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CHAPMAN-JOUGUET PRESSURES OF SEVERAL PURE AND MIXED EXPLOSIVES

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CHAPMAN-JOUGUET PRESSURES OF SEVERAL PURE AND MIXED EXPLOSIVES

By N. L. Coleburn

ABSTRACT: The Chapman-Jouguet pressures and reaction product isentropic exponents of fifteen pure and mixed explosives were measured. Smear camera shadowgraphs were made of cylindrical shock waves these explosives transmit into water. From these measurements and the water shock Hugoniot, the co-ordinates of the intersection point were determined in the pressure-velocity plane between the water shock wave and the rarefaction wave reflected back into the detonation products. The isentrope passing through the Chapman-Jouguet pressure-volume point was obtained assuming the products obey a polytropic equation of state (PV^k = constant).

Chapman-Jouguet pressures of 187.2 kilobars, 264.1 kilobars, and 245.5 kilobars respectively were measured for cast charges of TNT, Composition B and pentolite. Pressed charges of RDX at 1.63 g/cm^3, PETN at 1.568 g/cm^3, and Tetryl at 1.614 g/cm^3 gave detonation pressures of 283.7 kilobars, 239.9 kilobars, and 226.4 kilobars respectively.

PUBLISHED SEPTEMBER 1964

NOLTR 64-58 25 June 1964

Chapman-Jouguet Pressures of Several Pure and Mixed Explosives

The work described in this report is a part of that undertaken to determine the detonation pressures of military explosives by a convenient experimental method. This work was done in the Explosion Dynamics Division of the Explosions Research Department under Task No. RUME-4E-000/212-1/F008-08-11 Problem Assignment No. 002.

It is hoped the results will be of interest to those who are concerned with the theoretical as well as practical applications of detonation parameters to problems in warhead design and underwater explosion effects.

The author is very grateful to Dr. S. J. Jacobs for his inspiration and advice; Dr. H. Sternberg, H. Hurwitz and W. A. Walker for many helpful discussions and the computer computations. W. A. Brown and E. H. Duck gave invaluable assistance in the experiments.

R. E. ODENING
Captain, USN
Commander

C J Aronson
C. J. ARONSON
By direction

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LIST OF SYMBOLS

P - final pressure
V_o - initial specific volume
V - final specific volume
D - detonation velocity
u - particle velocity
s - entropy
E - energy per gram
R-H- Rankine Hugoniot
C-J- Chapman-Jouguet
c - velocity of sound
ρ - density
k - isentropic exponent
U - shock wave velocity
α - a dimensionless quantity, $= P\ (\partial V/\partial E)_P$

I. INTRODUCTION

The generally accepted theory of a steady state detonation wave is based on the following assumptions:

(1) The flow is one dimensional, obeys the conservation equations[1],

$$P_1 = \frac{1}{V_0} D u_1 \,, \qquad \text{(1) Momentum}$$

$$\frac{V_1}{V_0} = \frac{D-u_1}{D} \,, \qquad \text{(2) Mass}$$

$$E_1 - E_0 = \frac{1}{2} P_1 \, (V_0 - V_1) \,, \qquad \text{(3) Energy}$$

and is independent of lateral influences when its limiting velocity is reached,

(2) The velocity of a stable, unsupported detonation wave is determined by the Chapman-Jouguet condition, $D = u_1 + c_1$, or

$$\frac{P_1 - P_0}{V_1 - V_0} = \left(\frac{\partial P}{\partial V}\right)_{R-H} = \left(\frac{\partial P}{\partial V}\right)_s \,. \qquad (4)$$

(Suffixes 0 and 1 denote conditions in the material in front of and behind the shock front respectively. The suffix, s, denotes entropy and the suffix, R-H, differentiation along the Rankine-Hugoniot curve.) The hydrodynamic theory provides in principle for the calculation of the Chapman-Jouguet (C-J) properties, i.e, velocity, density, and pressure behind the detonation wave front in any explosive. For solid explosives the detonation velocity can be measured with precision[2,3,4], the C-J density[5] and pressure[6,7,8,9,10] with somewhat greater difficulty and less precision. (C-J temperature measurements[11,12] are not necessary for analyzing the above assumptions.) This paper gives experimentally derived values of the C-J pressures of fifteen pure and mixed explosives. The C-J pressures have been determined from measurements made on the shock waves transmitted into water by the detonations of these explosives.

