

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

4CR-72443



A Facsimile Report

Reproduced by
UNITED STATES
ATOMIC ENERGY COMMISSION
Division of Technical Information
P.O. Box 62 Oak Ridge, Tennessee 37830



FACILITY FORM 602	N71-10421	
	(ACCESSION NUMBER)	
	17	G3
	(PAGES)	(CODE)
	OR-11107	12
	(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

SCOT-13324 R

RECEIVED BY DTIC JUN 5 1970

UCRL-72443
PREPRINT

CONF-700803--4

MASTER

Livermore Radiation Laboratory
UNIVERSITY OF CALIFORNIA
LIVERMORE

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made in the preprint, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

ON THE DYNAMICS OF SHOCK INTERSECTIONS

A. K. Oppenheim
J. J. Smolen
D. Kwak
P. A. Urtiew
April 29, 1970

LEGAL NOTICE

This paper was prepared for submittal to Fifth Symposium
(International) on Detonation, Pasadena, California,
August 18-21, 1970.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ON THE DYNAMICS OF SHOCK INTERSECTIONS*

A. K. Oppenheim, J. J. Smolen, D. Kwak
University of California
Berkeley, California

and

P. A. Urtiew
Lawrence Radiation Laboratory
Livermore, California

Upon the recognition that collisions between shock intersections play a dominant role in the self-sustenance of detonations, an analysis of their dynamic properties is presented, covering a full scope of possible wave configurations in gaseous media as well as in condensed explosives. In both cases theoretical results and experimental records are shown to be in satisfactory agreement.

INTRODUCTION

In the last decade our concepts of gaseous detonation waves have been completely revolutionized [1,2]. Instead of the classical NDZ model of a plane shock followed by a steady-flow deflagration, it became evident that the self-sustaining wave is both nonsteady and nonhomogeneous. The mechanism of wave propagation was revealed to be associated with the action of a set of concentrated explosions that generate blast waves whose fronts are, as a rule, nonplanar. The latter collide with each other, creating intersection points which, in turn, undergo mutual collisions producing new shock centers, while for most of the time between collisions the wave system is in a state of decay. The overall steady state propagation is thus achieved as a result of a balance between the wave amplification due to new explosions and the wave decay during the remainder of the time.

This work was supported by the U. S. Air Force through the Air Force Office of Scientific Research under Grant AFOSR 129-67, by the National Aeronautics and Space Administration under Grant NAG-702 03-003-050, and by the National Science Foundation under Grant NSF GK-2156; it was carried out also, in part, under the auspices of the U. S. Atomic Energy Commission.

As it is apparent from the above, shock intersections and their collisions play a dominant role in the self-sustenance of detonation waves. Moreover, they provide simple diagnostic means for the study of the wave structure, since intersection points leave traces of their trajectories on the walls along which the detonation wave propagates, yielding an informative record of their dynamic behavior. The traces are produced as a result of the fact that shock intersections generate regions of high pressure and temperature which, as a consequence of refraction associated with the basic blast wave structure of the flow field, are localized in the immediate vicinity of the intersection points. These regions contain, moreover, concentrated vortices due to the action of the slip-line discontinuity that is concomitant to any asymmetric shock intersection. Thus the traces of the trajectories of the intersection points can be engraved on the walls by the sharp pressure peaks as well as by the twister action of the vortices. The latter is the prevailing mechanism producing the well-known smoke-foil records in gaseous detonations, while the former provides principal means for the attainment of similar records in condensed explosives.

The purpose of this paper is to present the dynamic properties of collisions between shock intersections in a gaseous medium as well as in a condensed phase explosive. While the

analysis of shock intersections is textbook material [3,4], their collisions have received only sporadic attention [1,5]. The basic features of these processes are, therefore, developed here from elementary concepts.

SHOCK INTERSECTIONS

In a detonating medium shocks are generated in blast waves where they appear primarily as their fronts. They form intersections between each other as a result of either head-on or rear-end collisions, as illustrated in Fig. 1.

In the case of a head-on collision, Fig. 1(a), at first the two fronts undergo, along the line of centers, a normal interaction producing a reflected shock [3,4,6]. At the next instant quadruple shock intersections are formed on both sides of the line of centers. When the intersection angle acquires a certain critical value, the quadruple shock intersection can no longer satisfy the dynamic compatibility conditions, and triple shock intersections set in.

The rear-end collision occurs, as illustrated in Fig. 1(b), when the second explosion is formed inside the blast wave of the first, or, what is of course equivalent, when an explosion occurs behind a plane shock. In this case, at first the two shock fronts merge along the line of centers, producing a transmitted shock and a reflected rarefaction fan. At the next instant, triple shock intersections are generated. The trajectories of these intersections, referred to simply as "triple-points," are represented in Fig. 1 by broken lines.

If the shock fronts are sufficiently thin in comparison to the flow field treated by the analysis, which is usually the case with strong shocks, in the immediate vicinity of an intersection point the curvatures of the fronts can be neglected and the surrounding flow field considered to be essentially the same as in the case of plane fronts. The various wave configurations that are, under such circumstances, dynamically compatible are depicted in Fig. 2. Shown first is a quadruple shock intersection equivalent, in effect, to an asymmetric regular reflection (Fig. 2(a)). As the strength of one of the waves participating in the intersection is increased while the other is assumed to remain the same as before, the reflected shock behind the stronger wave becomes annihilated and one obtains an inverse Mach intersection, shown next (Fig. 2(b)). Then, for still higher strength of both incident waves, a normal Mach intersection is obtained (Fig. 2(c)). In this case the Mach stem is normal to the incident flow and the reflected shock is identical to that of a symmetric regular reflection. Following this, one gets the conventional Mach intersection (Fig. 2(d)). The limiting case for this configuration is attained when the reflected shock becomes normal to local flow (Fig. 2(e)). After that one can have either a conventional (Fig. 2(f)) or a choked (Fig. 2(g)) "arrowhead" intersection.

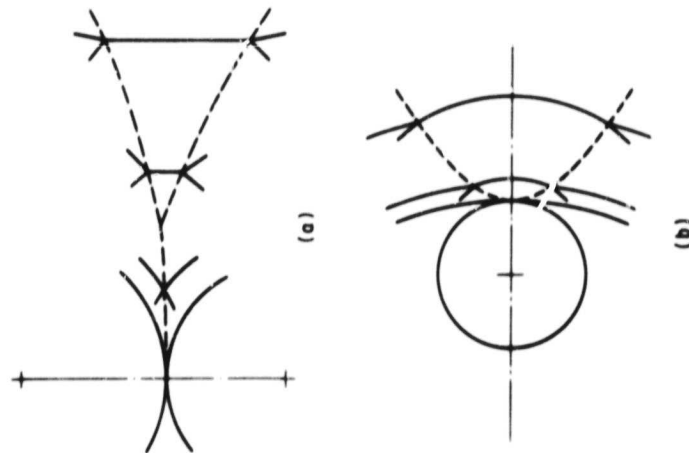


Fig. 1 - Illustration of the formation of shock intersections in an explosive medium: (a) head-on collision between blast waves; (b) rear-end collision between blast waves

intersection—one in which all three shocks are of the same family (i.e., they turn the flow in the same sense), the latter being associated with a Prandtl-Meyer expansion while the flow behind the reflected shock is locally sonic.

