MASTER

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INTERACTIONS OF DETONATION WAVES IN CONDENSED EXPLOSIVES

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ABSTRACT

Flow patterns similar to regular and Mach reflection resulting from the interaction of detonation waves in condensed explosives have been observed with rotating mirror cameras and flash radiography. The principal emphasis of the study has been with the oblique collision of plane detonation waves. In this configuration the assumptions of steady flow, infinitesimal reaction zone thicknesses, the Chapman-Jouguet hypothesis and simple reaction-product equations of state permit an analytic solution for the detonation parameters for regular reflection and the computation of the critical angle for the onset of Mach reflection. These critical angles have been measured for Composition B, 9404-03 PBX, Baratol, and nitromethane. Additional data obtained on Composition B include a measurement of Mach stem pressure and stem shape. In inhomogeneous explosives Mach stems and reflected shocks have displayed substantial curvatures and flash x-ray studies have revealed anomalous density regions in the symmetry planes in both regular and Mach reflection experiments. These observations, along with deviations in computed and measured critical angle values, have indicated a degree of failure of the simplified theory to provide an exact, detailed description of the interaction phenomena; this failure is currently believed to result primarily from the non-uniform structure of the detonation wave.

INTRODUCTION

There are a variety of conceivable interactions of discontinuous waves which involve one or more detonation waves. A classification of possible interactions and a brief description of their characteristic flow have been given by Larisch¹. In the following only those interactions that result from an initial oblique collision of plane incident detonation waves will be considered.

In considering these interactions investigators^{1,2,3} have simplified the description of detonation waves to waves in which the unreacted explosive is discontinuously changed to its completely reacted state. This simplification permits the analysis of detonation interactions in the same manner as shock waves⁴ and suggests that the interaction flow patterns will be similar to those of shock interactions. This similarity was partially confirmed by Foektistova⁷, who observed in an unnamed explosive a "Mach wave" similar to the Mach stem in shock reflections and measured the critical

angle of incidence at which this irregular flow commences in the collision of two diverging detonation waves. A short time later Dunne reported evidence of the triple wave configuration characteristic of a Mach reflection and a measurement of the critical angle for diverging waves in two pre-shocked explosives^{8,9}. These were deduced from the indentations left on a steel "witness" plate over which the interacting waves passed. He later reported calculations of flow parameters of a regular detonation interaction whose flow pattern was assumed to be identical with that of regular shock reflection³.

Since each detonating explosive has a finite length reaction zone (although too narrow to be detected in some explosives) it would be expected that the flow in a detonation interaction would depart to some extent from the classical regular and Mach reflections. However, the relative simplicity of these flow patterns lessens the task of predicting the behavior of a particular interaction so it would be of some value to ascertain how well actual interactions are described by the classical flow models. In the work reported thus far no direct observations have been made of the flow patterns in the regime of the presumed regular reflection; its existence was inferred from the lack of any disturbance being propagated ahead of the initial intersection point of the incident waves. The flow in the irregular Mach interactions has been observed in more detail for diverging waves although the entire flow pattern has not yet been established.

In the following section a brief description will be given of the classical regular and Mach interactions of plane waves, along with the analysis of regular interactions; it will be seen that the assumption of the Chapman-Jouguet hypothesis and of a polytropic gas equation of state for the explosive's reaction products is sufficient to completely describe the regular phenomena in terms of the adiabatic gas constant and the incident angle. Following this, experiments will be described in which the complete flow patterns of both regular and Mach reflections of plane detonation waves have been observed in condensed explosives with flash radiography. Smear camera studies of both types of interactions will be presented which include the determinations of the critical angles for Mach reflection and Mach stem growth rates for four explosives, a measurement of a stem shape, and a Mach stem pressure determination for Composition B. In a final section these measurements will be compared with predicted values and the possible sources of some observed discrepancies explored.

*Analyses of shock wave interactions in non-reactive gases are given in review articles by Bleakney and Taub⁴ and Pack⁵ and in the classic book by Courant and Friedrichs⁶.

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Regular Reflection

An idealized regular flow pattern is sketched in Fig. 1. The incident waves D are plane steady-state detonation waves whose pressures are maintained at the Chapman-Jouguet value. The angle of incidence is defined as the half angle α . The reflected shock waves S will also be plane near the interaction point A provided the particle flow relative to A is supersonic behind the reflected shocks; should it be subsonic, rarefaction or compression waves could reach the interaction point and attenuate the reflected waves. The flow configuration is stationary with respect to a reference frame moving with A and in this frame a fluid particle will traverse the interaction region along a path similar to PP'. For the flow pattern to remain stationary the reflected shock must return the particle flow to its original incident direction while remaining attached at A.

