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TECHNICAL REPORT MIT-23-P

THE STRUCTURE OF GASEOUS DETONATION WAVES

by

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James A. Fay

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Technical Report MIT-23-P

PROJECT SQUID

A COOPERATIVE PROGRAM
OF FUNDAMENTAL RESEARCH
AS RELATED TO JET PROPULSION
OFFICE OF NAVAL RESEARCH, DEPARTMENT OF THE NAVY

Contract Nonr1858(25), NR-098-038

THE STRUCTURE OF GASEOUS DETONATION WAVES

by

James A. Fay
Massachusetts Institute of Technology
Cambridge, Massachusetts

August 1959

PROJECT SQUID HEADQUARTERS
JAMES FORRESTAL RESEARCH CENTER
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PRINCETON, NEW JERSEY



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THE STRUCTURE OF CASEOUS DETONATION WAVES*

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Massachusetts Institute of Technology

August 1960

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I Introduction

For the past twenty years a large fraction of detonation research has been concerned with the problems of wave structure and detonation initiation. In view of two recent reviews (21, 45) of detonation wave phenomena, the latter of which generously covers the question of the development of detonation waves, it seemed to the author more appropriate to confine this review to a discussion of the attempts to understand more fully the structure of gaseous detonation waves. It will consider the experimental and theoretical studies of wave structure, the influence of tube walls, the phenomenon of spinning detonation, and the possibilities of standing detonation waves. It concludes with some subjective remarks concerning the unsolved problems of this field.

The peculiar disadvantage of detonation research is that it was too successful at too early a date. The quantitative explanation of the velocity of such waves given over fifty years ago by Chapman and Jouguet has not been improved upon, and has perhaps intimidated further inquiry. Nevertheless, the theoretical ideas of Zeldovitch, Döring, and von Neumann have instigated a new look at the internal structure of the detonation wave, with results which are not yet entirely assayable. This recent research has had interesting and fruitful connections with chemical kinetics and gas dynamics. There is thus abundant evidence that detonation research is neither complete nor sterile and that, in fact, the unanswered questions are becoming more profound.

In the ensuing discussion, it is assumed that the reader has some acquaintance with the properties of gaseous detonations and the gas

dynamical theory explaining them, such as are summarized by Lewis and von Elbe (37). In this theory the detonation wave is assumed to consist of a shock wave followed closely by a combustion reaction which reaches thermodynamic equilibrium. (It is this combined shock and combustion wave which is usually termed the detonation front.) The detonation wave velocity and other properties are seen to depend upon fluid mechanical and thermodynamical laws alone and not upon the chemical kinetics of the combustion reaction.

It is perhaps worthwhile to point out that the study of the detonation wave structure is a study of the connection of the combustion kinetics to some observable properties of the wave, such as thickness, shape, stability, etc. The earliest detonation theories attempted to predict the wave velocity on the basis of chemical kinetics, and their failure has undoubtedly delayed efforts at understanding the relevance of rate processes to some aspects of detonation wave properties. This review is an attempt to summarize those researches which have contributed some experimental evidence or theoretical understanding to the linking of kinetics with detonation wave phenomena.

II Experimental Observations of Detonation Wave Structure

An attempt to measure the pressure within the detonation combustion zone was made by Gordon (19), who found that the time response of his piezoelectric gage was insufficient to reveal more than an indication of a falling pressure in the combustion zone of oxy-hydrogen mixtures, and that the Chapman-Jouguet (C-J) pressure was found to be achieved almost immediately behind the detonation front. Kistiakowsky (28) proposed the determination of gas density within the reaction zone by absorption of X-rays in noble gases added to the detonable mixture, providing space and time discrimination of about 1 mm. and a few microseconds, respectively. In a series of papers, Kistiakowsky and co-workers (32, 34, 35) reported results of measuring the density profiles of H_2-O_2 , $CO-O_2$, CH_4-O_2 , and $C_2H_2-O_2$ detonations diluted with krypton or xenon at reduced pressures where reaction zones were several millimeters in thickness. In addition to giving an overall measure of the thickness of the wave (or the gross reaction time), these measurements showed that the C-J density was achieved at the end of the reaction zone (within the 10 per cent experimental accuracy), but that the full density increase across the shock front predicted by Zeldovitch (60), Döring (8), and von Neumann (54), was not reached, although there was a decrease through the zone as expected. It was concluded that, if the pressure (and hence density) should fall quite abruptly behind the shock wave, then the small wave tilt and finite discrimination distance of the experiment would adequately explain the failure to measure the shock density jump. These measurements failed to reveal in any mixture the existence of an induction zone of high constant density behind the shock wave, at least of dimension comparable with the

overall dimension of the reaction zone itself. (In the case of an oxy-hydrogen detonation, the measured density profile is in reasonable agreement with a calculation by Duff (14) based on a kinetic system devised from other sources, and no measureable induction zone under normal detonation wave conditions was indicated.)

The gross thickness of detonation waves has also been determined by Just (26) by measuring light emission, by Pusch (47) using an integrating schlieren beam, by Orfel (44) from schlieren pictures and by Martin and White (40) from interferograms. Fig. 1 compares the thickness of a stoichiometric oxy-hydrogen detonation as measured by these various techniques at different initial pressures. There is general agreement (35, 4, 26, 44) that the thickness varies inversely with the pressure, as for an overall second order reaction.