The dynamic compatibility conditions which a wave intersection must satisfy stem from the requirement that each component has to obey the jump conditions for an oblique gasdynamic discontinuity, while the flow field generated by the intersection has to have uniform pressure and its particle velocities with respect to the intersection point must be mutually parallel. It is the latter condition that gives rise to a slip-line discontinuity. For a given Mach number of incident flow, M_1 , the jump conditions specify the angle of incidence, θ , the flow deflection angle, δ , and the downstream flow Mach number, M_2 , as a function of the coordinates of a point on the Hugoniot curve.

In terms of nondimensional pressure ratio, $P = p/p_1$, specific volume ratio, $v = v_1/v_1$, and the local velocity of sound parameter,

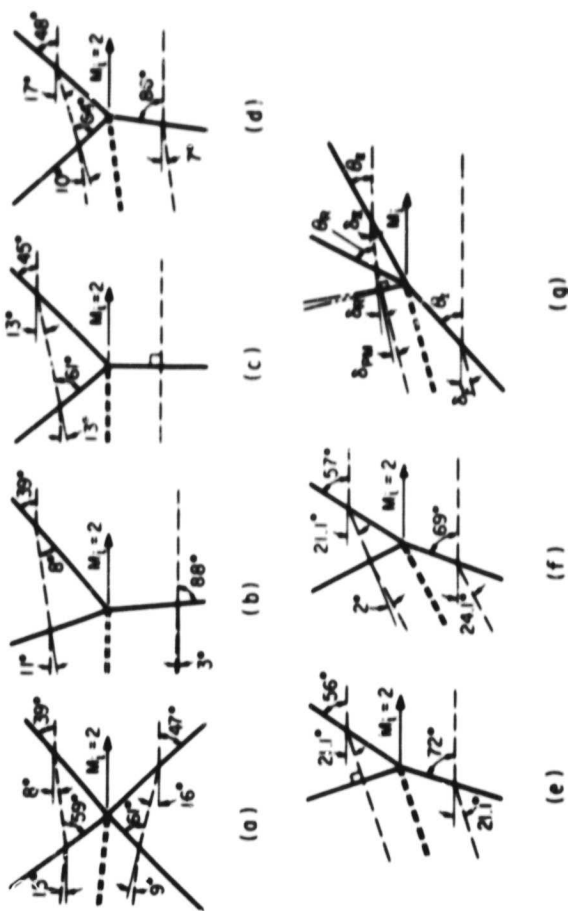


Fig. 2 - Typical shock intersection patterns: (a) quadruple intersection (equivalent to an asymmetric regular reflection); (b) inverse Mach intersection; (c) normal Mach intersection; (d) conventional Mach intersection; (e) limiting case of the conventional Mach intersection where reflected shock is normal to local flow; (f) conventional "arrowhead" intersection; (g) choked "arrowhead" intersection (sonic flow behind reflected shock)

$$\Gamma_k = \frac{a^2}{P_k v_k} \quad (k = 1, 2) \quad (1)$$

these parameters can be expressed as follows [5]:

$$\theta = \sin^{-1} \left(\frac{M_1}{M_2} \right) \quad (2)$$

$$\delta = \cot^{-1} \left[\frac{\Gamma_1 M_1^2}{\Gamma_2 M_2^2} - 1 \right] \tan \theta \quad (3)$$

$$M_2^2 = \frac{\Gamma_1 M_1^2 - (P - 1)(1 + v)}{\Gamma_2 v} \quad (4)$$

where, with reference to Eq. (2), M_2 , the Mach number of the normal component of incident flow, is related to the coordinates of the Hugoniot curve by the equation:

$$\Gamma_1 M_2^2 = \frac{v^2}{P_1 v_1} = \Gamma_1 M_1^2 \sin^2 \theta = \frac{P - 1}{1 + v} \quad (5)$$

Thus, for a given M_1 , Eqs. (2), (3), and (4) become functions of the pressure ratio alone, if the specific volume ratio is eliminated by the use of the Hugoniot equation. The latter can be expressed most conveniently in the form of a rectangular hyperbola, which, for a shock front, represents the Rankine-Hugoniot curve passing through the point $P = 1$ and $v = 1$. Its equation is then:

$$(P + \beta P^2)(v - \beta v^2) = (1 + \beta P)(1 - \beta v) \quad (6)$$

and it represents, indeed, an excellent approximation for most gaseous substances. In this case Eq. (5) becomes:

$$\Gamma_1 M_2^2 = \frac{P + \beta P}{1 - \beta v} \quad (7)$$

and, since $M_2 \rightarrow 1$ as $P \rightarrow 1$, the velocity of sound parameter becomes related to the asymptotes of the Rankine-Hugoniot hyperbola as follows:

$$\Gamma_1 = \left(\frac{\beta^2}{1 - \beta} \right) \frac{1 + \beta P}{1 - \beta v} \quad (8)$$

For a perfect gas with constant specific heats, $\gamma = 1.4$ while $\beta = (r-1)/(r+1)$ ($r = 1.4$).

As a consequence of the fact that the conditions of uniform pressure and flow direction immediately behind a wave intersection, the key to the solution of most problems in this domain is the relationship between the pressure and the flow deflection angle, known as the shock polar. Computer plots of such polars and of their auxiliary diagrams for the evaluation of the incidence angle, θ , and the Mach number, M_2 , based on Eqs. (1) through (8) for the case of a perfect gas with $\gamma = 1.4$ (i.e., $\beta = 1/5$), are given in Plates 1, 2, and 3. With their use, the various intersections depicted in Fig. 2 (except for case (g)) were solved graphically [5], as shown in Fig. 3.