In analyzing this flow the configuration is assumed to be at steady state with uniform pressure P, specific volume V and particle velocities u in each of three regions (0), (1), and (2). As shown in Fig. 1, the parameters in these regions will be subscripted with 0's ahead of the detonation front, 1's between the detonation and reflected shock wave and with 2's behind the shock. The normal component of u_1 is just the detonation velocity D, and the normal component of u_1 at the detonation front will be denoted by c. This latter quantity is D less the particle velocity in the laboratory frame and if the Chapman-Jouguet hypothesis is assumed, it is also the sound speed in the reaction products. Continuity of the tangential component of u across the detonation front dictates that

$$D \tan \alpha = c \tan(\alpha + \Delta). \quad (1)$$

Use of trigonometric relations and noting that $\tan \alpha = \cot \alpha'$ permits the solution for $\tan \Delta$:

$$\tan \Delta = \frac{[1 - (c/D)] \cot \alpha'}{(c/D) + \cot^2 \alpha'}. \quad (2)$$

A similar treatment at the reflected shock front permits the expression of $\tan \Delta'$ in terms of $\cot \alpha'$ and the ratio $r = (u_{2n}/u_{1n})$

$$\tan \Delta' = \frac{(1-r) \cot \alpha'}{1+r \cot^2 \alpha'}. \quad (3)$$

To satisfy the assumed steady flow configuration behind the reflected shock the direction of the particle flow must be parallel to the symmetry axis, so that $\Delta = \Delta'$, and the right hand sides of equations (2) and (3) may be equated. The result is an expression relating the unknown parameters r and α' to the incidence angle α , and to the normal detonation state, as manifested by the ratio (c/D).

It follows from consideration of mass conservation that

$$r = V_2/V_1 \quad (4)$$

and the pressure ratio across the reflected shock may be obtained from the momentum conservation relation

$$P_2/P_1 = 1 + \frac{u_{1n}(u_{1n} - u_{2n})}{P_1 V_1} = 1 + \frac{u_1^2(1-r) \cos^2 \alpha'}{P_1 V_1}. \quad (5)$$

With some trigonometric manipulation

$$P_2/P_1 = 1 + \frac{(1-r)}{G(1+r^2 \cot^2 \alpha')}, \quad (6)$$

where, as with $\tan \Delta$,

$$G = \frac{P_1 V_1}{u_1^2} = \frac{P_1 V_1}{c^2 + D^2 \tan^2 \alpha} = \frac{(c/D)[1 - (c/D)]}{(c/D)^2 + \cot^2 \alpha} \quad (7)$$

depends only upon the angle of collision of the detonation waves and the state behind them.

Equation (3) can be employed to express $\cot \alpha'$ in terms of the unknown parameter r and initial conditions:

$$\cot \alpha' = \frac{(1-r)}{2r \tan \Delta} \left[1 \pm \sqrt{1-r \left[\frac{2 \tan \Delta}{1-r} \right]^2} \right]. \quad (8)$$

Substitution of (8) into (6) yields

$$P_2/P_1 = 1 + \frac{(1-r)}{G \left[1 + \left[\frac{1-r}{2 \tan \Delta} \right]^2 \left[1 \pm \sqrt{1-r \left[\frac{2 \tan \Delta}{1-r} \right]^2} \right]^2 \right]}. \quad (9)$$

which essentially represents, for a given incident angle α and detonation condition (c/D), the locus of P-V states available to reflected shock wave as permitted by the assumed geometry of the flow.

The intersections of the loci described by equation (9) with the explosive's reflected-shock Hugoniot, centered at the detonation state, produce the values of the pressure and volume ratios for which regular reflection can occur. The reflected-shock Hugoniot may be obtained from measurements or through the assumption of a reaction-product equation of state. In Fig. 2 are shown a family of the loci described by (9), along with a typical reflected-shock Hugoniot. It is seen that above a certain angle of incidence--between 45° and 47° in the case depicted--solutions cease to exist. The angle at which this occurs is called the critical angle α_{cr} for regular reflection. At this angle only a single solution is obtained for the

state behind the reflected shock, but at a still lower angle two solutions are obtained. Of these two solutions the one having the lower pressure ratio is chosen, for it is the one which extrapolates to the proper pressure ratio for a head-on collision ($\alpha = 0$) of the detonation waves. It is obvious that with r determined α' may be obtained from (9).

If the Chapman-Jouguet hypothesis and a polytropic-gas reaction-product equation of state are assumed, it is possible to express the reflected-shock angle and the state parameters in an analytic form dependent only on α and a single other parameter. The CJ hypothesis can be stated as assuming c to be identical with reaction-product sound speed, which with a polytropic-gas equation of state, leads to a value for the ratio (c/D) of

$$(c/D) = 1 - \frac{P_1}{\rho D^2} = \frac{\gamma}{\gamma+1} \quad (10)$$

where γ is the constant ratio of specific heats.

