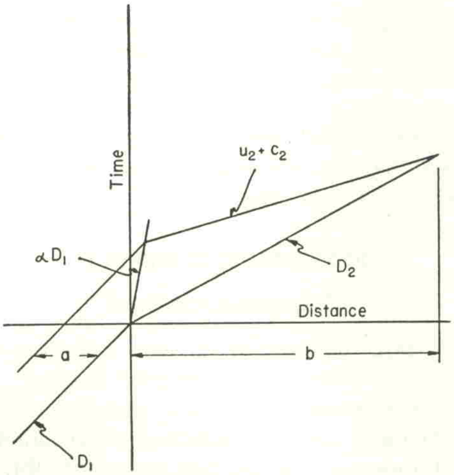

FIG. 4. Distance-time representation of the interactions between the von Neumann spike in the explosive and the metal plate.

gases. Therefore, to a good approximation

$$p_m/p_x=2\rho_2D_2/(\rho_1D_1+\rho_2D_2). \tag{3}$$

An estimate of the reaction zone length can be made from a determination of the distance required for the end of the rarefaction corresponding to the Chapman-Jouguet plane to overtake the shock wave in the metal. This distance is b in Fig. 3. If it is assumed that the metal is a perfect impedance match to the explosive so that no wave is reflected back into the explosive, an $x-t$ representation of the interaction will be as shown in Fig. 4. The interface is initially assumed to be at $x=0$. A detonation wave comes in from the left with a velocity D_1. The reaction zone length is a. The velocity of the interface through the reaction zone is αD_1, the shock velocity in the metal is D_2, and the velocity of the foot of the rarefaction wave is u_2+c_2. D_2 and α will vary as the interaction proceeds. The values used in the formula below and those indicated in Fig. 4 are the appropriate average values. As long as the flow behind the shock can be considered isentropic (a good approximation), u_2+c_2 depends only on pressure and is the value corresponding to the C-J state transmitted into the metal. Simple analytical geometry leads to the following relation between the reaction zone length in the explosive and the interaction distance in the metal:

$$a=b[D_1(u_2+c_2-D_2)(1-\alpha)][D_2(u_2+c_2-\alpha D_1)]^{-1}. \tag{4}$$

The appropriate average value of D_2 can be determined from the free surface velocity-plate thickness relation since at every value of thickness this relation gives the corresponding shock velocity by using the equation of state. It can easily be seen that the appropriate average to be used in the above equation is the inverse average; i.e.,

$$D_2=\left(\frac{1}{b}\int_0^b \frac{dx}{D(x)}\right)^{-1}. \tag{5}$$

Likewise α should be determined from a similar inverse average of the interface velocity.

It is possible to calculate in detail the free surface velocity as a function of plate thickness by using the procedure outlined by Courant and Friedrichs[8] under the assumption mentioned above; namely, that the flow behind the shock can be considered isentropic. In particular, if the reaction zone rarefaction and the Taylor wave are both assumed to be centered rarefaction waves, and if a ratio of explosive charge length and reaction zone length is assumed, the ratio of slopes of the free surface velocity-thickness curve for the two waves at the point corresponding to the end of the reaction zone can be calculated. This ratio is about 25 if the charge length is 200 times the reaction zone length and if the spike pressure is 1.5 times the Chapman-Jouguet pressure. In practical cases the ratio of charge length to reaction zone length is much greater than 200 so the change of slope would be even larger than indicated above. This calculation justifies the sharp change in slope of the free surface velocity-plate thickness curve shown in Fig. 3.

It should be remembered that it was assumed in this calculation that the reaction zone rarefaction could be approximated by a centered rarefaction wave. However, most reaction rate expressions show that equilibrium is approached asymptotically in time. If such expressions are appropriate for solid explosives, and there is no experimental evidence that they are, the ratio of slopes could conceivably approach unity. However, the long reaction tail predicted by these kinetic expressions corresponds to a very small percentage of the total detonation reaction, and a rapid rate of change of slope would be expected not at a plate thickness corresponding to the C-J state but at a thinner one, corresponding to essentially complete reaction.

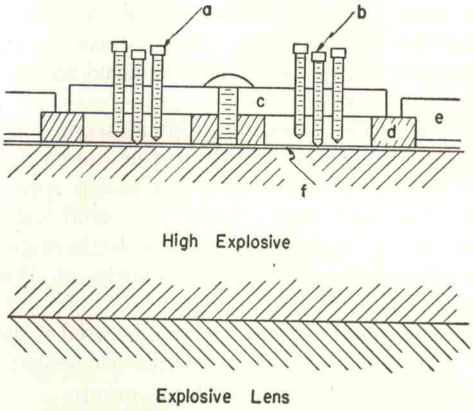

FIG. 5. Cross section of an experiment to determine the free surface velocity of a very thin plate or foil. (a) 0–80 pointed steel screws used as surface velocity pins. (b) Center ground contact pin also used to hold foil against the high explosive. (c) Texalite pin mounting plate. (d) Aluminum backing plate $3\frac{1}{4}$ in. o.d., $\frac{1}{4}$ in. thick. (e) Blast shield 8 in. o.d., $\frac{3}{8}$ in. thick. (f) Aluminum foil.

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[8] R. Courant and K. O. Friedrichs, *Supersonic Flow and Shock Waves* (Interscience Publishers, Inc., New York, 1948), p. 164.