Both Gordon (19), who measured the pressure in the rarefaction wave following the detonation, and Kistiakowsky and Kydd (33), who measured the density, found reasonable agreement with the one-dimensional rarefaction wave theory as proposed by Döring and Burkhardt (9) and Taylor (49).

An interesting feature of both the schlieren (44) and interferometer photographs (40) is the "turbulent" nature of the density distribution within the reaction zone. Figs. 2 and 3 show typical schlieren and interferometer photographs of oxy-hydrogen detonations under conditions where the combustion zone is easily discernable. The density spottiness within the reaction zone is completely absent in the wake, except for regular large scale variations in the transverse direction reminiscent of spinning detonations. Schlieren photographs (44) show that the density fluctuations persist down to the discrimination distance of the schlieren system

(about 1 mm.) when the reaction zone is shortened by increasing the pressure.

Opel (44) notes that when the reaction zone thickness is small compared with the tube diameter, the detonation wave is plane (at least on a scale comparable with the tube diameter), but on a scale comparable with the wave thickness the flow appears to be far from one-dimensional and steady. At sufficiently low pressures, the wave thickness becomes comparable with the tube diameter and the detonation front is no longer plane (Fig. 4). Sometimes regularities in the structure appear (Fig. 5), clearly associated with the lateral dimension of the tube and perhaps with the phenomenon of spin.

III Theory of Detonation Wave Structure

With but few exceptions, the theory of detonation wave structure has concerned itself with steady, plane (i.e., one-dimensional) waves with no transport effects. The independently-developed theories of Zeldovitch (60), Döring (8), and von Neumann (54) assumed a model in which the detonation consisted of a shock wave followed by a chemical relaxation from the initial thermodynamically metastable state of the reactants to a stable equilibrium state of the products. This approach was concerned with the conservation of mass, momentum and energy, and chemical kinetics were only casually treated in terms of single reaction models. Nevertheless, these developments spurred an intensive effort in experimental observations of wave structure.

This theory, and those subsequently to be discussed, may be recapitulated in the following manner. For a steady, plane flow devoid of transport effects, the differential statements of mass, momentum and energy conservation are:

$$\frac{d}{dx} (\rho u) = 0 \quad (1)$$

$$\frac{d}{dx} (p + \rho u^2) = 0 \quad (2)$$

$$\frac{d}{dx} (h + \frac{1}{2} u^2) = 0 \quad (3)$$

where p , ρ , h , and u are pressure, density, specific enthalpy and velocity respectively, and x is the dimension normal to the wave front. The general (non-equilibrium) caloric equation of state provides an integral relation between enthalpy and pressure, density, and composition:

$$h = h(p, \rho, y_1) \quad (4)$$

where y_1 is the mole fraction of each constituent, (it being understood that only a set of y_1 will be used which is consistent with the conservation of atomic species).

The Zeldovitch-Döring-von Neumann (ZDN) theory works with the three obvious integrals of equations (1)-(3) and equation (4). For a given upstream thermodynamic state and velocity (denoted by subscript 1), the mass and momentum integrals relate the pressure and density:

$$p - p_1 = \rho_1 u_1^2 \left\{ \frac{1}{\rho} - \frac{1}{\rho_1} \right\} \quad (5)$$

which is a straight line (Rayleigh line) in the p, ρ^{-1} plane (see Fig. 6) passing through the upstream thermodynamic state. The composition of the gas is determined for any point along this integral by noting that the integrals of equations (1)-(3) and equation (4) may be combined to give:

$$h(p, \rho, y_1) - h(p_1, \rho_1, y_{11}) = \frac{(p - p_1)(\rho + \rho_1)}{2 \rho \rho_1} \quad (6)$$

which is the equation of a family of curves (Hugoniot curve) in the p, ρ^{-1} plane depending only upon the initial thermodynamic state (but not initial velocity). If the y_1 are chosen to be y_{11} , then the shock wave Hugoniot is found. If the y_1 are chosen to be those which obtain at thermodynamic equilibrium; that is, y_1 are determined by p and ρ , then a single equilibrium Hugoniot curve results (see Fig. 6).

The ZDN theory assumes that the integrals of equations (1)-(3) which are compatible with equation (4) are determined by the intersection in the p, ρ^{-1} plane of the Rayleigh line (equation (5)) and the family of Hugoniot curves (equation (6)) having values of y_1 which lie between those defining the shock Hugoniot and the equilibrium Hugoniot. The experimentally observed detonation, following Chapman and Jouguet, is held to be that for

which the flow velocity, when equilibrium is reached, is equal to the local equilibrium sound speed (or the equivalent statement that it is the wave of minimum value of u_1), which might be termed the classical Chapman-Jouguet (C-J) condition. In the p, ρ^{-1} plane this solution is given by the Rayleigh line tangent to the equilibrium Hugoniot curve. The point of tangency (E in Fig. 6) is the sonic point.

In considering the implications of the ZDN theory, Brinkley and Richardson (2) pointed out that the characteristic directions in unsteady plane flows (i.e., the directions in the x, t plane across which discontinuous changes in the spatial derivatives of the dependent properties are mathematically possible) propagate at a velocity relative to the gas which is equal to the sound speed computed under the restriction of no change in chemical composition (frozen sound speed). If an expansion wave is not to overtake a detonation, the C-J condition would require that the flow velocity with respect to the wave front equal the frozen sound speed when equilibrium is reached.