The use of the polytropic-gas equation of state in the Hugoniot energy relation

$$\Delta E = \frac{P_2 V_2 - P_1 V_1}{\gamma - 1} = 1/2(P_2 + P_1)(V_1 - V_2) \quad (11)$$

leads to an expression for the pressure ratio on the reflected shock Hugoniot:

$$P_2/P_1 = \frac{1 - \mu^2 r}{r - \mu^2} = 1 + \frac{(1-r)(1+\mu^2)}{r - \mu^2}, \quad (12)$$

where

$$\mu^2 = \frac{\gamma - 1}{\gamma + 1}. \quad (13)$$

By equating (12) and (9) and with appropriate substitutions from other relations, either r , α' , or s , where

$$s = \tan \alpha' = r \cot \alpha, \quad (14)$$

can be expressed as the single variable in cubic equations, depending otherwise only on γ and α . The choice of the variable s permits a more compact writing of the cubic equation

$$\begin{aligned} & [(1+\mu^2)G] s^3 + \tan \Delta [1 + (1+\mu^2)G] s^2 \\ & - [(1-\mu^2) - (1+\mu^2)G] s + [\mu^2 + (1+\mu^2)G] \tan \Delta = 0. \end{aligned} \quad (15)$$

The parameters r and α' are related to s by

$$r = \mu^2 + G(1 + s^2) \quad (16)$$

and

$$\alpha' = \frac{\tan \Delta + s}{1 - s \tan \Delta}. \quad (17)$$

An examination of the coefficients of equation (15) for small values of the incident angle reveals a negative discriminant and three real and unequal roots. Of these, one root is negative and does not represent a physically realistic configuration ($\alpha' < 0$) while the other two are positive and correspond to the double solutions obtained by the graphical method discussed earlier. As α is increased the discriminant increases and vanishes as the two positive roots become equal. For larger angles of incidence the discriminant becomes positive and the roots imaginary. Therefore the angle of incidence for which the discriminant vanishes corresponds to the upper limit α_{cr} for which real solutions exist for regular reflection. Equating the discriminant to zero and (through (10) and (13)) expressing G and $\tan \Delta$ in terms of γ and α_{cr} leads to an expression involving only the latter two parameters. This relation--a sixth order polynomial in $\cot^2 \alpha_{cr}$ --is too lengthy to reproduce here; a plot of its single acceptable solution is presented in connection with the discussion in a later section.

Mach Reflection

For angles of incidence greater than those for which the reflected shock can return the flow to its original direction an irregular flow will ensue, which is presumed to be Mach reflection. In the classical Mach interaction (Fig. 3) a stem M grows from the initial intersection point I of the incident waves at a uniform rate. The stem and reflected shocks intersect the incident waves at common points A , forming the familiar triple-wave configurations. Also attached at the triple intersection points are density discontinuity slip planes C which form boundaries between those fluid particles that have passed through the incident and reflected waves from those that have passed through the stem. The triple-wave configuration is stationary with respect to a reference system moving with A and in this reference system the particle flow is parallel to the slip planes. The pressure is uniform in the entire region behind the reflected shock waves and the stem.

The analysis of Mach reflection is similar to that of regular reflection except the particle flow is now parallel to the slip planes and the pressures behind the reflected shocks and the stem must be matched in finding an acceptable solution to the flow equations. Another parameter must be introduced, the angle χ , which defines the growth rate of the stem. An analysis of the flow in the pseudostationary reference system fixed with respect to A will not provide any information about χ , which, in practice, is determined experimentally.

Calculations of flow parameters of Mach reflection are somewhat more difficult than regular reflection since the stem, being an overdriven detonation wave, cannot be described as simply as a Chapman-Jouguet wave. Solutions of the flow equations for the entire flow will not be presented here. However, treating χ as a known "initial" condition, the computation of the pressure behind the center of the stem can be easily accomplished in a manner somewhat

analogous to that followed in finding graphical solutions in regular reflection. A simple exercise in geometry yields an expression for the stem velocity D_s

$$D_s = \frac{D}{\sin \alpha (1 - \tan \chi \cot \alpha)} \quad (18)$$

Applying the momentum conservation relations to the flow across the stem leads to the relation for the ratio of the pressure behind the stem P_3 to that of the steady-state detonation pressure P_1

$$P_3/P_1 = \frac{D_s^2 [1 - (c/D)r]}{D^2 [1 - (c/D)]} \quad (19)$$

where c has the same connotation as before and r is now equal to V_3/V_1 . The combination of (18) and (19) yields

$$P_3/P_1 = \frac{\csc^2 \alpha [1 - (c/D)r]}{[1 - \cot \alpha \tan \chi]^2 [1 - (c/D)]} \quad (20)$$

Equation (20) is analogous to equation (9) in the analysis of regular reflection and represents the loci of pressure-volume states permitted by the initial conditions and the assumed geometry of the flow. While in regular reflection solutions were obtained from the intersections of the appropriate loci with the reflected shock Hugoniot, here the detonation Hugoniot for the overdriven stem is necessary to locate the attainable states. As before the detonation Hugoniots may be obtained experimentally or by the various equations of state describing the explosive. The procedure for obtaining graphical solutions for attainable states is similar to that illustrated in Fig. 2.