II. EXPERIMENTAL

METHOD

To determine the C-J pressure of an explosive, measurements are made on the shock wave its detonation transmits into an inert material placed at the end of the charge. This method requires an accurate knowledge of the equation of state of the inert material. Water, whose transparency permits continuous observation of shock wave propagation by high speed photography, is one of the most convenient of such materials, its equation of state having been the subject of intensive study[13,14,15,16,17] in recent years.

Figure 1 illustrates the experimental technique used for measuring the shock wave transmitted into water by the detonating explosive. In this method, first reported by Holton[18] and used by Cook, Keyes and Ursenbach[10], and Coleburn, Drimmer and Liddiard[19], a cylindrical explosive charge is immersed in water with its upper end protruding above the surface. When the explosive is initiated on its protruding surface by a plane-wave generator, the detonation wave from the explosive strikes the water at normal incidence, and the resulting shock wave is recorded (with backlighting) by a rotating-mirror smear camera. (The camera used in these experiments had a writing speed of 3.8 mm per microsec. Backlighting was accomplished by using a lens to collimate the light from an exploding tungsten wire.) A careful analysis of the resulting photograph (Fig. 2 is typical) yields the shock wave velocity within the water at the original water-explosive interface, at the instant the shock wave crosses this interface. The equation of state of water then produces from this number the pressure and particle velocity of the water at the same point. (The water used in the experiments of this work was distilled water at an initial temperature of 20°C.) From these values the C-J pressure of the explosive was calculated by means of the equations about to be derived.

ANALYSIS

In the following analysis, a square-step shock across the interface is assumed. The errors in this assumption are believed negligible if the conditions at the interface are considered at the time when the shock has barely penetrated into the inert material. The usual conservation equations (1-3) apply, and all processes are performed adiabatically. If u_1 is the particle velocity of the product gases at the C-J plane of a one-dimensional detonation wave, then for an isentropic expansion (Fig. 3), the particle velocity, u_p of the product gases is obtained from the Riemann relation,

$$u_p - u_1 = -\int_{\rho_1}^{\rho_p} \frac{c}{\rho}\, d\rho \quad . \tag{5}$$

An evaluation of this integral will give a value for $u_p - u_1$. Then, if u_p can be determined by independent means, u_1 can be calculated, permitting a determination of the C-J pressure. An expression is easily derived for the right-hand side of equation (5) which by further manipulation provides an equation for the C-J pressure in terms of the particle velocity and pressure of the water at the interface. This equation contains another unknown, k, the exponent in the relationship for the expansion of the reaction products along an isentrope. The equation is solved by the simultaneous use of a second equation containing k, the C-J pressure, and the known, or independently measured detonation velocity, D.

The velocity of sound, c, in the product gases at the detonation front is defined by the relation,

$$c_1^2 = V_1^2 \left(-\frac{\partial P}{\partial V}\right)_s \qquad (6)$$

with

$$P_1 >> P_0 , \quad \left(\frac{\partial P}{\partial V}\right)_s = -\frac{P_1}{V_0 - V_1} ,$$

so that

$$\frac{c_1^2}{V_1^2} = \frac{P_1}{V_0 - V_1} , \qquad (7)$$

and since from equations (1) and (2) $D^2 = \frac{V_0^2 \; P_1}{V_0 - V_1}$, one obtains

$$D = \frac{V_0}{V_1} \; c_1 = \frac{\rho_1}{\rho_0} \; c_1 \qquad (8)$$

From the isentropic equation of state

$$pv^k = A, \qquad (9)$$

one obtains

$$c_1^2 = kP_1 V_1 = Ak\rho^{k-1} \qquad (10)$$

where A and k are constants. Since $P_1 = Du_1 \rho_0$ substituting for D its equivalent, $(\rho_1/\rho_0)\, c_1$, and combining the result with equation (10) gives