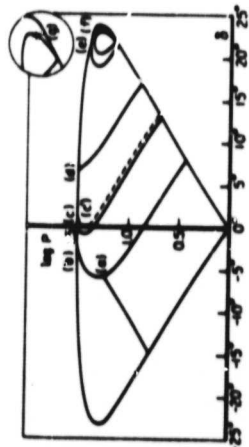


Fig. 3 - Shock polar solutions of the intersection processes represented in Fig. 2

COLLISIONS BETWEEN INTERSECTIONS

As pointed out in the introduction, the most important events in the self-sustenance of detonations are collisions between shock intersections. Since, as it is evident from Fig. 1, any intersection pattern produced by explosions must evolve into a triple-point intersection, while in the most common case of shock-induced explosions represented by Fig. 1(b), such intersections are formed immediately at the outset, only this case need be thus considered.

Symmetric Collision

A symmetric collision between triple-point intersections is described schematically in Fig. 4, showing the wave configurations immediately before and after this event. As a rule, the intersection point "consumes" the weaker incident shock, I. In order for a collision to occur, this shock, must be thus "consumed" from two sides, and the collision takes place then at the moment when it becomes annihilated. Immediately after this, the two stronger shocks, II, of the previous configuration acquire the role of the weaker shocks, I',

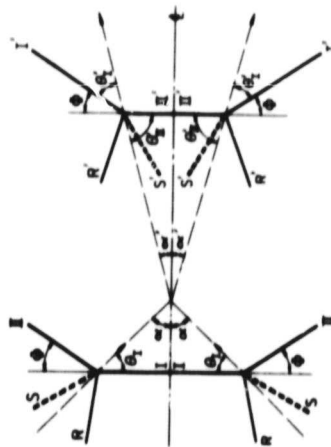


Fig. 4 - Schematic diagram of a symmetric collision between triple-points

while either a new stronger shock, II', is formed "pushing" the triple points away from the axis of symmetry, or a regular reflection is obtained, as that of Fig. 2(c), so that the resultant triple point "slides" along the axis of symmetry. In the latter case a Mach intersection will eventually be formed, as illustrated by Fig. 1(a). Of particular significance to the self-sustenance of detonations is here the fact that, as a result of this process, in both cases a high pressure and temperature region associated with a concentrated vortex is created in the immediate vicinity of the collision point.

Solutions

The wave system resulting from a symmetric collision is fully determined by the fact that the weaker incident shock after collision was the stronger shock before, while, due to symmetry, the newly formed stronger shock is perpendicular to the axis of symmetry. The process of collision has, therefore, two invariants: the pressure ratio, P , across the wave which remains unaffected by this process, and the angle between the two shock fronts, θ .

Exploiting the plane of collision invariants, one can thus construct a chart for the evaluation of the resultant wave system. Figure 5 represents such a chart for the case of a perfect gas with $\gamma = 1.4$. The wave systems that can be obtained after collision are represented there by continuous lines determined by taking for P the pressure ratio across the weaker incident shock. The corresponding wave systems before collision are represented by broken lines; these were obtained simply by taking for P the pressure ratio across the stronger shock of the same intersection. The chain-dotted lines denoted by θ represent the loci of the normal reflected shock solutions (case (e) of Figs. 2 and 3), while those denoted by θ' are the regular reflection limits (case (c) of Figs. 2 and 3) beyond which the angle of reflection, $\theta' = \theta$.

On the $P - \theta$ plane of Fig. 5, each point of intersection between a continuous line and a broken line represents a solution of a collision process, specifying fully the wave systems immediately before and after this event. Once the solution in terms of P and M_1 is known, the angles between the trajectories of the triple points can be determined from the auxiliary $\theta = \theta(P)$ plot, Plate 2, as, by reference to Fig. 4,

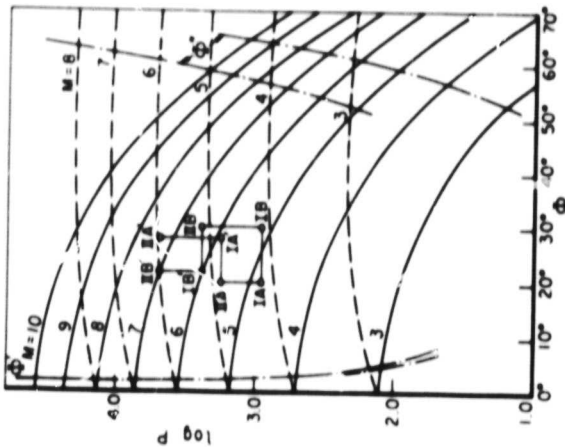


Fig. 5 - Solutions of collision processes between triple-points on a plane of collision invariants (the case of a perfect gas with $\gamma = 1.4$)

$$\alpha = 90^\circ - \theta_1$$

while

$$\alpha' = 90^\circ - \theta_2' = 90^\circ - \theta - \theta_1' \quad (9)$$

Thus, making use of Fig. 5 and Plates 1 and 2, the angles between the trajectories of the triple-point intersections before and after symmetric collision, were evaluated for a set of incident flow Mach numbers, and the results are given in Figs. 6 and 7. From the latter one should note that $\alpha - \alpha'$ becomes negligibly small as θ tends to zero which corresponds to $M_1 = 1$, the condition which is attained when the reflected shock becomes reduced to a characteristic. Moreover, as it appears there, the relationship between θ_1 and θ is practically independent of the incident flow Mach number, especially if its value is high enough. Since this means that in Eq. (9) $\theta_1 + \theta_1'$, one has

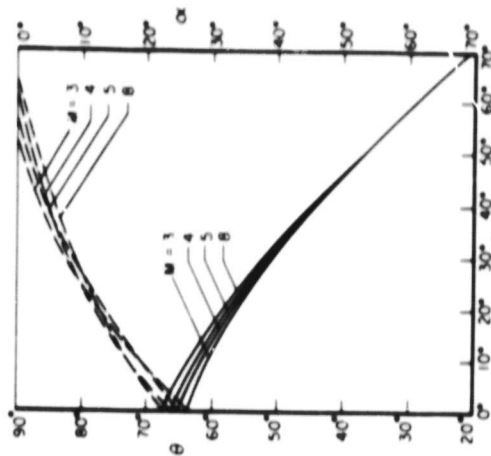


Fig. 6 - Solutions of collision processes corresponding to Fig. 5 expressed in terms of shock incidence angles