Kirkwood and Wood (27) focussed attention on the fact that the set of equations (1) through (4) above is an incomplete specification of the problem; to these must be added the kinetic equations defining the time rate of change of chemical composition:

$$\frac{dy_i}{dt} = u \frac{dy_i}{dx} = R_i(p, \rho, y_j) \quad (7)$$

The C-J condition was found to be identical with that determined by Brinkley and Richardson (2), with the exception of the possibility of "pathological" detonations first suggested by von Neumann (54). Subsequently, Wood and Kirkwood (56) pointed out that the frozen C-J sonic point (F in Fig. 6) lies below the equilibrium C-J point on the equilibrium Hugoniot, and that for a single reversible chemical reaction

(i.e., one for which the equilibrium $A \rightleftharpoons B$ is achieved), there is no integral of equations (1)-(4) and (7) reaching the frozen C-J point after passing along the upper branch of the Rayleigh line. In a later paper (57), they acknowledge that for general reaction schemes there may be no integrals passing through the frozen C-J point. The several solutions involving reversible reactions which have been computed lend support to this contention, for the final state is either on the upper branch of the equilibrium Hugoniot (Duff (14)) or at the equilibrium C-J point (Linder, Curtiss, and Hirschfelder (38)).

A solution to this dilemma may be found by considering the propagation of the expansion wave into the reacting mixture behind a normal detonation wave (Wood and Parker (58)). Although initially the rarefaction head propagates at the frozen sound speed, after a time long compared with the chemical equilibration time very little of the disturbance continues to propagate at such a speed, and the effective leading edge of the pulse travels at the (lower) equilibrium sound speed. Thus, no appreciable disturbance of the expansion wave would overtake the equilibrium C-J detonation. This physically acceptable point of view is taken by Wood and Salzburg (59), who use the methods of non-linear mechanics to conclude that the frozen C-J condition is "structurally unstable", i.e., there are no integrals of equations (1)-(4) and (7) which will pass through such a point.

Even the most precise velocity measurements (Peek and Thrap (46)) failed to distinguish convincingly between the frozen and equilibrium C-J hypotheses. However, Duff, Knight and Rink (12) point out that the frozen and equilibrium C-J densities differ by more than 10 per cent, and their accurate X-ray absorption measurements give densities very close to

the frozen C-J value. This ambiguity of the experimental measurement is discussed further in Section IV below.

There has been disagreement as to whether the equations (1) through (3) ought to include transport effects. Zeldovitch (60) argues that such effects are negligible unless some chemical reaction is complete within a few kinetic mean free paths, which he rejects as chemically implausible. This same view is held by Brinkley and Richardson (3). However, Hirschfelder et al. (24, 38, and 6) computed solutions to equations (1)-(4) and (7) which include the effects of viscous dissipation, heat conduction, and diffusion. They find that the combustion zone merges with the shock wave when the chemical rates are sufficiently great to make the reaction zone width of the order of a kinetic mean free path, and that the ZDN theory is inapplicable under these conditions. In support of Zeldovitch's viewpoint, all measurements to date show reaction zones of the order of 10^4 mean free paths in thickness.

IV Wall Effects:

Lewis and Friauf (36), in commenting upon the fact that experimental detonation velocities were slightly less than those calculated, suggested that incomplete chemical reaction might reduce the wave velocity below its theoretical value. Berets, Greene, and Kistiakowsky (1) remarked that heat losses to tube walls would have a similar effect. Using a model of one-dimensional flow, with friction and heat addition, Zeldovitch (60) showed that the reduction in wave velocity (velocity deficit) should be proportionate to the reaction zone thickness and inversely proportional to the tube diameter. He also noted that the C-J condition should be modified under such circumstances; the flow becomes sonic not at chemical equilibrium, but when the rate of chemical reaction balances the frictional force and heat loss to give a non-singular behavior at the sonic line. Döring (8) states that wall effects are measured by the dimensionless parameter β :

$$\beta = \frac{(\text{reaction time}) \times (\text{wave velocity})}{\text{tube diameter}}$$

but does not suggest that the velocity deficit (difference between theoretical and experimental velocities) is proportional to this parameter.

The accurate measurements of Kistiakowsky and co-workers (1, 29, 30, 31, 34), and Guenoche and Manson (23) established the correctness of Zeldovitch's prediction, and is the basis for extrapolating velocity measurements to infinite tube diameters.

A related phenomenon is present in the detonation of unconfined solid explosives, where the detonation velocity varies with the charge diameter. Jones (25), noting the radial expansion of the gases in the combustion zone of an unconfined charge, developed an analysis for the

reduction in velocity due to this radial outflow. Wood and Kirkwood (55) obtained substantially the same results relating wave velocity with radial outflow by considering a slightly curved (convex to unreacted components) detonation with a reaction zone thickness small compared with the radius of curvature. They also note a modification of the C-J condition due to the radial flow. Introducing some simplifications, they found that for a typical solid explosive, the fractional decrease in velocity was about three times the wave thickness divided by the radius of curvature.