The assumption of the Chapman-Jouguet hypothesis and a polytropic-gas equation of state for the reaction products leads to some simplification of the analysis. Consider first the difference in specific energy between an allowed state of an overdriven detonation in the stem and a CJ state:

$$\Delta E = \frac{P_3 V_3 - P_1 V_1}{(\gamma - 1)} + \Delta Q$$

$$= 1/2 P_3 (V_0 - V_3) - 1/2 P_1 (V_0 - V_1) \quad (21)$$

where ΔQ is the specific chemical energy released in the overdriven detonation wave less that of the CJ wave. The use of (10) and the mass conservation relation and some manipulation leads to a solution for the pressure ratio,

$$P_3/P_1 = \frac{1 - \delta}{1 - \gamma(1 - r)} \quad (22)$$

where

$$\delta = \frac{2(\gamma - 1) \Delta Q}{(\gamma + 1)(P_1 V_1)} = \frac{2(\gamma - 1)(\gamma + 1) \Delta Q}{D^2} \quad (23)$$

When (22) is used to eliminate r from (20), a quadratic expression in P_3/P_1 is obtained, whose solution is

$$P_3/P_1 = C^2 + C \sqrt{C^2 - (1 - \delta)} \quad (24)$$

where

$$C = \frac{\csc \alpha}{[1 - \cot \alpha \tan \chi]} \quad (25)$$

If $\Delta Q \ll P_1 V_1$ then an approximate expression for the pressure ratio is given by

$$P_3/P_1 = C^2 + C \sqrt{C^2 - 1} \quad (26)$$

where the explicit dependence on the gas constant has disappeared.

EXPERIMENTAL

Experimental Systems

Ideally, in a two-dimensional interaction the incident waves would be plane, traveling at a constant velocity and be followed by a region of uniform flow. In the experiments reported here the incident detonation waves were initiated by explosive lenses either directly or through booster charges resulting in waves plane within 0.15 mm over a 100 mm diameter. In most instances a steady detonation velocity of the incident waves was essentially achieved in the first few millimeters of run. However, in one case (9404-03 PBX) the incident waves were initiated at a pressure substantially below the steady-state value for the explosive. Consideration was taken of the relatively slow build-up to steady-state pressure in interpreting the observed interactions in this explosive. In general, no attempt was made to attain a flat pressure profile behind the incident waves, which would have required an impracticably long detonation run before the waves were allowed to interact.

The interactions were effected by initiating the faces of an isosceles triangular-shaped prism of explosive (Fig. 4), the angle of incidence then being determined as one-half the apex angle of the prism. The prism faces of the solid explosives were machined flat within 0.005 mm. The prism thickness T ranged between 7.6 cm and 15.2 cm. The explosive density was controlled to within ± 0.003 g/cm³. A suitable prism-shaped container was constructed for the liquid explosive (nitromethane), the initiating charges being isolated from the nitromethane by 0.05 mm Mylar. The liquid explosive was maintained at a constant temperature between 20° and 21.5°C and initiated by a booster charge of

TNT. The incident waves were allowed to run for approximately 2.5 cm before colliding, by which distance they had decayed to a steady velocity.

The interactions produced in the explosive prisms were viewed by pulsed x-ray radiography^a along a direction parallel to the intersection line of the colliding waves (see Fig. 4). This provided the density distribution in the interaction region from which flow discontinuities could be identified. The x-ray pulse was produced by a burst of 20 MeV electrons impinging on a 3 mm diameter tungsten target resulting in radiation intensities up to 0.4 roentgen at the explosive prism, which was positioned on the beam axis approximately 3 meters from the target. The x-ray film was placed approximately 0.5 meters behind the prism in a protective aluminum case.

In separate experiments, the interactions were observed with a smear camera as they emerged from the base of the explosive prism. The slit of the camera was focused at the center of the prism base where the effect of side rarefactions was minimum. Lucite was placed directly on the prism base to suppress air shock. This technique was used to detect the presence of a Mach stem and to determine its shape and width.