$$k = \frac{c_1}{u_1} \quad . \qquad (11)$$

From the C-J assumption, $D = u_1 + c_1$, therefore

$$u_1 = D/(k+1) \qquad (12)$$

and

$$c_1 = kD/(k+1). \qquad (13)$$

Equation (10) permits a substitution of c_1 into the right-hand member of equation (5), making possible its integration with the result,

$$u_2 - u_1 = \frac{2c_1}{k-1}\left(1 - \frac{c_2}{c_1}\right) , \qquad (14)$$

where it is recalled, subscript 2 refers to the state within the product gases behind the C-J plane. Simple substitutions for u_1 and the sound velocities produce the desired relation for the C-J pressure. From equation (10),

$$\frac{c_2}{c_1} = \left(\frac{\rho_2}{\rho_1}\right)^{\frac{k-1}{2}} \tag{15}$$

and the isentropic law,

$$\frac{\rho_2}{\rho_1} = \left(\frac{P_2}{P_1}\right)^{\frac{1}{k}} , \tag{16}$$

it follows that

$$\frac{c_2}{c_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{2K}} , \tag{17}$$

and thus

$$u_2 - u_1 = \frac{2c_1}{K-1}\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{2K}}\right] . \tag{18}$$

Substituting for u_1 and c_1 their values in equations (12) and (13), one gets finally for the C-J pressure

$$P_1 = P_{H_2O}\left[1 - \frac{(k^2-1)u_{H_2O} - (k-1)D}{2kD}\right]^{-\frac{2k}{k-1}} . \tag{19}$$

(P_{H_2O} and u_{H_2O} have been substituted for P_2 and u_2 by working this assumption of continuity of pressure and particle velocity across the interface.)

A second equation in P_1 and k is needed to solve equation (19). This is obtained by inserting the value of u_1 from equation (12) into equation (1) yielding,

$$P_1 = \frac{\rho_0 D^2}{k+1} . \tag{20}$$

No simple explicit solution is obtained for P_1 and k and the solution is therefore obtained by iteration. This process is speeded by use of the linear impedance-matching relation[8,9,10]

$$P \doteq P_{H_2O}\,\frac{(\rho_0 U)_{H_2O} + (\rho_0 D)_E}{2(\rho_0 U)_{H_2O}} , \tag{21}$$

to produce a close (3%) first estimate of P_1, which then is applied to equation (19), etc.

III. DATA AND RESULTS

The results obtained for fifteen pure and mixed explosives are listed in Table I. Each of the explosives was formed into cylinders, 5.0-cm diameter and 15-cm long. The cast charges (designated by the suffix c in Table I) were machined to the above dimensions and detonated unconfined. Each pressed charge consisted of three machined pellets, 5.1-cm diameter, 5.0-cm long, confined in a 5.1-cm inner diameter glass tube, 15-cm long. All charges were initiated by a 5.1-cm diameter pentolite-baratol plane wave generator.

In Table I the listed detonation velocities (D) were measured* simultaneously with the shock wave velocities in the same experiment or were obtained from previous studies[3,4] which have established for $\rho_0 > 1$ g/cm^3,

$$D = D_{(\rho_0 = 1)} + \left(\frac{dD}{d\rho_0}\right)(\rho_0 - 1) \quad . \qquad (22)$$

The initial shock wave velocities, U_{H_2O}, were obtained by differentiation of the distance-time data for the first 2-cm of the shock wave travel in water as measured from the bottom face of the charge. An equation of the form, $x = a_0 + a_1 \log t$, and polynomials of the form, $x = b_0 + b_1 t + b_2 t^2 + \ldots b_n y^n$, with limiting values of n ranging from n=2 to n=6, were fitted to the x-t data and differentiated. The velocities at the explosive-water interface and at other points in the water were obtained from these equations and compared for consistency and smoothness in the decay of the water shockwave. Usually the logarithmic equation and the polynomial with n=6 gave initial values of U_{H_2O} which agreed within one percent and were judged the most reliable values for use in the determination of P_{C-J}. The corresponding pressures and particle velocities in the water were obtained from a seventh power polynomial fit[20] to the Rankine-Hugoniot data of Walsh and Rice[16], and the static compressibility measurements of Kennedy[14] and others. P_{C-J} was then obtained by use of equation (19). With the exception of PETN (pentaerythritol tetranitrate), EDNA (N, N'dinitro-ethylenediamine), Comp B (4 experiments), and TNT (5 experiments), the data given are the average results from three experiments with each explosive. The mean deviations in the initial shock velocities were less than 1.3 per cent with the exceptions of RDX (1.9 per cent) and 75/25 RDX/TNT (1.6 per cent). An error analysis of equation (19) shows that the error of 1.3 per cent in U_{H_2O} leads to 3.9 per cent error in both k and P_{C-J}. The values of P_{C-J} are given in Table I and are compared in Table II with P_{C-J} measured in previous experiments.