A more sophisticated model for gaseous detonations in finite diameter tubes has been introduced by Fay (18). Viewed in coordinates fixed in the detonation wave, an aerodynamic boundary layer developing on the tube wall has a negative displacement thickness, causing a gradual divergence of the streamlines. This area enlargement is propagated through the subsonic reaction zone, causing a streamline divergence and thus wave curvature which is constant everywhere except very close to the wall. (See Fig. 7). Assuming a turbulent boundary layer, and using measured wave thicknesses, Fay finds good agreement between measured velocity deficits and those predicted on the basis of this model.

A further consequence of this model is that the continued growth of the boundary layer leads to a continued divergence of the streamlines and further acceleration of the supersonic flow in the core. It is thus possible to construct a steady, two-dimensional flow that is subsonic in the reaction zone, becomes sonic at a C-J surface approximately parallel to the wave front (at which point thermodynamic equilibrium has not been reached), and then becomes supersonic as the streamlines continue to diverge. There is thus no possibility of sound waves overtaking the detonation front, and the wave is stabilized by boundary layer effects.

Before proceeding, it is useful to emphasize the difference between the C-J condition for the plane wave (e.g., Kirkwood and Wood (27)) and that for the two-dimensional curved front wave (e.g., Wood and Kirkwood (55)). In the former case the requirement is that, as a consequence of joining a steady and unsteady flow, the reaction rates be zero (i.e., chemical equilibrium exists and the steady flow velocity equals the sound speed -- frozen or equilibrium, depending upon whether the emphasis is upon mathematical rigor or physical intuition). In the latter case, in order for the gas to accelerate smoothly from subsonic to supersonic flow, the accelerating effect of the chemical reaction rates must balance that of the streamline divergence at the point where the steady flow velocity equals the frozen sound speed -- a condition which can only be attained if the gas is not in chemical equilibrium. In this respect, the restriction is analogous to the flow of reacting mixtures through converging-diverging nozzles, and it is perhaps misleading to label it a C-J condition. There is no ambiguity involved in the two-dimensional C-J condition, although it has not been generally proven that there is a unique solution to the two-dimensional flow problem which will satisfy this condition.

A further interesting aspect of the two-dimensional detonation wave model is the possibility of explaining the wave densities measured by Duff, Knight, and Rink (12). At atmospheric pressure, some schlieren photographs show stationary wave patterns which Fay and Opel (17) interpret as Mach waves (see Fig. 8), perhaps originating from boundary layer effects near the reaction zone. These Mach lines indicate that the flow Mach number is about 1.10 to 1.15, depending upon the mixture. Assuming that the reaction is nearly complete at the equilibrium C-J point and

that a further isentropic expansion to the observed Mach number (based on equilibrium sound speed) takes place, they found that the computed density was very close to that measured by Duff et al. (12). Although this explanation has not received enthusiastic acceptance (13), the two-dimensional model does indicate that supersonic flows should be achieved. In an isentropic flow, a stream-tube area increase of one per cent would accelerate the flow from Mach 1 to Mach 1.10, and such area increases should be attained several wave thicknesses behind the front according to the quantitative results of the velocity deficit theory (18).

If the flow immediately behind the detonation front is supersonic (about Mach 1.1), then a following expansion wave or small amplitude compression wave would not overtake it, but would fall further and further behind. The double waves in hydrocarbon-oxygen mixtures discovered by Cher and Kistiakowsky (3) consisted of a second small amplitude compression wave receding from the detonation front at a relative velocity of about 4 per cent of the detonation velocity. This would be the relative velocity of a sound wave moving against a Mach 1.08 flow behind a detonation. Edwards, Williams, and Breeze (15) note that the pressure behind a detonation remains constant for a short period, before beginning to drop due to the expansion wave. This again indicates a lagging of the expansion wave behind the detonation and hence the supersonic character of the flow.

V Spinning Detonation

Some progress has been made in observing the structure of spinning detonation waves. Duff and Knight (10) showed that gross distortions of the shock front occurred in a spinning detonation. Denissov and Troshin (7) observed the tracks left by the detonation on an oil coating on the tube wall, and found two types: a spiral track (which they call spinning detonation), and a truncated symmetrical track (called pulsating detonation). Duff, Knight and Wright (11) report spin detonation measurements in pure acetylene. Vertical slit streak photographs by Duff and Knight (10) and Toennies and Wagner (50) show quite clearly the motion of the luminous pressure peak from side to side of the containing tube.

There is considerable evidence that spin occurs only near detonation limits, whether that limit is due to reduced tube diameter, or pressure, or composition. Gordon, Mooradian and Harper (20) find spin near composition and pressure limits in oxy-hydrogen-noble gas mixtures in a tube of fixed diameter. Troshin and Shchelkin (51) note that $2\text{H}_2 + \text{O}_2$ detonations spin at either reduced pressure or tube diameter. Mooradian and Gordon (41) note that overdriven detonation waves in mixtures beyond the composition limits always spin when decaying through the C-J velocity.

The acoustic descriptions of spinning detonation (Manson (39) and Fay (16)) are not complete theories, but merely show that the measured spin frequency is identical with one of many possible transverse vibrational frequencies in the reacted gases. No explanation has yet been given as to why the vibratory motion in the detonation wake should be predominantly transverse or under what conditions it should occur.