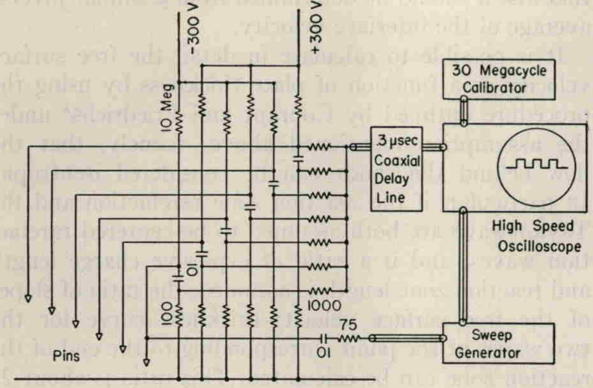

FIG. 6. Electronic circuitry used to measure free surface velocity. The component values are the same for all circuits. Resistance values are ohms and capacitor values μfd unless otherwise indicated.

EXPERIMENTAL TECHNIQUE

Free surface velocity was measured by recording the time of arrival of the metal surface at a series of metal contactors or pins. The technique used is identical with that described by Minshall.[9] In these experiments two or in some cases four velocity measurements were made in each experiment by using either two or four groups of pins each consisting of six pins set in a $\frac{1}{4}$-in. diameter circle. The spacing between pins measured perpendicular to the free surface was 0.003 in. for the thin plates 0.030 in. thick and under, and 0.006 in. for all thicker plates. A cross section through a thin foil experiment is shown in Fig. 5.

The electronic circuitry used is indicated in Fig. 6. As each pin is shorted to the moving plate, a condenser is discharged through the network producing a signal on the oscilloscope. Successive pins have alternate polarities so that an ideal record would resemble the square wave indicated in the figure. A time base is provided by a trace from an accurately calibrated 30-megacycle crystal oscillator displaced slightly from the velocity record.

The high-speed recording oscilloscopes used in these experiments were similar to the system described by the Radiation Laboratory.[10] A sweep speed of 10 in./μsec was used and twenty thousand volts post acceleration was required in order to obtain single traces intense enough to photograph clearly at this high writing speed.

A photograph of a setup ready to be used is shown in Fig. 7. The pulse-forming networks are sealed in the plastic blocks located near each pin group.

Precautions were necessary to eliminate two possible sources of error. The shock wave in air preceding the free surface was strong enough to discharge the pin circuits before the arrival of the surface. This difficulty was eliminated by maintaining a methane atmosphere around the pins. If velocity measurements were made on a machined and polished surface, the first several pins were often discharged prematurely by what appeared to be a fine spray of metal jetted out from the surface. This spray was eliminated by using unworked surfaces whenever possible and covering the surface with a very thin, almost invisible coating of light oil.

EXPERIMENTAL RESULTS

Experimental Data

Thirty-three separate experiments were performed in which eighty-seven measurements of free surface velocity were made. In the first twelve of the experiments the metal used was dural and the remainder pure aluminum was used. Walsh[7] has shown that the particle velocity-shock velocity relationship is identical within experimental error for both metals. The explosive was Composition B which was cast into large blocks and then machined into pieces $5\frac{1}{2}$ in.×$5\frac{1}{2}$ in.×3 in. The composition and density of the explosive varied by roughly 2 percent RDX and 0.01 g/cc from charge to charge and within a given charge. These charges were prepared in 1950 and are not of as high a quality as those prepared currently.

All of the experimental results were corrected to the following standard conditions: metal density = 2.71 g/cc; explosive density 1.67 g/cc; explosive composition 63 percent RDX; and detonation velocity 7.868 mm/μsec. The following error expression was used in this correction:

$$\delta u_2/u_2 = -0.861\delta\rho_1 - 0.0023\delta \text{ percent RDX} + 0.192\delta\rho_2.$$

In most cases the corrections made velocity changes of less than 1 percent. A random error of $1\frac{1}{2}$ percent is

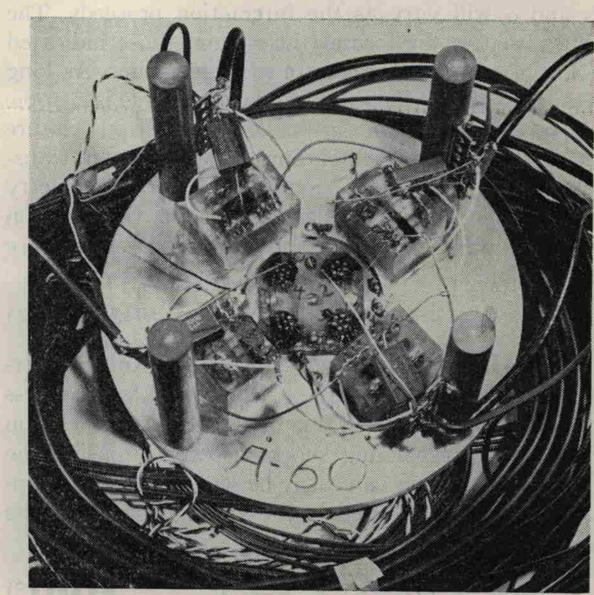

FIG. 7. A photograph of an experiment ready to be fired.

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[9] F. S. Minshall, J. Appl. Phys. 26, 463 (1955).

[10] M.I.T. Radiation Laboratory Report No. 1001 (1946).