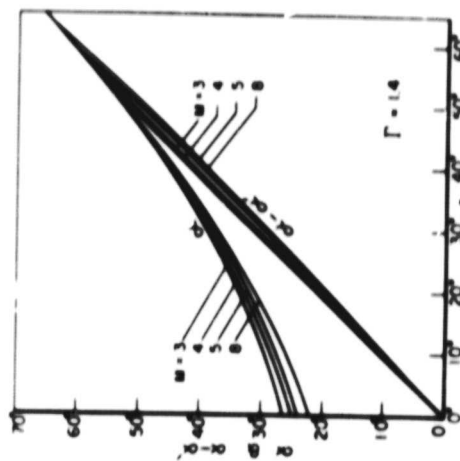


Fig. 7 - Solutions of collision processes corresponding to Fig. 5 expressed in terms of the triple-point trajectory angles

are associated then with "arrowhead" inter-
sections in the vicinity of $M_j = 1$. Under such
circumstances Eq. (19) reduces to

whence, as a consequence of Eq. (12), noting that $M_2 = M_1 \cos \sigma$,

Now, for an 84:16 nitromethane-acetone mixture, a composition corresponding most closely to that used for experiments reported in Ref. [6], $a_1 = 1.89$ mm/sec and $b = 1.7$, while the density at atmospheric pressure is $\rho = 1.0915$ g/cm³. From Eq. (1) it follows that $\beta = 38.4 \times 10^{-4}$, while according to Eq. (13), $\beta = 0.412$, and, assuming that, when the records were obtained from, which it appeared that $a = 4.5$, the triple-points traveled, on the average, at a Mach number $M_1 = 3$, one gets from Eq. (21) $c = 0.491$.

With the use of Plates 4-7, shock intersection processes which can occur in the medium under study can be now evaluated. Thus, similarly as before, one obtains a master diagram on the plane of collision invariants, Fig. 12, and the $\theta = \theta(\theta)$ plot, Fig. 13, which was deduced from Fig. 12 with the help of Plates 4 and 5), yielding finally the trajectory angles $\sigma = \sigma(\theta)$ and their change due to collisions, $\sigma - \sigma_0$, Fig. 14.



Fig. 12 - Solutions of collision processes between triple-points on the plane of collision invariants for an 84:16 nitromethane-acetone mixture expressed in terms of $\Gamma_1 = 38.4 \times 10^3$, $b = 1.7$ ($\beta = 0.412$) and $c = 0.491$.

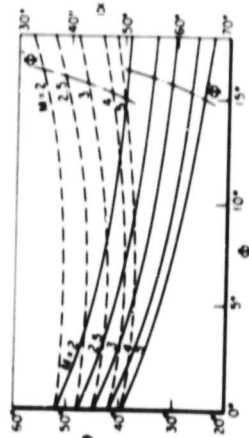


Fig. 13 - Solutions of collision processes corresponding to Fig. 12 expressed in terms of shock incidence angles

It should be noted in this connection that, as a consequence of the large difference in the value of Γ across the incident shock, all the solutions given in Figs. 12-14 correspond to choked "arrowhead" interactions, the pattern represented by case (g) in Figs. 2 and 3. (It

As it appears from Fig. 14, the approximate rule of Eq. (10) is not as good now as it was in the case of the perfect gas of Fig. 7. However in the vicinity of $\theta = 0$, one still has $\bar{\sigma} \approx \sigma^*$. Since the experimentally recorded traces are quite fuzzy, one cannot discern a 1 to 2° change in the direction of σ . Let us take for example $\sigma = \sigma^* = 1^\circ$ at $M_\infty = 3$. The wave configurations immediately before and after triple-point collision, evaluated for these conditions from Figs. 12-14, are shown in Fig. 15. Denoted there also are pressure levels in the various

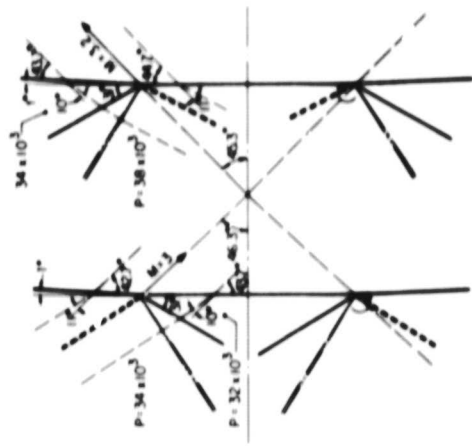


Fig. 15 - Estimated shock inter-section patterns in a detonating nitromethane-acetone mixture

flow regimes. As it appears the concentrated stresses induced by the slip-line discontinuities in r regions where the pressure is about 2 kbar higher than behind the incident shock.

Since, as it was pointed out in the introduction, this is followed by rarefaction due to the decaying blast wave structure of the flow field, the high pressures can exist only in the immediate vicinity of the triple-point. One has thus precise peaks of an order of 2 kbar concentrated at the triple-point trajectories — a phenomenon at the triple-point intensity to produce the recorded traces. This result can be considered as providing as good a proof as one can wish at this juncture of the essential correctness of our theory in its applicability to a condensed explosive.

In a multiwave structure of a detonation wave, shock intersections form basic elements. Concom-

Fig. 14 - Solutions of collision processes corresponding to Fig. 12 expressed in terms of the triple-point trajectory angles