Observed Flow Patterns

A radiograph of a regular reflection in the explosive Composition B-3 (60% RDX, 40% TNT, $\rho = 1.730 \pm .003 \text{ g/cm}^3$) is reproduced in Fig. 5. This and the following radiograph (Fig. 6) are negative prints, i.e., the darker regions correspond to lower densities in the explosive, whereas Fig. 7 is a positive print. This interaction is regular in the sense that no disturbance is propagated ahead of the intersection point of the two incident waves (as determined from smear camera observations). The low-density wedge-shaped area in the upper portion of the radiograph is the unreacted explosive. The lower boundaries of this region are the incident waves which are colliding at an angle of incidence of 42° (2° below the measured critical angle) in a prism 15.2 cm thick. The incident waves have traveled through approximately 14 cm of explosive at a velocity of $0.800 \pm .007 \text{ cm}/\mu\text{sec}$. The curved reflected waves are identified as shock waves since it can be shown that the component of particle velocity normal to these waves is supersonic. The curvature of the reflected waves could result from at least two factors: the nonuniform flow behind the incident waves caused by the rarefaction centered at the back side of the explosive lenses and a rarefaction centered at the apex of the prism which can always reach the trailing segments of the reflected waves.

^aA description of the x-ray equipment at the Phermex facility of the Los Alamos Scientific Laboratory, where the radiographs were taken, may be found in a recent article by D. Venable¹⁰.

The narrow high-density zone trailing the interaction point represents a significant departure from the classical regular reflection flow pattern (in which this region behind the reflected waves would be of uniform density). The gradual widening of this perturbed zone suggests that it originates at the interaction point.

To demonstrate the flow pattern of Mach reflection a radiograph of two detonation waves interacting at an angle of incidence of 60° in Composition B-3 is reproduced in Fig. 6. The semicircular dark area in the upper part of the figure is a mask to cover fragment damage to the film. Immediately below this mask are the incident waves which have traveled 19.3 cm in a prism 15.2 cm thick. The Mach stem has traveled approximately 15 cm (along the prism altitude line) and grown to a width of 7.5 mm, as deduced from smear camera observations of similar interactions. The curved reflected shock waves are quite easily identified although the stem and the density discontinuity slip planes are not as well resolved. The boundaries of the narrow low density region trailing the stem are identified as the density discontinuity slip planes. It should be noted that the flow located between a slip plane and an adjacent reflected wave is not uniform but that each slip plane is bounded on its outer side by a high density zone.

The relatively poor resolution of the stem and slip planes in Fig. 6 is probably due to edge effects. Since in Mach reflection the entire flow behind the reflected shock waves and stem is subsonic, rarefaction waves from the rear and sides of the prism will induce considerable curvature in the various discontinuities, resulting in a reduction in resolution of surfaces which ideally would be plane. This is illustrated in Fig. 7 which is a radiograph of a 50° Mach interaction in the explosive Baratol (76% Barium nitrate, 24% TNT, $\rho = 2.61 \text{ g/cc}$) in which the interaction is viewed in a direction parallel to the motion of the stem (i.e., a head-on view of the stem along the altitude of the prism). The stem width at the center of the prism is approximately 1.2 cm after having traveled for 18 cm in a prism with an altitude of 20.3 cm. The effect of side rarefaction has been to decrease the width of the stem away from the center of the prism. The side effects are more pronounced in this interaction since the prism thickness is 7.6 cm, one-half that of the Composition B-3 prism. In this explosive, as in Composition B-3, the region between the slip planes is at a lower density relative to the adjacent flow. Again, it can be seen that the slip planes are bounded by high-density zones, which in this explosive are quite narrow. The low-density region between the slip planes extend beyond the original positions of the prism sides as a result of the lateral motion of the reaction products away from the sides of the prism.

The detailed shape of the Mach stem can be found from the smear-camera record of the arrival of the initial waves of an interaction at the explosive prism base. A smear-camera photograph of a 60° interaction emerging from a

Composition B-3 prism after 10.2 cm of stem run is shown in Fig. 8. The thin converging traces of light in the upper part of the photograph mark the arrival of the incident waves at the explosive surface. Separating the incident waves is the Mach stem, which in this case is 4.2 mm wide. The arrival of the reflected shock waves can also be seen from the faint traces of light trailing the intersections of the incident waves and the stem. The bright light in the lower portion of photograph is from the interaction transmitted into air after traversing a thin Lucite plate placed against the explosive surface. The shape of the stem is best represented by an arc of a circle with a radius of 23 mm. Curvature is observed to a greater or lesser degree in all Mach stems and results in a lower effective stem velocity of those parts of the stem away from the center of the interaction. In this interaction the stem normal at the triple point is inclined approximately 5.2° to the direction of stem motion, which amounts to an effective velocity about $1/2\%$ less than at the center of the stem (and a correspondingly lower pressure).

