse waves, causing localized high pressure with resultant explosion of the reactive gas. In this manner, the process is maintained.

Experiments with solids were performed using no side wall confinement in order to determine whether or not the reflection of a shock was necessary to regenerate and maintain the cellular structure. A typical result is shown in Fig. 6. It is quite clear from the pattern that confinement is not necessary to the generation of the transverse waves. This cellular pattern is typical of rectangular

geometries for gas phase systems and for solid phase systems with or without confinement. While confinement usually improves the regularity of the structure (compare Fig. 6 with Fig. 7), it is not in itself a sufficient condition as shown in Fig. 8.

The observed transverse wave patterns were found to be strongly a function of the explosive physical characteristics. Thus, the spacing observed in cast TNT was an order of magnitude larger than that for pressed TNT at the same loading density (compare Fig. 9 with Figs. 6, 7, 8). Similarly, in pressed TNT, the spacing between trajectories decreased with decreasing loading density over the range 1.59 - 1.64 g/cc. Both of these results correlate with the behavior of the failure diameter for cast and pressed TNT. The failure diameter (that charge diameter below which a self-sustaining detonation will not propagate) for cast TNT is an order of magnitude larger than for pressed TNT of the same loading density and the failure diameter for pressed TNT decreases as the charge density decreases (13). These correlations are understandable in light of the gas phase result that the spacing is proportional to the reaction zone thickness. Present failure theories predict small failure diameters for small reaction zone thicknesses. Thus, the determination of the quantitative relationship between spacing and reaction zone thickness should be pursued in order to generate meaningful reaction zone thicknesses, the lack of which is the principal weakness of extant failure theories.

In certain cases, patterns like those shown in Figures 10 and 11 occurred. In Fig. 10, an axis of symmetry can be seen, with transverse wave trajectories emanating from it. Several of these axes are observed in Fig. 11. (It should be noted that the source of oscillation existed within the charge, and the observed pattern is a result of intersection of the waves generated by the source with the argon layer on the surface of the charge). Furthermore, due to asymmetries in the initiating system or in the geometry of the main charge, a preferred direction may obtain and persist. An example of this is shown in Fig. 12 for pressed TNT. The only asymmetry was that very light confinement (wood 1.27 cm thick) was placed in contact with the side of the charge where the waves originated. The facts that in certain cases, one or more axes of oscillation were observed and in other cases waves moving in certain directions were suppressed, coupled with the fact that the spacing between transverse waves moving in one direction was relatively uninfluenced by the interaction with waves moving in the opposite direction, indicate strongly that the transverse waves are a manifestation of an intrinsic oscillatory instability of the detonation and are not the cause of the instability.

Once the charge dimensions drop below a certain minimum value (the "ideal" charge diameter for circular cylinders) the spacing becomes a function of the charge dimensions, increasing with decreasing charge size (see Fig. 13). The effect of confinement is twofold; it reduces the minimum ideal diameter and increases the regularity of the structure. Again, the correlation between charge diamensions and

spacing is explicable in terms of reaction zone effects; the smaller the charge dimensions, the more important are side rarefaction effects and, hence, the larger the reaction zone.

Measurement of spacings between trajectories when the detonation underwent a transient phase, as shown in Fig. 14, and as occurs during buildup to detonation and failure disclosed that the spacing adjusts slowly to charges. Thus, the spacing was found to be still varying as much as ten or twelve periods after the detonation had achieved a steady average velocity, and a unique cell pattern did not correspond to each state variable set.

Open shutter photographs, while elucidating the structure, give no indication of the magnitude of the velocity and pressure fluctuations obtaining. Streak camera measurements were made upon detonating cast TNT of density 1.62 g/cc, resulting in velocity fluctuations as great as 2 millimeters/microsecond. This corresponds approximately to 100 kilobars difference in pressure, a very remarkable variation indeed! Such large pressure fluctuations resulting from the inherent instability of the detonation may have important implications in military applications, particularly in shaped charge warheads, where a high degree of axial symmetry is required for good jet development. The presence of large pressure fluctuations in detonating cast TNT may be the principal factor behind the notoriously poor performance of TNT loaded precision shaped charge rounds.