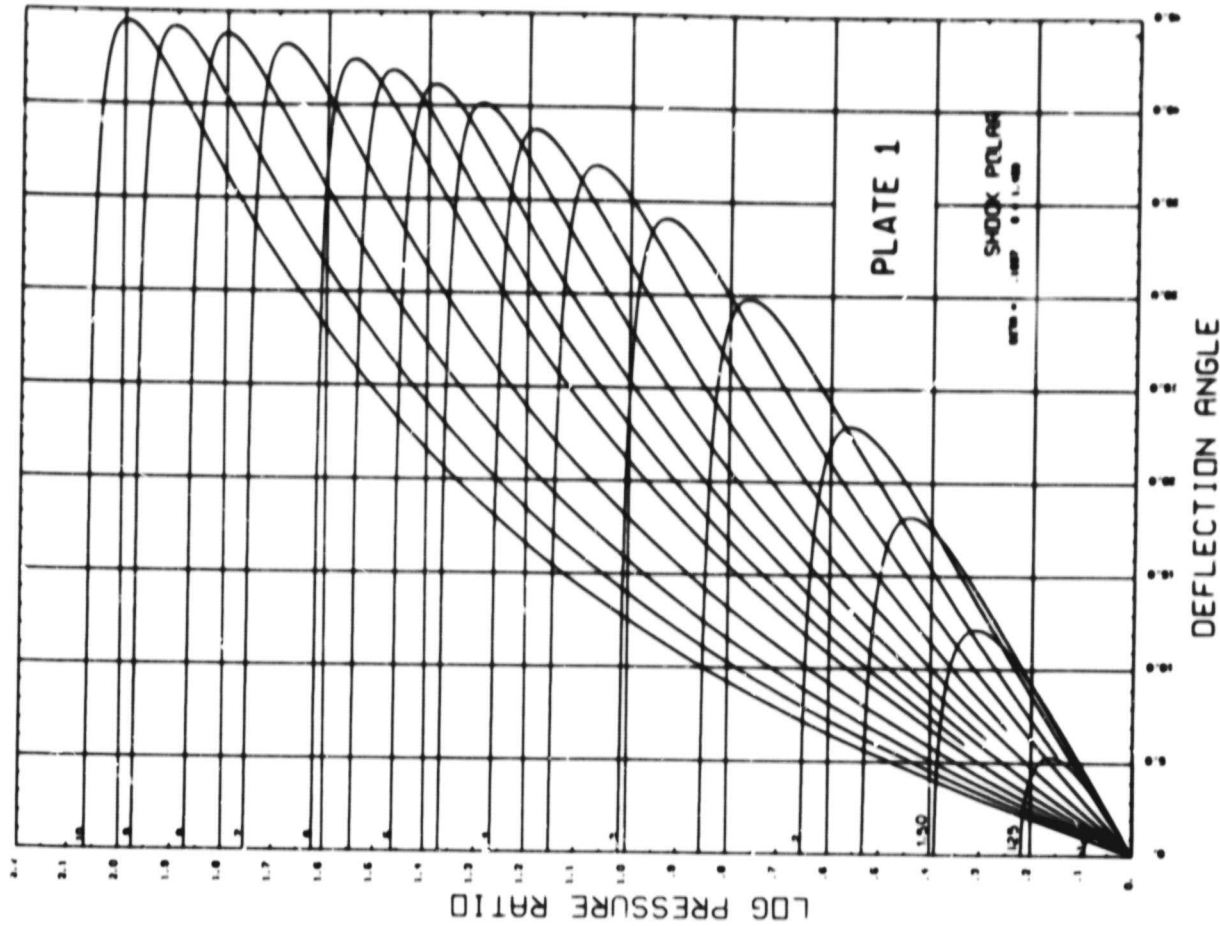
is for this reason that one needs the rarefaction poles included in Plate 4). The limit lines shown on these diagrams denote the first instant when the regular reflection can be also obtained, so that to the right of these lines there is a regime of ambiguity in that two types of dynamically compatible solutions are possible. Since, however, the regular reflection, corresponding in this case to solution (c') in Fig. 3, has at first a pressure behind the reflected shock higher than that behind the "arrowhead" intersection, the latter intersection is more likely to occur. This is due to the fact that, in the course of detonation, shock waves appear as fronts of decaying blast waves, and these, as a rule, are associated with rarefaction, favoring thus the establishment of a wave pattern that corresponds to a lower pressure.

tant to this is the fact that collisions between intersection points play a dominant role in the dynamic aspects of the self-sustenance of detonations. Presented here was a simple theory of wave intersections and their collisions that applies to gaseous media as well as to condensed explosives, covering a full scope of possible wave configurations. It appears from this that the prevalent type of wave pattern in gaseous media is a Mach intersection, while in the condensed explosives it is the "arrowhead" intersection.

The theoretical results are in good agreement with experimental observations, suggesting that collisions between intersections should be recognized as valuable diagnostic means for the investigation of the structure and self-sustenance of detonations in condensed explosives, as much as these means have been already exploited in studies on gaseous detonations.

REFERENCES

1. R. A. Strehlow, "Gas Phase Detonations: Recent Developments," *Combustion and Flame*, Vol. 12, No. 2, pp. 81-101, April 1968.
2. J. H. Lee, R. I. Soloukhin, and A. K. Oppenheim, "Current Views on Gaseous Detonations," *Astronautica Acta*, Vol. 14, No. 5, pp. 565-584, June 1969.
3. R. Courant and K. O. Friedrichs, *Supersonic Flow and Shock Waves*, p. 318, Interscience Publishers, Inc., New York, 1948.
4. A. H. Shapiro, *The Dynamics and Thermodynamics of Compressible Fluid Flow*, Vol. 1, p. 553, The Ronald Press Company, New York, 1953.
5. A. K. Oppenheim, J. J. Smolen, and L. J. Zajac, "Vector Polar Method for the Analysis of Wave Intersections," *Combustion and Flame*, Vol. 12, No. 1, pp. 63-76, Feb. 1968.
6. P. A. Urtiew, "Reflected Shock-Velocity Particle-Velocity Relationship in Solids," *J. Applied Physics*, Vol. 40, No. 10, pp. 3962-3967, Sept. 1969.
7. P. A. Urtiew, A. S. Kusubov, and R. E. Duff, "Cellular Structure of Detonation in Nitromethane," *Combustion and Flame*, Vol. 14, No. 1, pp. 117-122, Feb. 1970.
8. P. A. Urtiew and A. S. Kusubov, "Wall Traces of Detonation in Nitromethane-Acetone Mixtures," in this symposium.
9. A. N. Dremin and O. K. Rozanov, "Measurement of Shock Adiabats in Nitromethane-Acetone Mixtures," *Bulletin of the USSR Academy of Sciences, Division of Chemical Sciences*, No. 8, pp. 1417-1419, Aug. 1964.