Stem Growth Rate and Critical Angle Measurements

The angles of incidence for which regular and Mach reflections occur have been determined for Composition B-3, Baratol, 9404-03 PBX (94% HMX, $\rho = 1.84 \pm .003 \text{ g/cm}^3$), and nitromethane. By observing with a smear camera the arrival of the initial waves of an interaction at the prism base the presence of a stem and its width could be established. A stem was always observed above a certain angle of incidence and from the absence of a stem regular reflection was implied.

From the measured stem width, the known detonation velocity, angle of incidence and stem run the average stem growth rate was calculated. The observed stem growth rates expressed in terms of the angle χ (see Fig. 3) are shown in Fig. 9.

The data for Composition B-3 were obtained by measuring the average growth rate for stem runs of 5.1 cm, 7.6 cm, and 10.2 cm. Within experimental error the growth rates were constant over each of these intervals and the data points are averages of these growth rates. The growth rates for Baratol are averages over 5.1 cm and 10.2 cm of run whereas for 9404-03 PBX the growth rates for angles below 54° are for 10.2 cm of stem run and above 54° for 5.1 cm of run. All growth rates for nitromethane are for 7.6 cm of stem run. Stem widths in Baratol were not measured below 39° because of the difficulty in preparing a sufficiently smooth surface to reliably measure smaller stems.

The critical angle of incidence was found from these data by extrapolating the stem growth rate to zero. This procedure (extrapolation) was made necessary by the relatively small and slowly changing growth rate near the critical angle. The values of the measured critical angles are listed in Table 1 in the following section.

A limited number of auxiliary observations were made of the effect on α_{cr} of slightly overdriving the incident detonation waves in Composition B-3. A suitable thickness of 9404-03 PBX was used for a booster explosive such that the incident waves were initiated at a pressure approximately 15 kilobars above the steady state pressure. In the first 7.6 cm of stem run the growth rate was at least doubled but there was no detectable change in α_{cr} .

Stem Pressure Measurement

One further experiment was performed in which an approximate Mach stem pressure was found from free-surface velocity measurements of thin metal plates being driven by the stem. The stem was formed in a 60° interaction in Composition B-3 and had grown to a width of approximately 4.2 mm after a stem run of 10.2 cm. Upon the arrival of the stem at the explosive prism base a shock wave was transmitted into a metal plate placed against the explosive. The resultant velocity of the free-surface motion of the plate was measured by the "flash gap" method. The time required for the free surface to move a known distance was determined by recording with a smear camera the light caused by the metal free surface colliding with thin argon-filled gaps placed at appropriate distances in front of the plate (in this case, 0.508 mm and 1.016 mm). The average free-surface velocity was then related to the original shock pressure in the plate from existing shock Hugoniot data¹¹. The two plate materials--magnesium and 2024 Dural--were of such shock impedance at the stem pressure involved to cause a shock to be reflected from the explosive-metal interface back into the reaction products. The states of the reflected shocks were determined by matching pressures and particle velocities at the interface and were used to construct a straight line approximation of the reflected shock Hugoniot of the reaction products. The original state behind the stem was then approximately given by the intersection of the reflected shock Hugoniot with the explosive Rayleigh line, defined by $P = (\rho_0 D) u_s$, where the stem velocity D was determined in a separate experiment. (Actually, the impedance of magnesium was very near to that of the reaction products. An acoustic approximation from the magnesium state point to the Rayleigh line gave an equally accurate state of the reaction products.)

Because of the nonuniform structure of the stem detonation wave several plate thicknesses were used (ranging from 0.76 mm to 1.52 mm) which allowed an estimate to be made of the rate of attenuation of the transmitted shock wave¹². This in turn allowed an estimate to be made of the pressure characteristic of the reaction products behind the reaction zone yet not far enough behind the wave front to be seriously affected by the rarefaction trailing the stem or the Mach interaction transmitted into the plate. For the 60° interaction in Composition B-3 the stem velocity was measured to be 0.935 cm/usec, the stem pressure to be $0.665 \pm .025$ megabars and the associated particle velocity to be 0.316 cm/usec at the center of the stem.

Table 1

Explosive	Measured α_{cr}	Calculated α_{cr}	
		Polytropic	BKW
Comp. B	44.0 $\pm$ 1 $^\circ$	45.5 $^\circ$	49.8 $^\circ$
Nitromethane	42.8 $\pm$ 1.5 $^\circ$	47.7 $^\circ$	47.3 $^\circ$
Baratol	36.0 $\pm$ 3 $^\circ$	43.4 $^\circ$	--
9404-03 PBX	48.0 $\pm$ 2 $^\circ$	45.4 $^\circ$	--

Table 2

Explosive	CJ State		Calculated γ From CJ State	γ , Implied By Measured α_{cr}
	P(megabars)	D(cm/usec)		
Comp. B	0.294	0.800	2.77	3.24
Nitromethane	0.141	0.629	2.17	3.88
Baratol	0.140	0.493	3.53	(uncalc., > 4.00)
9404-03	0.376	0.881	2.80	2.13