The acoustic theory was used by Chu (5) to determine the reflection characteristics of a wave propagating upstream through the burned gases behind an overdriven detonation, and he found that no amplification resulted. Voitsekhovskii (52) has proposed a spinning detonation theory based on the properties of two-dimensional shock and detonation wave interaction patterns which propagate around the periphery of the tube.

VI Standing Detonation Waves

Several attempts are being made to stabilize detonation waves in steady-flow supersonic combustion tunnels. The general method is to preheat the oxidant (and sometimes the fuel), expand both separately to lower temperatures and supersonic velocities, mix the two coaxial streams by diffusion, and then cause a shock wave to form in the supersonic combustible stream. If the preheating temperature is sufficiently high, it is hoped that a shock wave followed by combustion will be maintained stationary in the supersonic flow field.

Closed tunnel experiments have been reported by Gross and Chinitz (22). A typical schlieren photograph of the standing wave is shown in Fig. 9, and its similarity to photographs of normal detonations such as Figs. 2 and 4 should be noted. In the closed tunnel, the shock wave is initiated by a wedge in the flow, usually at the wall. The measurements of pressure and temperature changes across the standing wave agree reasonably well with one-dimensional flow theory, and the exceptions are thought to be due to flow divergences.

An open tunnel, or overexpanded nozzle experiment has been reported by Nicholls et al. (42, 43). Contrary to the closed tunnel results, a clear separation, or ignition delay, is observed between the shock wave and the luminous reaction zone (see Fig. 10). A theoretical treatment equivalent to that of Duff (14) gives fair agreement between the measured and computed ignition delays. Again, there were indications that the flow was not one-dimensional.

A novel type of continuous detonation wave has been reported by Voitsekhovskii (53). A detonation propagates continuously around an

annulus which is fed steadily from the inside radius with combustible and exhausted from the outside radius. Thus the combustible is replenished before the detonation completes a cycle.

VII Conclusion

The most striking experimental observation of detonation wave structure is the strong indication that such waves are not steady, and have a non-uniform random structure on a scale comparable with the wave thickness. This is true even for waves of several millimeters in thickness, which are the thinnest so far resolved. One cannot help conjecturing that there is no such thing as a steady (in the usual aerodynamic sense) detonation wave.

This remarkable fact has yet to be incorporated into the wave structure theories. The existing theories, either one- or two-dimensional, all refer to steady flow, and their success in predicting velocities, pressures and densities must stem from the fact that, on the basis of a space or time average, they do not violate the conservation laws. This happy coincidence should not blind us to the fact that these theories, as far as one can determine, do not describe what actually transpires in an experiment.

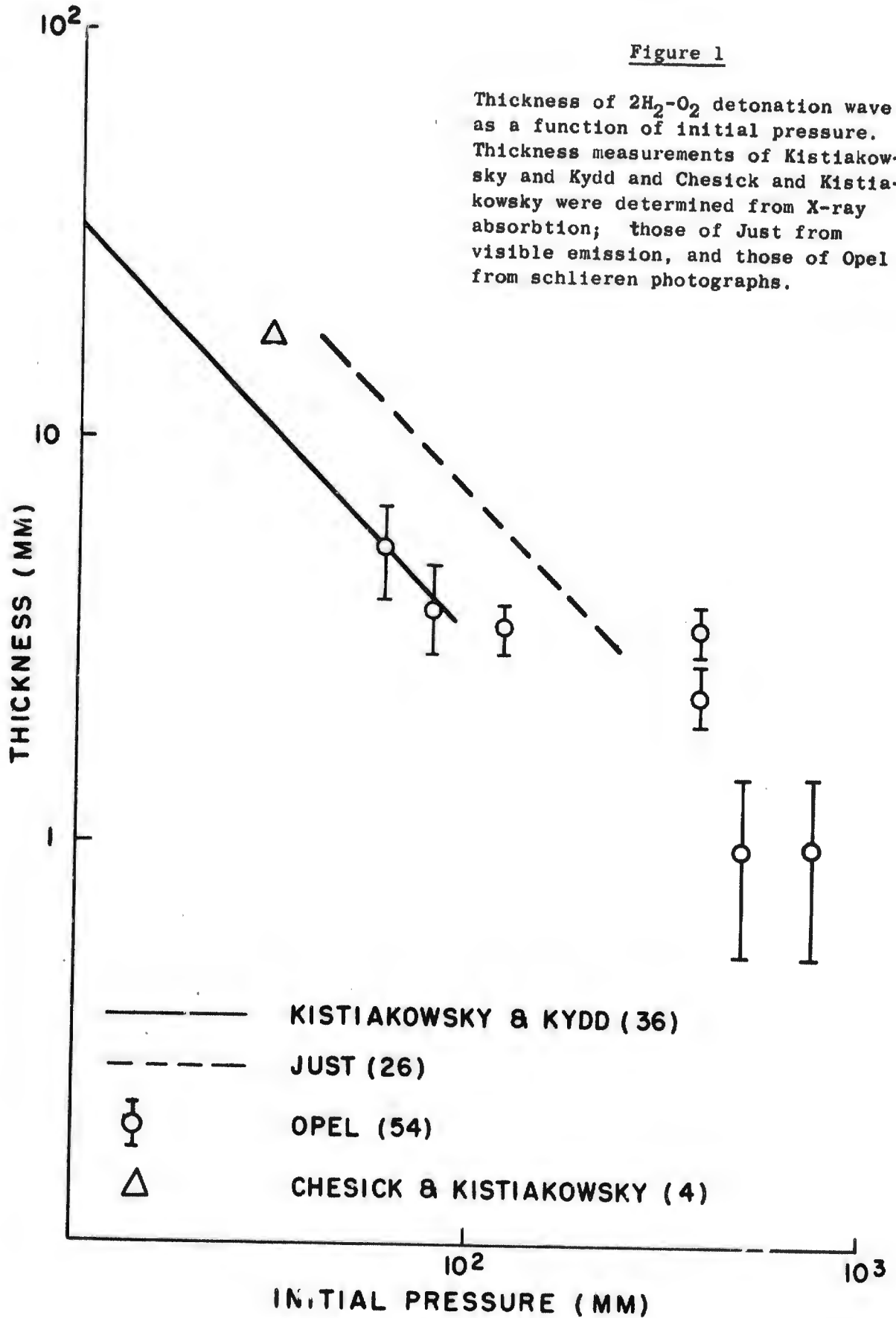
This does not imply that steady flow models are useless. For example, a steady flow two-dimensional curved front detonation must be convex (not concave) to the oncoming flow if a sonic surface is to exist downstream of the reaction zone. The author has never observed concave detonation fronts with a thickness smaller than the radius of curvature, whereas convexities are usually prominent (see Figs. 4 and 5).