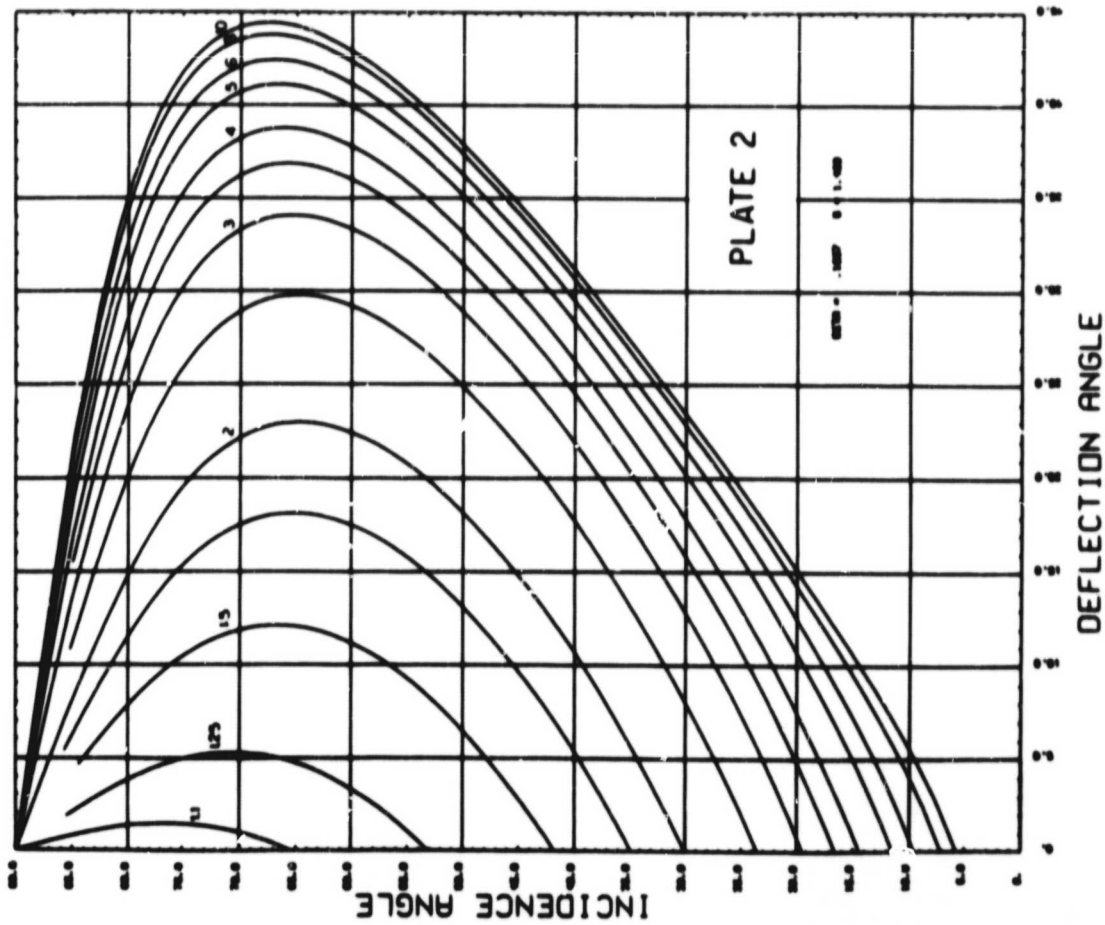


Plate 2 - Auxiliary $\theta = \theta(d)$ plot for Plate 1

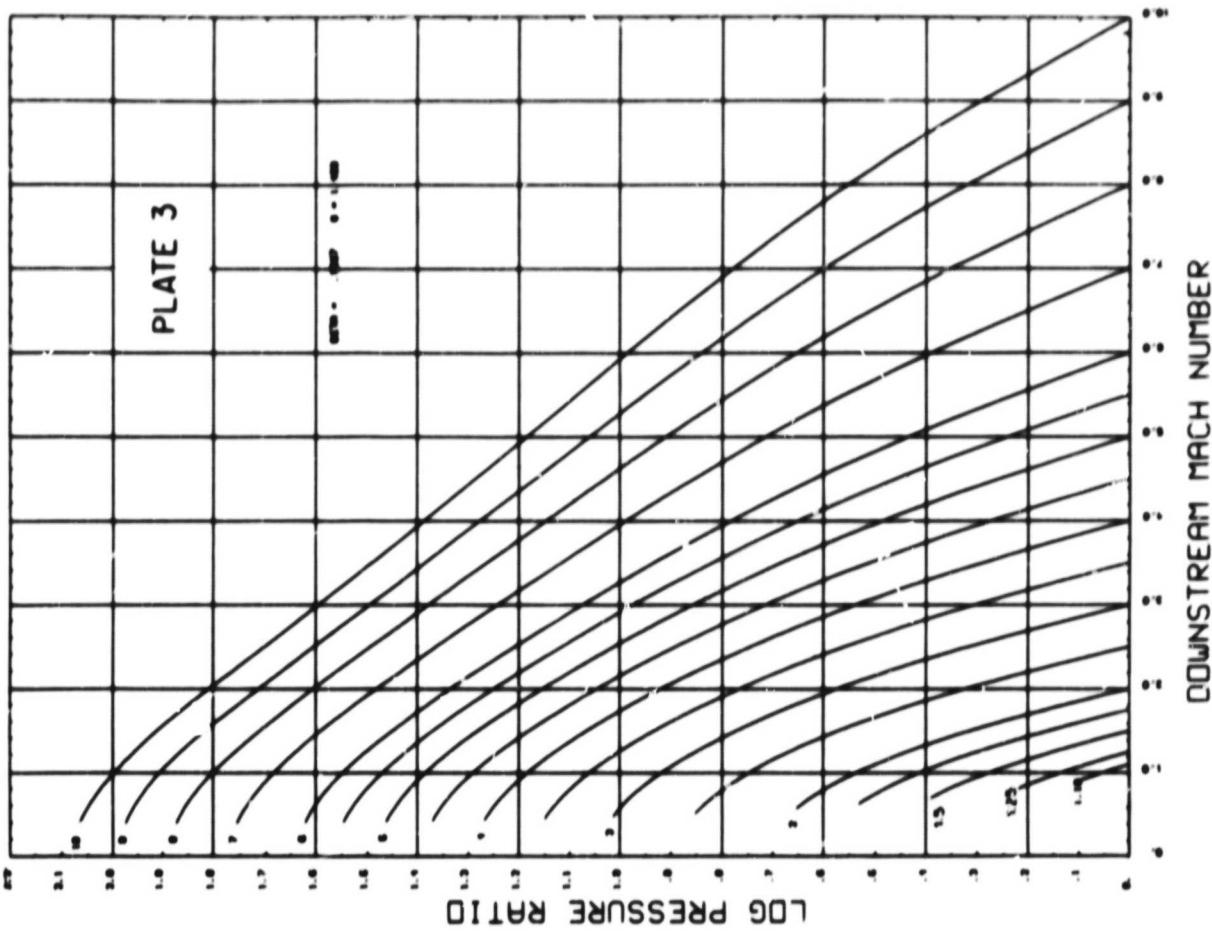


Plate 3 - Auxiliary $M_j = M_j(P)$ plot for Plate 1

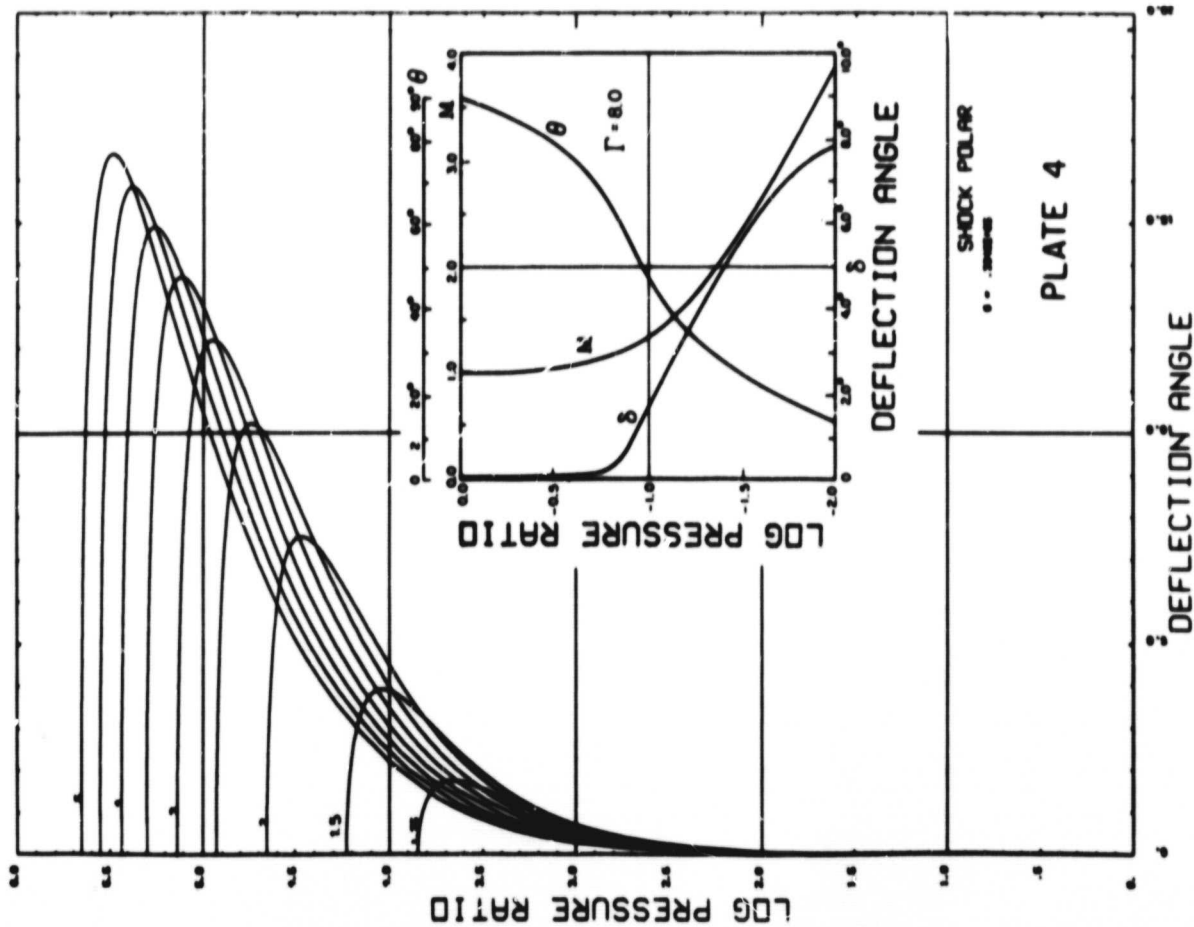


Plate 4 - Shock polars for the case of an 84:16 nitromethane-acetone mixture expressed in terms of $\Gamma_1 = 38.5 \times 10^3$, $b = 1.7$ ($\delta = 0.412$) and $c = 0.491$; insert: rarefaction polar for $\gamma = \Gamma = 8$