CALCULATIONS AND DISCUSSION

The principal features of the flow patterns in detonation interactions are observed to be the same as those of shock interactions. However, the flow that has passed near the interaction point in regular reflection and near the triple intersection points in Mach reflection significantly deviates from that expected on the basis of a simplified description of the detonation wave. Since the origin of these perturbations appears to be located in that region where the reflected waves are very near the incident wave fronts it is concluded that they are caused by a nonuniform flow near the wave front, such as the chemical reaction zone, a turbulence layer, or other unidentified flow irregularities. Since the critical angle is governed by the flow near the interaction point it would be expected that α_{cr} would also be affected by these irregularities.

The reliability of a calculated value for α_{cr} will depend on the extent to which the detailed structure of the detonation waves and the interaction flow is known and on how accurately the equation of state of the partially and completely reacted explosive can be represented. In spite of this rather involved dependence of the critical angle on the

interaction flow, the relative ease and accuracy with which it can be measured makes it a convenient interaction parameter to consider. It should first be noted that in comparing a measured critical angle to its calculated value, consideration must be given to the several limiting angles it can represent. As in shock interactions there will exist a theoretical maximum angle of incidence for which regular reflection can exist, the critical angle for regular reflection. There will also be a theoretical minimum angle of incidence for which Mach reflection can occur. The range of angles bounded by either of these limiting angles can overlap and there is nothing in the theory to determine which interaction will occur within this common range. There exists another limiting angle α_s , the so-called sonic angle, which is the angle of incidence at which the flow behind the reflected shocks becomes subsonic (relative to the interaction point). If α_{cr} falls within the common range of angles cited above, the boundary conditions behind the interaction may perturb the interaction flow enough to change the interaction from a regular to a Mach reflection. In the absence of sufficient experimental information to provide a precise description of the interaction it will be

assumed that the observed α_{cr} corresponds to the critical angle of incidence α_{cr} for regular reflection, as is observed to be the case in shock interactions⁵.

In the analysis of regular reflection it was shown that the critical angle for regular reflection is a function of the adiabatic constant alone for Chapman-Jouguet detonation waves whose reaction products can be represented by a polytropic-gas equation of state. As was mentioned there the relation between α_{cr} and γ has been calculated and it is shown in Fig. 10. Since the value for γ is given by (10) in terms of steady-state detonation parameters, the critical angle for each explosive can be calculated from experimentally determined quantities. The values for γ calculated from (10) are shown in the third column of Table 2 for four explosives, while in the fourth column are the adiabatic constants implied by the measured critical angles. The corresponding predicted α_{cr} are shown in the second column of Table 1 for comparison with the measured α_{cr} . It is seen that there exists a substantial difference between the calculated and measured values of α_{cr} (or, equivalently, between the calculated and implied γ).

First, considering the likelihood that a poor representation of the equation of state of the explosive's reaction products is a cause of part of the discrepancies, it is noted that experimental data on the CJ-centered reflected shock Hugoniot are virtually nonexistent for the pressure ranges of interest. However, for Composition B Deal¹² has reported that the reflected-shock Hugoniot and isentrope could be represented by a polytropic gas equation of state within the pressure range explored (up to 0.515 megabars). The adiabatic constant that best represented the data was found to be 2.77, which is in excellent agreement with that calculated from the measured detonation and particle velocities (by equation (10)). Using this γ the ratios of pressures behind the reflected waves to the Chapman-Jouguet pressure given by equations (15) and (16) are shown in Fig. 11 for angles of incidence between 0° and the critical angle. It is seen that pressures up to approximately 0.800 megabars are predicted for this explosive (with a CJ pressure of 0.294 megabars which is considerably above the range of pressures from which γ was determined. Also shown in Fig. 11 are ratios of pressure across the stem given by equation (26).

One further state point on the reflected Hugoniot of Composition B-3 nearer to the predicted pressure at α_{cr} has been reported by Boyd and Venable¹³ where the zero-particle-velocity pressure of a head-on collision of plane detonation waves was found to be 0.687 megabars. If the reflected Hugoniot is represented by an adiabatic constant γ_p independent of that implied by the measured ratio c/D then the best value for γ_p becomes 2.59. Graphically solving for the critical angle for this γ_p (by the method illustrated in the analysis section) it is found that $\alpha_{cr} = 46^\circ$, which differs even more from the observed value.

