caused by the composition and density fluctuations within a given charge. The average values of the velocities measured are presented in Table I. These data are also presented in Fig. 8.

Two subjects deserve comment before conclusions are drawn from this data. First, the standard deviations reported in Table I are unfortunately large. However, this large standard deviation arises mainly from a systematic source. As discussed above, velocities are determined from measurements of position and time of the metal free surface by means of pins set in a circle. If the metal surface is not perfectly plane and if it does not move perfectly parallel to its initial position, a systematic error in the arrival time of the surface at each pin will be introduced which may be reflected into the surface velocity as determined by least squares techniques. It can be shown that the velocity calculated is related to the true velocity as follows:

$$V=V_{\text{calc}}\left(1+\frac{R\alpha}{d}\epsilon\sin\theta\right),$$

where R is the radius of the pin circle, d is the incremental pin spacing, α is the angle of tilt of the surface, ϵ is a constant $=0.11$ for the pin geometry used in these experiments, and θ is an angle which describes the orientation of the pin circle with respect to the tilted wave. A wave tilt of as much as 0.03 radian was observed for some of the charges used. Therefore, this cause alone could produce a velocity error of 15 percent in plates 0.030 in. thick or thinner and $7\frac{1}{2}$ percent for thicker plates. For this reason many measurements were made, especially on the thinner plates, so as to obtain a reliable value for the average velocity.

Second, it is desirable to place all of the pins close enough to the free surface so that the velocity measurement can be completed before a second disturbance arrives at the surface. This was done for all but the thinnest foil. One might expect a weak shock wave to be the second disturbance to arrive at the surface giving it a small increase in velocity at about the middle of the velocity measurement. Examination of the records does not indicate a noticeable increase in velocity. However, the velocity associated with the 0.0085 in. foil may be slightly high.

Explosive Pressure

Two pressures in the explosive can be estimated from the surface velocity plot of Fig. 8. A least squares straight line has been fitted to the experimental measurements at thicknesses greater than 0.030 in. Each of the average velocities was given a weight equal to the number of measurements included. A smooth curve was drawn through the remaining four measurements on thin plates. The Chapman-Jouguet pressure can be determined from the free surface velocity

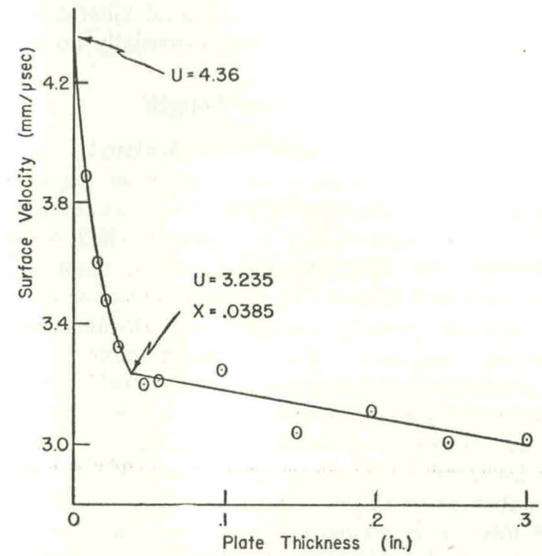

FIG. 8. Measured free surface velocity as a function of plate thickness.

indicated by the intersection of these two lines, 3.235 mm/μsec.

In the metal[11]

$$p_m=\rho_2u_2D_2$$

$$=2.71\times\frac{3.235}{2}\times7.55=0.3309 \text{ megabar.}$$

In the explosive

$$p_{C\text{-}J}=\frac{p_m(\rho_1D_1+\rho_2D_2)}{\rho_2D_2}=0.272 \text{ megabar.}$$

Thus the Chapman-Jouguet pressure in Composition B explosive containing 63 percent RDX at a density of 1.67 g/cc is 0.272 megabar. This number is thought to be correct to within 2 percent.