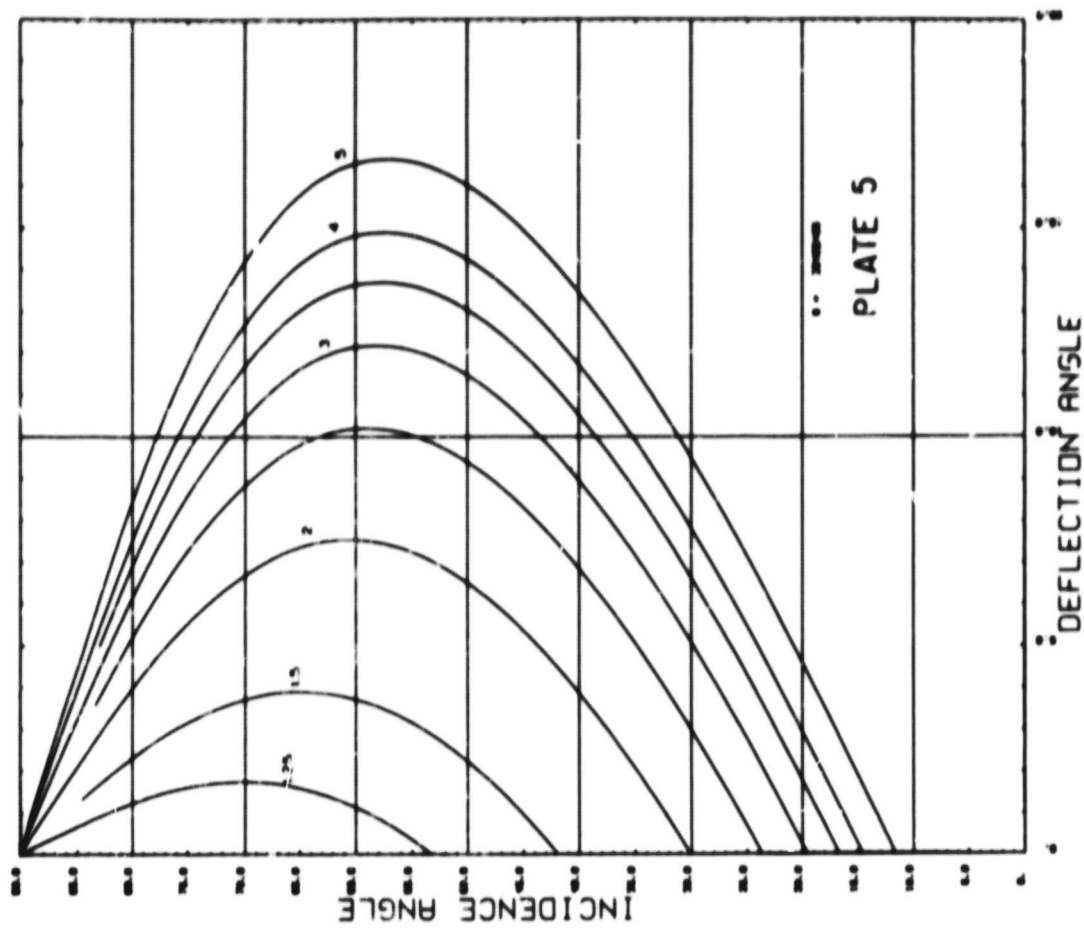


Plate 5 - Auxiliary $\theta - \theta(1)$ plot for Plate 4

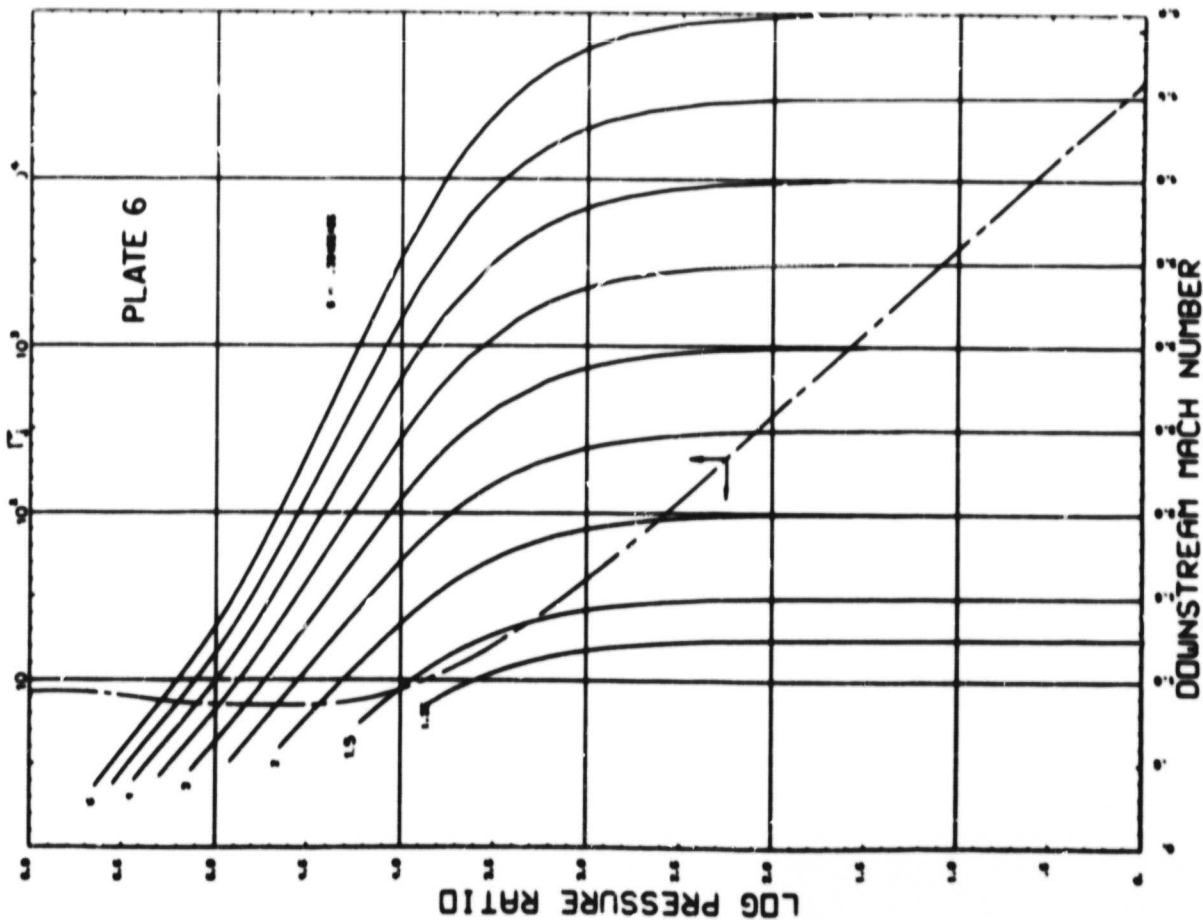


Plate 6 - Auxiliary $M_j - M_j(P)$ plot for Plate 4

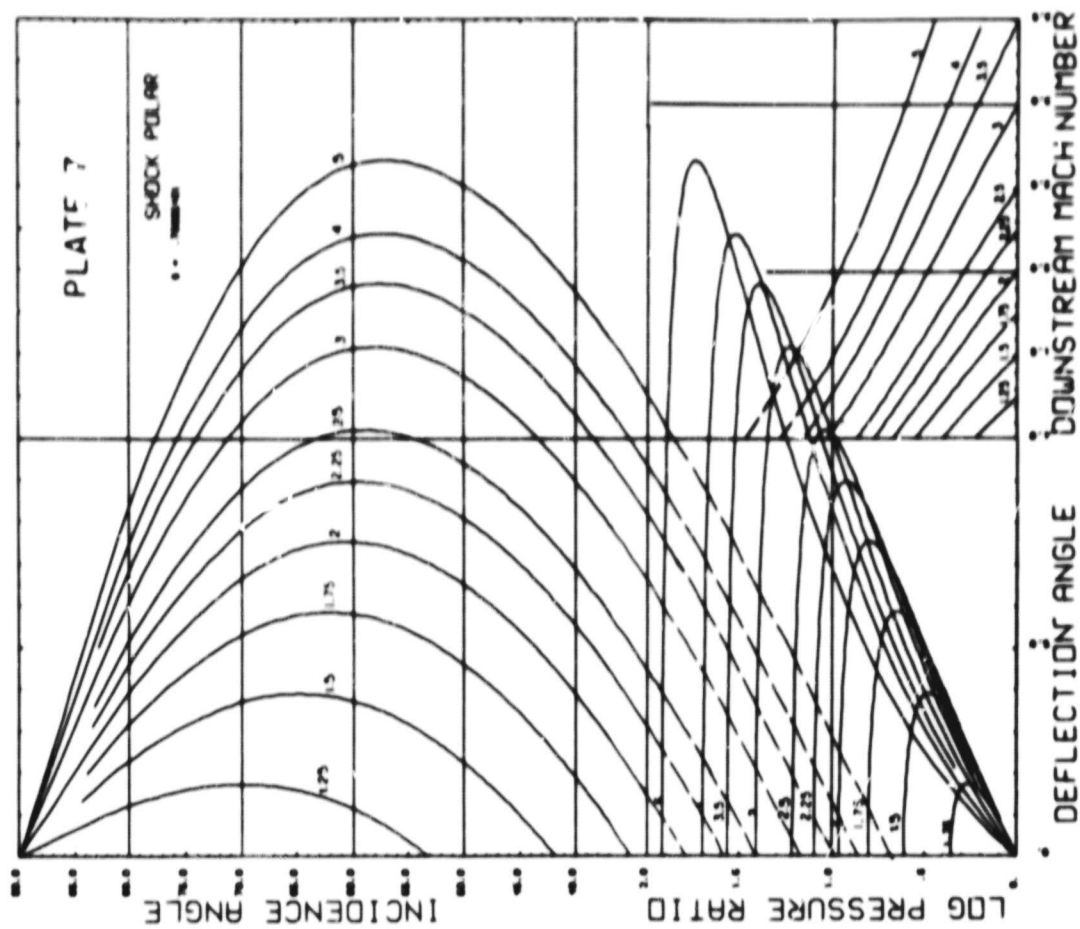


Plate 7 - Reflected shock polars and the auxiliary diagrams for the case of an 84:16 nitromethane-acetone mixture expressed in terms of $\Gamma_1 = 8$, $b = 1.7$ ($\beta = 0.412$) and $c = 0.49$