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Measurement of the Chapman-Jouguet Pressure and Reaction Zone Length in a Detonating High Explosive

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The Chapman-Jouguet pressure and the reaction zone length in detonating Composition B containing 63 percent RDX at a density of 1.67 g/cc have been measured by determining the initial free surface velocity imparted to aluminum plates as a function of plate thickness. The *C-J* pressure is 0.272 megabar and the reaction zone length is 0.13 mm. The experimental free surface velocity-plate thickness curve provides powerful confirmation for the pressure profile in a detonating explosive predicted by the hydrodynamic theory of detonation proposed by Zeldovich, von Neumann, and Doring.

INTRODUCTION

IN 1945 Goranson[1] suggested that the reaction zone of a detonating solid explosive could be investigated by determining the initial free surface velocity imparted to thin metal plates as a function of plate thickness. In particular he showed that reaction zone length and Chapman-Jouguet pressure could be estimated in this way. Unfortunately, the original results obtained by Goranson are available only in a classified report from this laboratory. This paper describes similar but improved theoretical and experimental results obtained during and since 1950.

THEORY OF THE EXPERIMENT

The generally accepted picture of the structure of a steady-state, plane detonation wave was proposed independently by Zeldovich,[2] von Neumann,[3] and Döring.[4] The wave is assumed to consist of a nonreactive shock followed by a steady-state reaction zone which is terminated at the Chapman-Jouguet surface where the local flow velocity plus sound speed equals the detonation velocity. It can be shown that this condition is fulfilled at the point of tangency in the p-v plane of a straight line from the initial state to the final Hugoniot curve calculated for a fixed composition of the product gases.[5] Figure 1 shows a representation of the detonation process in the p-v plane. Reference to the laws of conservation of mass and momentum shows immediately that if viscosity and heat conduction are neglected, the succession of state points assumed by the reacting explosive is represented by the straight line from p_1v_1 to the *C-J* point. The rate at which an element of explosive passes from p_1v_1 to the *C-J* state depends on the kinetics of the reactions involved and cannot be determined from hydrodynamic considerations. It follows, therefore, that the pressure-distance profile of a detonation wave consists most probably of a monotone but otherwise unspecified decrease in pressure from p_1 to $p_{C\text{-}J}$ in an unspecified distance. Two profiles often considered are shown qualitatively in Fig. 2. They correspond to a reaction rate determined by grain burning and to a rate determined by a first or second order adiabatic reaction of the Arrhenius type. The unsteady flow behind the Chapman-Jouguet plane has been investigated by Taylor.[6] This flow may be simply described as a rarefaction wave ending either in cavitation or in a steady-state region required to match

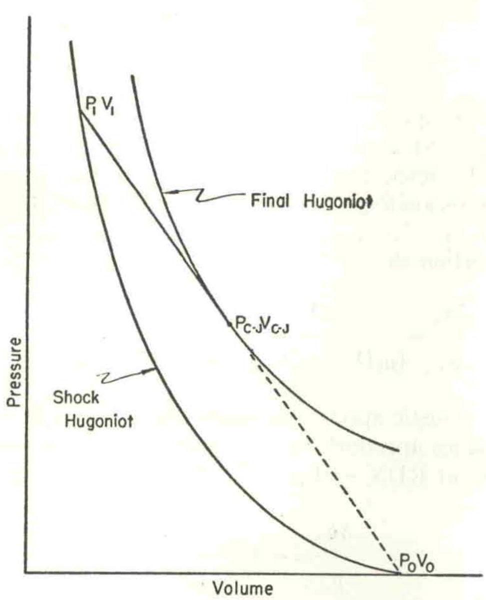

FIG. 1. A representation of the detonation process in the pressure-volume plane.

[1] R. W. Goranson, Classified Los Alamos Report LA-487.
[2] Y. B. Zeldovich, J. Exptl. Theoret. Phys. (USSR) **10**, 542 (1940).
[3] J. von Neumann, O.S.R.D. Report No. 549, (1942).
[4] W. Döring, Ann. Physik **43**, 421 (1943).
[5] More specifically, the *C-J* point is the tangent point on a Hugoniot curve for the product gases whose composition is assumed fixed at the equilibrium values appropriate for the tangent point. The relation of this statement of the Chapman-Jouguet condition to the usual statement, namely, that the *C-J* point is the tangent point on a Hugoniot every point of which is in chemical equilibrium, is not clear at the moment because of uncertainties in the equation of state of the detonation products. The former statement can be derived from a recent theoretical investigation of the structure of a steady-state plane detonation wave by Kirkwood and Wood, J. Chem. Phys. **22**, 1920 (1954). It should be mentioned that this statement of the *C-J* condition has been shown to apply to all detonations which are not pathological in the von Neumann sense. Finally, no pathological detonation has yet been observed.
[6] G. I. Taylor, Proc. Roy. Soc. (London) **A200**, 235 (1950).

boundary conditions at the back boundary of the explosive products.