If the reaction products are represented by the more realistic Becker-Kistiakowsky-Wilson (BKW) equation of state¹⁴, the interaction flow parameters can be found graphically using equation (9) and the BKW reflected-shock Hugoniot¹⁴ for regular reflection, and equation (20) and the BKW detonation Hugoniot¹⁵ for Mach reflection. The pressure ratios found by these methods are shown in Fig. 11. The calculated critical angle is found to be 49.8° and is listed in the third column of Table 1. That this equation of state is a reasonably accurate representation of the reaction products for relatively high pressures can be seen from Fig. 11 by comparing the measured stem pressure ($0.665 \pm .025$ megabars) with that calculated using the BKW equation of state (0.650 megabars).

In comparing the observed α_{cr} with the several calculated values for Composition B-3 it is seen that the agreement between these values is progressively worse as increasingly better representations of the equation of state are used. This would indicate that a more accurate representation of the equation of state would not resolve the discrepancy between the measured and calculated critical angles so that the principal cause of this difference for Composition B-3 is probably associated with the flow irregularities responsible for the perturbed flow patterns.

Although no equation of state data exist for nitromethane in the range of pressures characteristic of interactions it is of some interest to consider this explosive briefly, it being homogeneous with a narrow reaction zone (thus far, undetected). Should the perturbed flow be caused by the nonuniform flow in the reaction zone or other irregularities characteristic of an inhomogeneous explosive, better agreement might be anticipated between the calculated and observed critical angles for this explosive. However, in comparing critical angles using either a polytropic or BKW equation of state (Table 1) the differences are about the same or greater than for Composition B-3.

Finally, it is noted that the measured critical angles of three of the four explosives are less than the calculated values. If all measured α_{cr} were found to be less than the predicted critical angle it might be argued that the critical angle for Mach reflection (which could be less than the critical angle for regular reflection) might determine the change from regular to Mach reflection. Again, it is difficult to evaluate this possibility without an accurate representation of the equation of state of the explosives from which these critical angles could be reliably calculated.

*The BKW reflected shock Hugoniot were calculated by the authors by slightly off-setting the BKW isentropes presented in reference 14 by the amounts computed as appropriate by Fickett¹⁶ in "constant- β " equation of state.

From the presented data and the various considerations mentioned above, it is clear that a thorough investigation of equations of state of explosives and detailed observations of the interaction flow patterns are required before the discrepancies between observations and calculations can be resolved. Although the classical regular and Mach interaction flow patterns describe the gross features of detonation interactions, the effect of the structure of the detonation waves must be considered when attempting to calculate with any precision the various interaction flow parameters.

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REFERENCES

1. E. Larisch, J. Fluid Mech. 6, 392 (1959).
2. K. P. Stanyukovich, Unsteady Motion of Continuous Media (Pergamon Press, Inc., New York, 1960).
3. Brian Dunne, Phys. Fluids 7, 1707 (1964).
4. W. Bleakney and A. H. Taub, Rev. Mod. Phys. 21, 584 (1949).
5. D. C. Pack, J. Fluid Mech. 18, 549 (1964).
6. R. Courant and K. O. Friedrichs, Supersonic Flow and Shock Waves (Interscience Publishers, Inc., New York, 1948). pp. 318-350.
7. E. A. Feoktistova, Dokl. Akad. Nauk SSSR 136, 1325 (1961). [English translation Soviet Phys. - Doklady 6, 162 (1961)].
8. B. B. Dunne, Phys. Fluids 4, 918 (1961).
9. B. B. Dunne, Phys. Fluids 4, 1565 (1961).
10. D. Venable, Phys. Today 17, 19 (1964).
11. R. G. McQueen and S. P. Marsh, J. Appl. Phys. 31, 1253 (1960) and R. G. McQueen, Private Communication.
12. W. E. Deal, Phys. Fluids 1, 523 (1958).
13. T. J. Boyd, Jr., and D. Venable, Bull. Am. Phys. Soc. 10, 275 (1965).
14. C. L. Mader, U. S. Atomic Energy Commission Report LA-2900 (1963).
15. C. L. Mader, Private Communication.
16. W. Fickett, Los Alamos Scientific Laboratory Internal Report GMX-10-35 and Private Communication.

Fig. 1. Classical Flow Pattern of Regular Reflection.

Fig. 2. Loci of accessible states, illustrating regular reflection in Comp. B-3 with polytropic-gas reaction products ($\gamma = 2.77$).

Fig. 3. Classical Flow Pattern of Mach Reflection.

Fig. 4. Explosive System.

Fig. 5. Radiograph of a 42° regular interaction in Composition B-3.

Fig. 6. Radiograph of a 60° Mach interaction in Composition B-3.

Fig. 7. Radiograph of a 50° Mach interaction in Baratol, viewed in the direction of stem motion.

Fig. 8. Smear camera record of a 60° Mach interaction in Composition B-3. Time increases downward.

Fig. 9. Measured stem growth rate.

Fig. 10. Calculated critical angles for a CJ-polytropic detonation.

Fig. 11. Calculated pressures of detonation interactions in Composition B-3.