If one takes seriously the possibility of unsteady detonations as the rule, rather than the exception, one can consider spinning detonation as only a slightly abnormal, rather than pathological, wave. Since it is the one unsteady wave with some regularity of structure which can be

understood, it would be profitable in general to devise a comprehensive theory explaining its origin and mode of excitation.

While the relationship of wave velocity and stability (i.e., spin and extinction) to tube diameter, reaction time (i.e., initial pressure) and composition are qualitatively known, we have no conclusive evidence of the appropriate scaling rules relating these quantities -- even empirical ones. It is true that the velocity deficit is accurately understood, but that is not a major property of the wave itself. It would appear that a well-documented clinical study of a single system, such as oxygen-hydrogen, which systematically determined these effects and simultaneously observed the wave structure, would be of immense value in illuminating this problem.

Perhaps the fundamental problem of detonation wave structure is the question of the basic stability or instability of these waves. Shchelkin (48) has recently given some attention to the possibility of instabilities, but it is clear that much more work needs to be done, both experimental and theoretical. Until this is done, one can hardly claim to have a satisfactory scientific understanding of detonation waves.



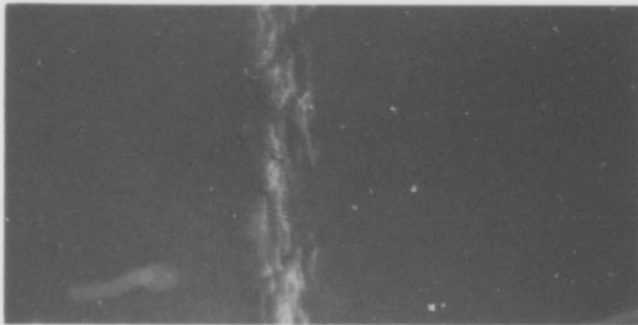


Figure 2

Schlieren photograph (44) of a $2\text{H}_2 + \text{O}_2$ detonation at 60 mm. initial pressure in a 5 cm. square tube. The wave moves from right to left.

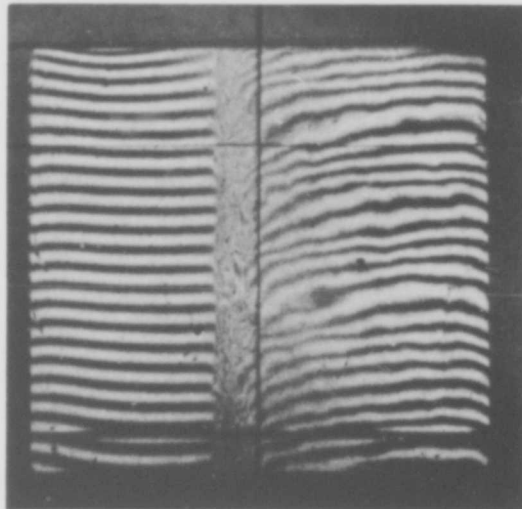


Figure 3

Interferogram (40) of a $2\text{H}_2 - \text{O}_2$ detonation at 78 mm. initial pressure in an 8 cm. square tube (Wave moves toward left).

Note the random character of the interference pattern within the combustion zone.

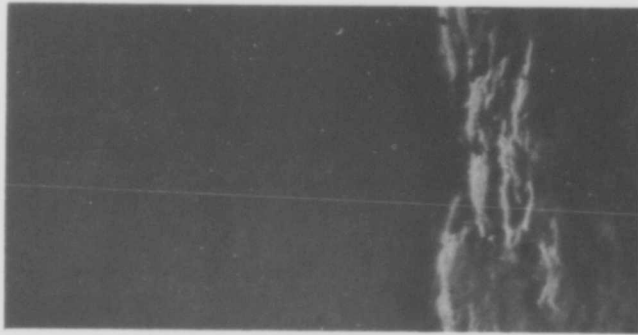


Figure 4

Schlieren photograph (44) of a 20 per cent C_2H_2 - 45 per cent O_2 - 35 per cent A detonation at 30 mm. initial pressure.