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*In Fig. 2 the top trace is due to light from the product gases as the detonation front propagates down the cylindrical charge to the air-water interface. The slope of this trace determines the detonation velocity of the explosive.

IV. DISCUSSION

Several previous measurements[7,8,21] have been made of the C-J pressure of TNT using the free-surface velocity method devised by Goranson[22]. Goranson and others have given theoretical proof that the free-surface velocity of a metal is, to a close approximation, twice the particle velocity at the shock front in the metal. For shock waves initiated in metals by a detonating explosive, the free-surface velocity is a function of the metal thickness. The pressure (the C-J pressure) at the end of the reaction zone in the explosive can be determined from this function and a knowledge of the Hugoniot equation of state of the metal. Using this method, Deal[7] measured 188.4 kb as the C-J pressure of pressed TNT at a density of 1.636 g/cm³ with D = 6932 m/sec. The agreement is apparently good between the value of 187.2 kb for cast TNT at ρ = 1.622 g/cm³ with D = 6790 m/sec given in Table I, and Deal's measurement. However, if one should use the relation

$$\frac{P_{C-J}\ (1)}{P_{C-J}\ (2)} = \frac{(\rho_0 D^2)\ (1)}{(\rho_0 D^2)\ (2)} \qquad (23)$$

to adjust for the well known result that at equal densities pressed TNT gives a higher detonation velocity than cast TNT, then application of the water shock method to measurements of the C-J pressure of pressed TNT would give a 5 per cent higher value (194 kb) than Deal's measurement. In this regard Deal[23] reported 209.4 kb for the C-J pressure of pressed TNT from measurements on shocks transmitted into air. Deal attributed the difference between the two measurements for pressed TNT to the failure of the polytropic gas law to hold for TNT over a widely separated range of pressures (C-J to 500 bars in air). On the other hand, Dremin[21] et al give the C-J pressure for cast TNT also at ρ_0 = 1.62 g/cm³, as 210 kb, twelve per cent higher than the measurements of this paper.

Cook, Pack and McEwan[24] have measured the C-J pressure of Composition B (60/40/1; RDX/TNT/Wax by weight) also using the water shock method. Their measurement of 230 ± 10 kb is significantly lower (13 per cent) than the 264.1 kb measured here. Deal[25] used metals and a variety of other inert materials including water to measure for Composition B (64/35/1; RDX/TNT/Wax by weight), a C-J pressure of 290.4 kb, and an isentropic exponent, k = 2.77. If the composition differences are neglected but corrections are made for the differences in detonation velocities and densities by equation (23), Deal's C-J pressure for Composition B would be about 3 per cent higher than the 264.1 kb measured here.

Good agreement is noted between the two methods employed by the U.S.A. workers to measure P_{C-J} for RDX. The free-surface velocity method used by Deal for RDX at a density of 1.80 g/cm^3 and D = 8754 m/sec, gave P_{C-J} = 341 kb and k = 3.05. Using the water shock wave measurements for RDX at ρ_0 = 1.63 g/cm^3 and D = 8341 m/sec we obtained P_{C-J} = 283 kb and k = 3.015. An extrapolation of these results using equation (23) shows the water shock measurements for RDX charges should give a P_{C-J} at 1.8 g/cm^3, about 1 per cent less than Deal's value. A similar extrapolation of the measurement of Dremin et al, of P_{C-J} = 287 kb for RDX at a density of 1.59 g/cm^3 indicates their measured detonation pressure of RDX at 1.63 g/cm^3 would be 7 per cent higher than the value measured by the water shock method.