CONCLUSIONS AND SUMMARY

This study has shown that the structural phenomenology of gaseous detonations is extendable to solid explosives of military interest. The cell size in gaseous detonations is a function of the effective heat release rate, i.e., that heat release rate experienced by the detonation front. This has been shown to be true for solids as well, and the cell size has been shown to be a function of the physical factors which affect the effective heat release rate, viz., granularity, loading density, confinement, charge dimensions, etc.*

The extension of transverse wave studies to unconfined solids led to the result that confinement and, hence, shock reflection of transverse waves is not necessary for the development of an oscillatory instability. The observation that one or more wave heads may become dominant in detonating solids provides strong experimental

The BRL has initiated a program to exploit the implications of this result. The goal of this program is to determine the quantitative relationship between the cell size and the effective heat release rate. Lack of a well-defined effective heat release rate has been a major weakness of failure theories. The relationship between transverse waves and the effective heat release rate will be used to develop failure criteria and elucidate the means of energy addition to the detonation front. An improved knowledge in this latter area is necessary to the solution of problems in non-ideal explosives.

support for the theoretical prediction that transverse waves are the result of an intrinsic instability of the detonative flow. Similarly, the fact that neither spacing nor direction of wave trajectories is affected by intersection of waves with those of the opposite family indicates that the transverse waves are a manifestation of, and not the cause of the oscillatory instability.

As with gaseous systems, for "steady-state" conditions in solids, i.e., when the detonation propagates with a time-average steady (Chapman-Jouguet) velocity, a unique cell pattern exists for each set of initial and boundary conditions. However, when the detonation state variables are allowed to change, as during buildup, failure, or other transient stages, the cell pattern readjusts slowly, and a unique structure does not correspond to each state variable set.

This study has shown that a remarkable similarity exists between the non steady fluid dynamic behavior of detonations in military explosives, where pressures are of the order of several hundreds of kilobars, and gas phase detonations, where pressures are of the order of a few bars or less. The experimental technique has been developed to the point where sufficiently high quality records of oscillatory behavior can be obtained to permit pursuit of a vigorous program into a relatively new and important area of detonation research.

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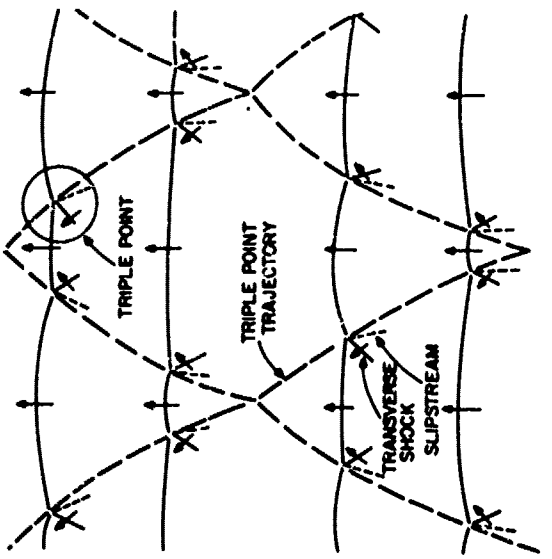

Fig 2. Schematic of shock configurations at four times in detonations which produced patterns in Fig 1.

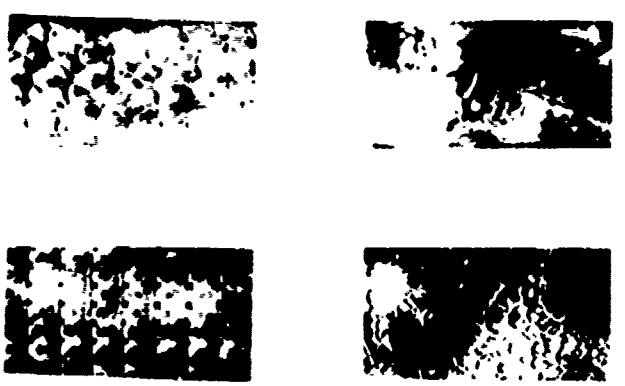

Fig. 1. Smoked foil records showing transverse wave (t.w.) trajectories obtained in gas phase detonation. Note wide range of regularity. Courtesy R. Strehlow