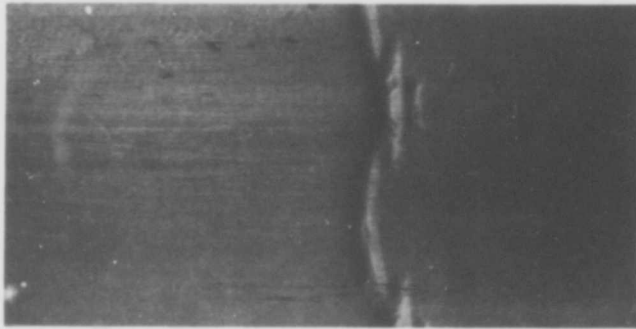


Figure 5

Schlieren photograph (44) of a decaying detonation wave in a 20 per cent C_2H_2 - 45 per cent O_2 - 35 per cent A mixture at 2 mm. initial pressure. The wave is travelling from right to left in a 5 cm. square channel at about half the C-J velocity.

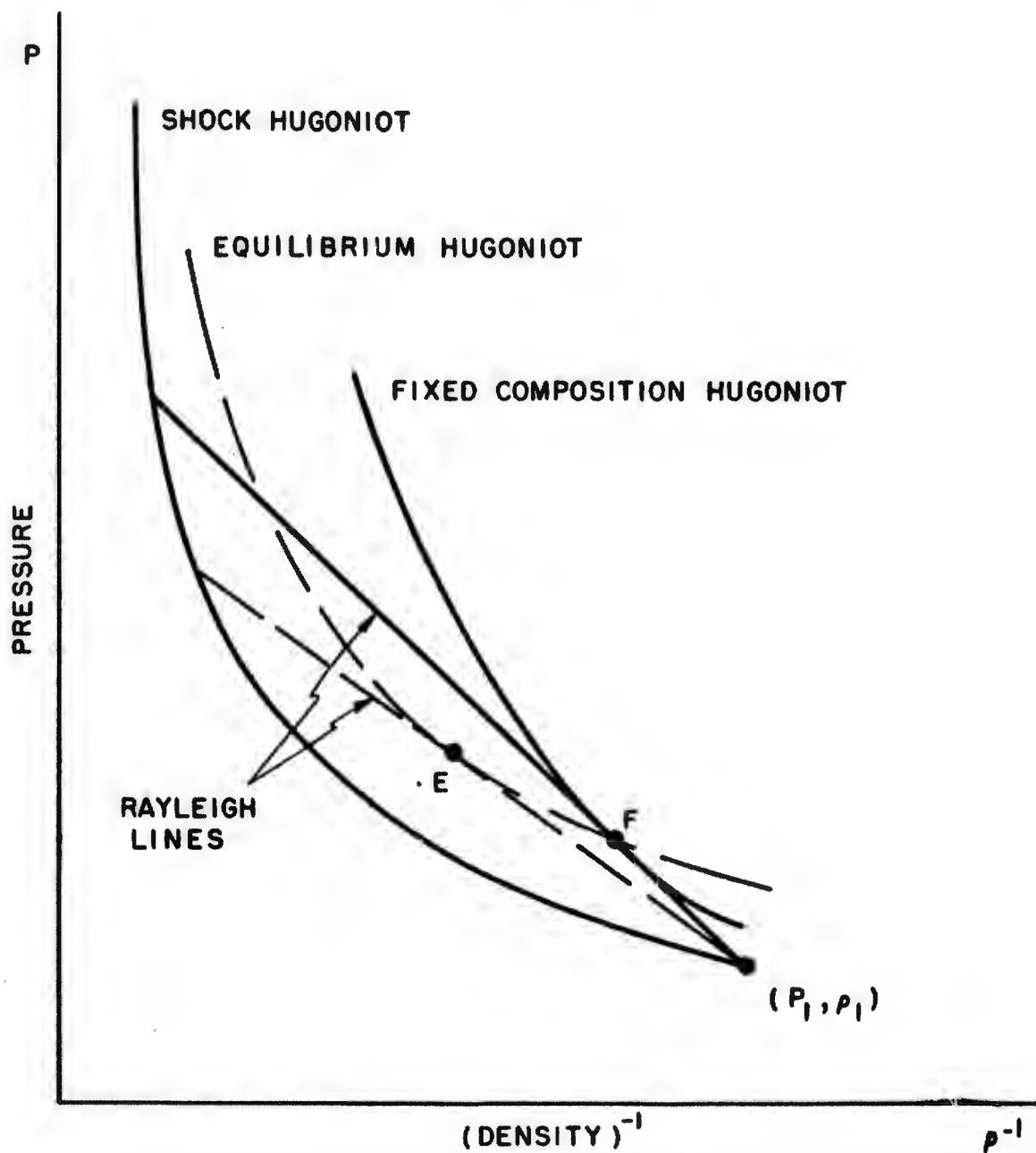


Figure 6

A plot of Rayleigh and Hugoniot curves in the p, ρ^{-1} plane for a steady, one-dimensional flow. Points E and F are the tangent points of the Rayleigh and Hugoniot curves for equilibrium and fixed composition, respectively.