The values of the experimentally derived isentropic exponents k, listed in Table I, range from 2.38 for EDNA to 3.74 for Baratol (73/27/1; Barium Nitrate/TNT/Nitrocellulose by weight). The value of k is often assumed equal to 3. Table I also lists values of the parameter $\alpha = P\,(\partial V/\partial E)_P$. This function is related to the C-J pressure (and k), and the derivative of the D-ρ_0 curve by the equation

$$\alpha = \frac{\rho_0 D^2}{P_{C-J}[1 + (d\ln D/d\ln \rho_0)]} - 2 \qquad (24)$$

as first derived by Jones[26] and discussed recently by Wood and Fickett[27]. The values of α in Table I range from 0.037 to 0.726. EDNA gives significantly lower α values (0.037 and 0.070), and 95/5 Trinitroaniline/Nylon (0.726) a much higher value than the usual approximation, α = 0.25.

V. CONCLUSIONS

The Chapman-Jouguet pressures of fifteen pure and mixed explosives have been determined using velocity measurements of shock waves transmitted into water by the detonation of cylindrical charges. The C-J pressures are in substantial agreement with the detonation pressures obtained from free-surface velocity measurements of explosive-propelled metal plates. In the water-shock measurements, a polytropic equation of state, PV^k = constant, was assumed for the detonation product gases. It may be concluded that this assumption adequately describes the product gas expansion from C-J pressures (~ 300 kilobars) to pressures somewhat less than 70 kilobars in water.

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TABLE I

Measured Chapman-Jouguet Parameters

Explosive	ρ_o (g/cm³)	D (m/sec)	$\frac{\rho_o}{D}\frac{dD}{d\rho_o}$	U_{H_2O} (m/sec)	P_2 (kb)	P_1 (kb)	k	α
BARATOL (c)	2.528	4990	0.9058	4475± 21	72.60	132.8	3.739	0.4866
EDNA	1.532	7639	0.6568	6462	191.8	265.9	2.375	0.0370
EDNA	1.562	7750	0.6601	6485	193.6	273.0	2.437	0.0700
PETN	1.538	7675	0.7915	5929	153.2	224.7	3.032	0.2506
PETN	1.568	7794	0.7947	6062	162.3	239.9	2.970	0.2123
RDX	1.630	8341	0.7016	6375±123	185.1	283.7	3.015	0.3491
TNT (c)	1.622	6790	0.7704	5532±17	127.6	187.2	2.994	0.2564
75/25 RDX/TNT	1.648	7952	0.6820	6364±102	184.3	275.9	2.777	0.2245
COMP B (c)	1.668	7860	0.6706	6226±28	174.1	264.1	2.801	0.2746
50/50 RDX/TNT (c)	1.627	7660	———	5914±51	152.3	231.1	3.131	———
50/50 PETN/TNT(c)	1.682	7662	0.6959	6053±79	161.5	245.5	2.925	0.3717
45/55 PETN/TNT(c)	1.677	7420	———	6026± 31	159.8	239.6	2.853	———
40/60 PETN/TNT(c)	1.673	7303	———	6040±48	161.1	238.3	2.744	———
35/65 PETN/TNT(c)	1.668	7358	———	6037±18	160.6	238.5	2.787	———
Tetryl	1.614	7581	0.6866	5886± 66	150.3	226.4	3.101	0.4292
95/5 Trinitroaniline/ Nylon	1.617	7000	0.6588	5245± 38	111.2	175.2	3.580	0.7263
Trinitrobenzene	1.644	7269	0.6450	5935± 16	146.9	219.2	2.964	0.4090

(a) All charges pressed except those marked with a subscript (c) which were cast.

(b) Three experiments were conducted for each charge in the Table except PETN and EDNA. One experiment was conducted for each listing of these latter explosives

TABLE II

P_{C-J} Values of This Work Compared with Those of Others

	TNT				RDX (pressed)			Comp B (cast)		
	This Work (cast)	Deal (7) (pressed)	Dremin (21) (cast)	Deal (23) (pressed)	This Work	Deal (7)	Dremin (21)	This Work	Cook, et al (24)	Deal (25)
ρ (g/cm^3)	1.622	1.636	1.62	—	1.63	1.80	1.59	1.668	1.68	1.714
D(m/sec)	6790	6932	—		8341	8754	8200	7860	7800	7991
P_{C-J} (kb)	187.2	188.4	210	209.4(b)	283	341	287	264.1	230±10	290.4
		194(a)			336(c)		303(d)			272(e)

(a) Corrected to ρ= 1.622 g/cm^3 by Eq. (23) page 6.