The extrapolation of the free surface velocity to zero plate thickness in what is thought to be a reasonable manner gives a limiting velocity of 4.36 mm/μsec. From this number and the extrapolation of the equation of state data for aluminum made by Fickett, a peak pressure in the explosive of 0.385 megabar is estimated for the von Neumann spike. It is interesting to note that the spike pressure appears to be only 1.42 the Chapman-Jouguet pressure. It should be emphasized that the extrapolation to zero thickness is only what appears to be a reasonable one. There is no theoretical justification for the assumed form of the curve because the form

[11] The equation of state data of Walsh, see reference 7, has been analyzed by Fickett (unpublished communication). An analytic form of the equation of state was derived which agreed with Walsh's data at low pressures and with Fermi-Thomas-Dirac calculations at high pressures. The following fit of shock velocity as a function of free surface velocity is appropriate for the pressure range of interest in these experiments:

$$D=4.8375+1.1235u-0.1095u^2+0.0066u^3.$$

depends on the details of the chemical kinetics of the detonation reaction about which essentially nothing is known.

Reaction Zone Length

The reaction zone length was calculated from Eq. (4) using a value of D_2 determined from the experimental results as required by Eq. (5). α was determined from the two values of interface velocity which could be estimated from the experimental data, namely, the initial and final values. The assumption was made that the interface velocity changed with distance in the same way the shock velocity did. A value of u_2+c_2 was obtained from the equation of state calculation for aluminum made by Fickett. The actual numbers used are as follows: $D_1=7.868$, $D_2=7.771$, $u_2+c_2=9.065$ mm/μsec, and $\alpha=0.232$; giving $a/b=0.139$. b was estimated to be 0.0385 in. Therefore, $a=0.005$ in. or 0.13 mm. This estimate of reaction zone length of slightly greater than one-tenth of a millimeter is probably accurate to within 20 percent except for the possible errors discussed below.

Two assumptions have been made in the estimation of reaction zone length. First the shock wave reflected from the metal back into the explosive has been ignored. This assumption is questionable because the changes in temperature and pressure caused by the wave may decisively influence the kinetics in the as yet unreacted explosive into which it moves. Therefore, the value of reaction zone length determined is probably best described as a lower limit value.

The effect of this reflected shock wave on the detonation kinetics and reaction zone length could be investigated by varying the metal used in experiments of this type. In particular, the effect could be maximized by using a heavy material like brass which has a large acoustic impedance and minimized by using magnesium which is almost a perfect impedance match for Composition B.

The second assumption concerns the shape of the reaction zone. The experimental results have been represented by a profile similar to that of a rarefaction wave in an inert material. However, as discussed above, there could be a slow reaction tail which would cause true reaction zone length to be somewhat longer than that indicated.

TABLE I. Measured free surface velocity as a function of plate thickness.

Plate thickness (in.)	Average velocity (mm/μsec)	Standard deviation of the mean (mm/μsec)	Number of measurements
0.0085	3.89	0.34	12
0.016	3.60	0.26	15
0.021	3.48	0.25	11
0.030	3.32	0.10	11
0.048	3.20	0.20	10
0.057	3.22	0.02	2
0.098	3.25	0.09	8
0.150	3.04	0.06	4
0.198	3.11	0.07	6
0.248	3.01	0.09	4
0.300	3.02	0.04	4

CONCLUSIONS

A conclusion can be drawn from the data presented above which is fundamental to the understanding of the detonation phenomenon. Namely, the experimental results provide powerful confirmation for the hydrodynamic theory of the detonation process proposed by Zeldovich, von Neumann, and Döring. In fact, this is thought to be the first experimental evidence published which directly verifies this theory which has, however, attained almost universal acceptance because of its hydrodynamic completeness.

The Chapman-Jouguet pressure in Composition B explosive containing 63 percent RDX at a density of 1.67 g/cc was measured to be 0.272 megabar. The reaction zone length for the same explosive is 0.13 mm.

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