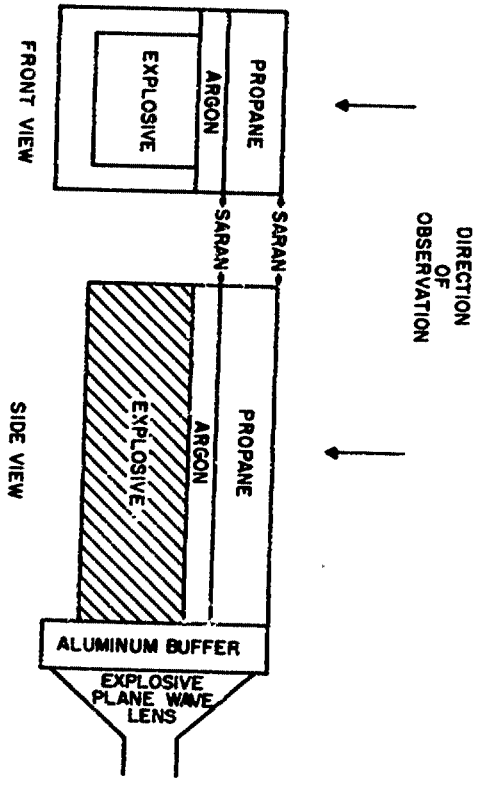

Fig 3. Schematic of explosive charge configuration used in experiments described in text.

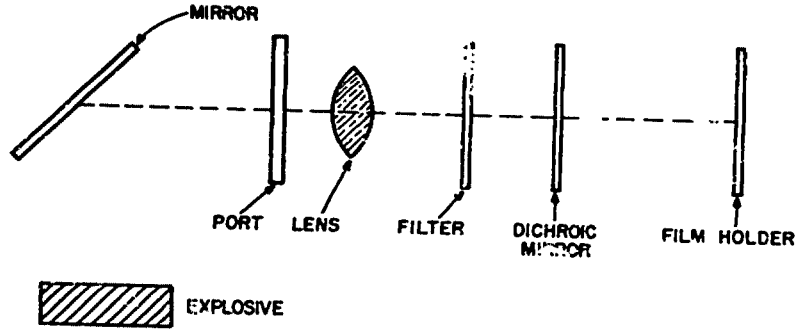

Fig 4. Schematic of recording apparatus used to obtain open shutter photographs of explosive events.

Fig. 6. Open shutter photo. Unconfined 3.8 x 3.8 x 15 cm cast TNT. In this and all subsequent figures, detonation propagated from top to bottom.

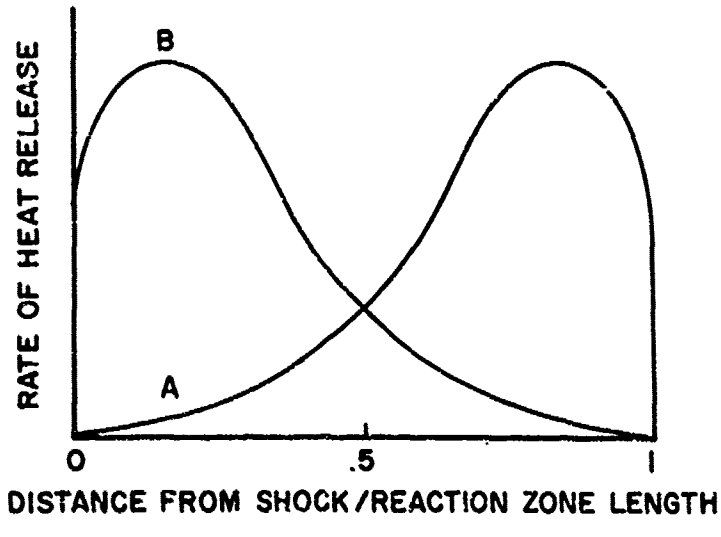

Fig. 5. Schematic of two possible types of heat release. According to theory, only type A leads to oscillatory behavior.

Fig. 8. Open shutter photo. Same experimental conditions as in Fig. 7. Note fine structure, incipient herringbone pattern.

Fig. 7. Open shutter photo. Cast 5 x 5 x 15 cm TNT confined in three sides with 1.27 cm thick bass. Note high degree of structural regularity.

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Fig. 10. Open shutter photo. Unconfined 2 x 5 x 15 cm pressed (density 1.63 g/cc) TNT. Note dominance of one wavehead.

Fig. 9. Open shutter photo. Unconfined 2 x 5 x 15 cm pressed (density 1.62 g/cc) TNT. Note small cell size.

Fig. 12. Open shutter photo showing top and side view. Unconfined 4.5 x 4.5 x 15 cm pressed TNT (density 1.63 g/cc). Note asymmetry of waves in side view.

Fig. 11. Open shutter photo showing top and end view. Pressed (density 1.63 g/cc) TNT 3.8 x 3.8 x 15 cm confined with brass 1.27 cm thick.

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Fig. 14. Open shutter photo showing cast TNT (upper) in contact with pressed TNT (lower). Note drastic change in cell size.

Fig. 13. Open shutter photo. Pressed TNT (density 1.63 g/cc) 0.95 x 5 x 15 cm. Note large structure due to reduced charge thickness.

 END