(b) Obtained from measurements on shocks transmitted in air.

(c) Corrected to ρ= 1.80 g/cm^3 by Eq. (23).

(d) Corrected to ρ= 1.63 g/cm^3 by Eq. (23).

(e) Corrected to ρ= 1.668 g/cm^3 by Eq. (23).

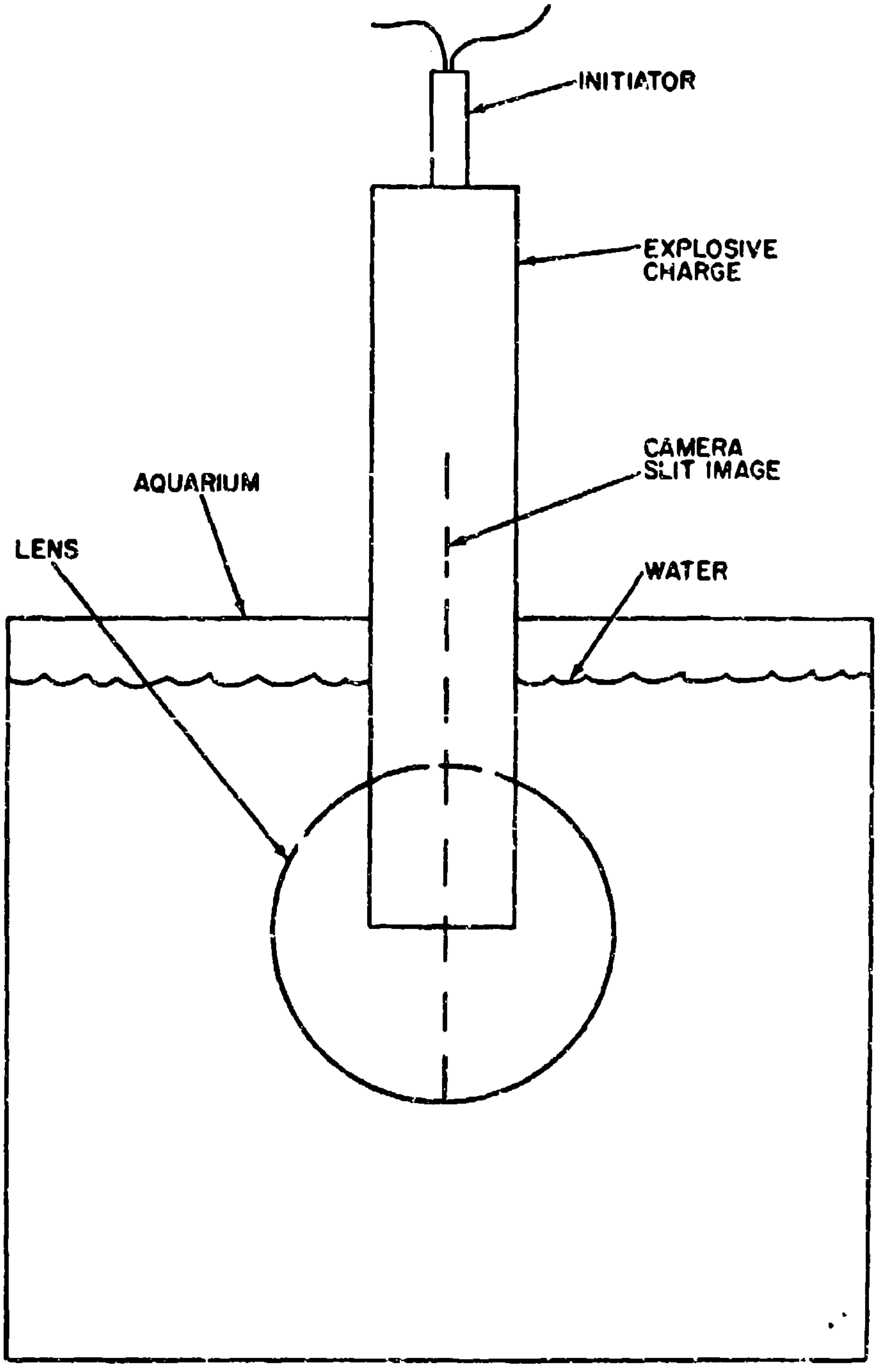

FIG. I ARRANGEMENT FOR MEASURING THE VELOCITY