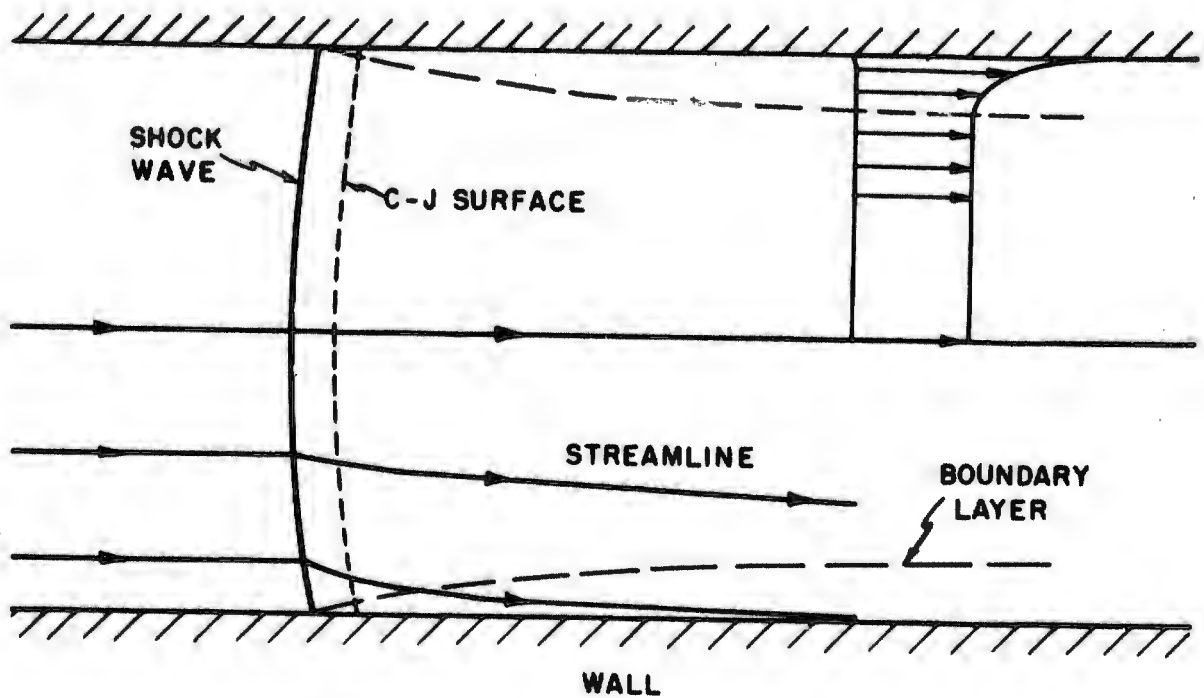


Figure 7

A sketch of the two-dimensional flow behind a detonation wave caused by the growth of a boundary layer in the burned gases at the tube wall. The flow is depicted for a coordinate system fixed in the wave front. The front is convex to the oncoming flow, causing the streamlines to diverge. The flow behind the C-J surface becomes increasingly supersonic due to the streamline divergence.



Figure 8

Schlieren photograph (44) of a detonation wave in a mixture of 20 per cent C_2H_2 , 45 per cent O_2 and 35 per cent A at 570 mm. initial pressure. The oblique compression wave pattern is stationary with respect to the detonation front. In a steady flow of Mach number 1.10, the Mach lines would be parallel to the oblique pattern of the photograph.

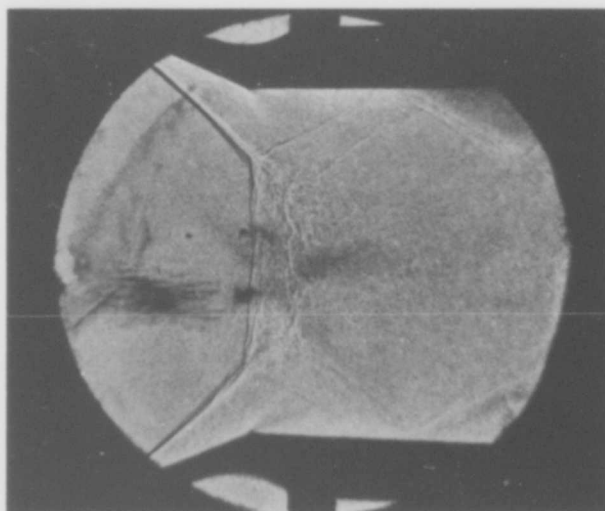


Figure 9

Schlieren photograph of a hydrogen-air standing detonation wave in a closed combustion tunnel (22). Steady flow from left to right. Compare with Figures 2 and 4.

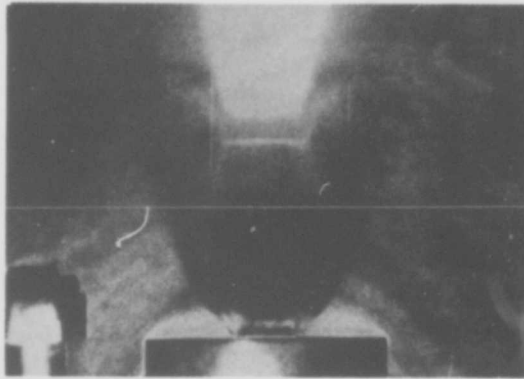


Figure 10

Combined visible and schlieren photograph of standing detonation wave in an open jet (42). Notice separation of shock wave and luminous zone.

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