When a plane detonation wave is incident normally on a metal plate, a shock wave is transmitted into the metal which is followed by a rarefaction wave corresponding to the pressure drop in the reaction zone of the explosive. The foot of this rarefaction wave will travel with a velocity equal to the sum of the local flow velocity and sound speed. It will overtake the shock in the metal after the shock has been attenuated by the rest of the rarefaction wave. The strength of the shock wave will decrease relatively quickly as this interaction proceeds because of the small thickness of the reaction zone. As a result, the velocity imparted to a thin metal plate, which depends directly on the strength of the shock in the plate, should change with plate thickness qualitatively as shown in Fig. 3.

It has been shown that to a very good approximation the shock particle velocity of a metal in the high

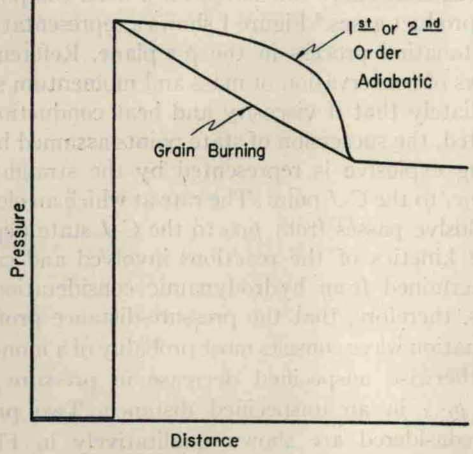

FIG. 2. Two representative pressure profiles for the reaction zone of solid explosives.

explosive pressure range is one-half of the free surface velocity.[7] This fact makes it possible to determine the Chapman-Jouguet pressure in the explosive from the free surface velocity of a metal plate corresponding to the end of the interaction caused by the reaction zone. This velocity is v in Fig. 3. An immediate consequence of the laws of conservation of mass and momentum is that the pressure behind a shock wave moving into a medium at rest is

$$p=\rho_0 uD, \tag{1}$$

where ρ_0 is the density of the unshocked material, u is the shock particle velocity, and D is the shock velocity. In all of the experiments discussed in the next section the metal used was aluminum or dural. For these materials Walsh[7] has determined experimentally a relation between shock velocity and free surface velocity

[7] J. M. Walsh and R. H. Christian, Phys. Rev. 97, 1544 (1955).

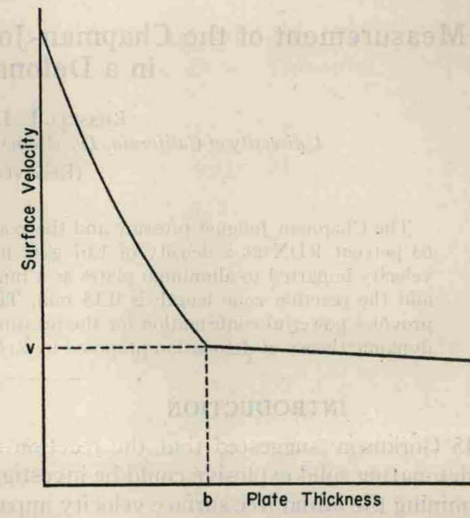

FIG. 3. Free surface velocity of a metal plate as a function of plate thickness showing the high velocity produced in thin plates by the von Neumann spike in the explosive.

in an investigation of the equation of state of the metals. The pressure in the metal can therefore be determined from the measured metal density, the free surface velocity, and this relation.

By applying the usual boundary conditions of equality of pressure and continuity of flow velocity at the interface between explosive and metal, the following expression can be developed relating incident pressure in the explosive to transmitted pressure in the metal:

$$\frac{p_m}{p_x}=\frac{\rho_2 D_2}{\rho_1 D_1}\left(\frac{\rho_1 D_1+\rho_3 D_3}{\rho_2 D_2+\rho_3 D_3}\right). \tag{2}$$

The subscripts 1, 2, and 3 refer to the properties of the undetonated explosive, the metal, and the explosive products, respectively. The pressure in the explosive, p_x, corresponding to the Chapman-Jouguet state can now be calculated if $\rho_3 D_3$ is known. An error analysis of this relation shows that

$$\frac{\delta p_x}{p_x}=\frac{(\rho_1 D_1-\rho_2 D_2)\rho_3 D_3}{(\rho_1 D_1+\rho_3 D_3)(\rho_2 D_2+\rho_3 D_3)}\frac{\delta(\rho_3 D_3)}{\rho_3 D_3}.$$

If the acoustic approximation is made that $\rho_1 D_1=\rho_3 D_3$ and values appropriate for Composition B (nominally 60 percent RDX−40 percent TNT) are inserted, then

$$\frac{\delta p_x}{p_x}=-0.1\frac{\delta(\rho_3 D_3)}{\rho_3 D_3}.$$

Thus it is clear that the Chapman-Jouguet pressure is quite insensitive to the value of $\rho_3 D_3$ assumed. Furthermore, the acoustic approximation is correct insofar as the velocity of the reflected shock can be assumed equal to the velocity of a rarefaction wave in the product