OF THE SHOCK WAVE TRANSMITTED IN WATER BY THE DETONATION OF A CYLINDRICAL EXPLOSIVE CHARGE.

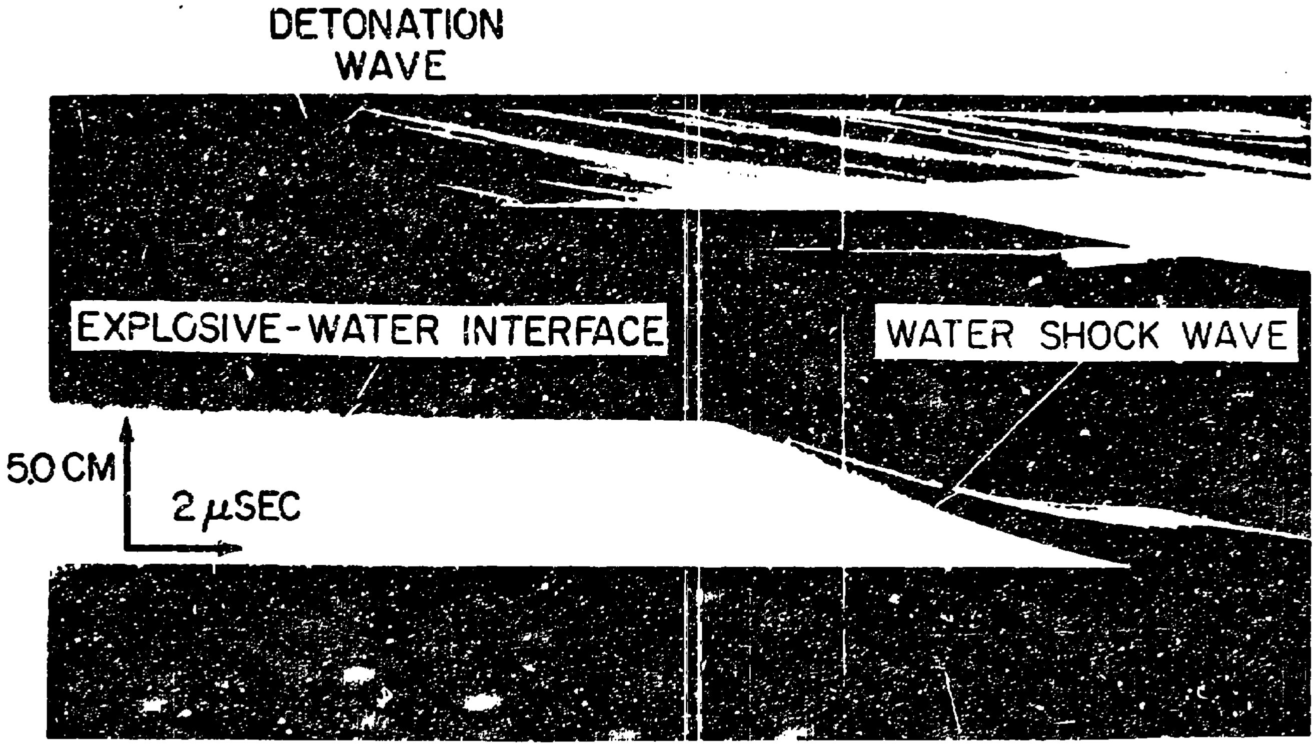

FIG. 2 SMEAR CAMERA SHADOWGRAPH OF THE SHOCK WAVE TRANSMITTED IN TO WATER WHEN THE DETONATION WAVE REACHED THE END OF A CYLINDER OF TRINITROBENZENE

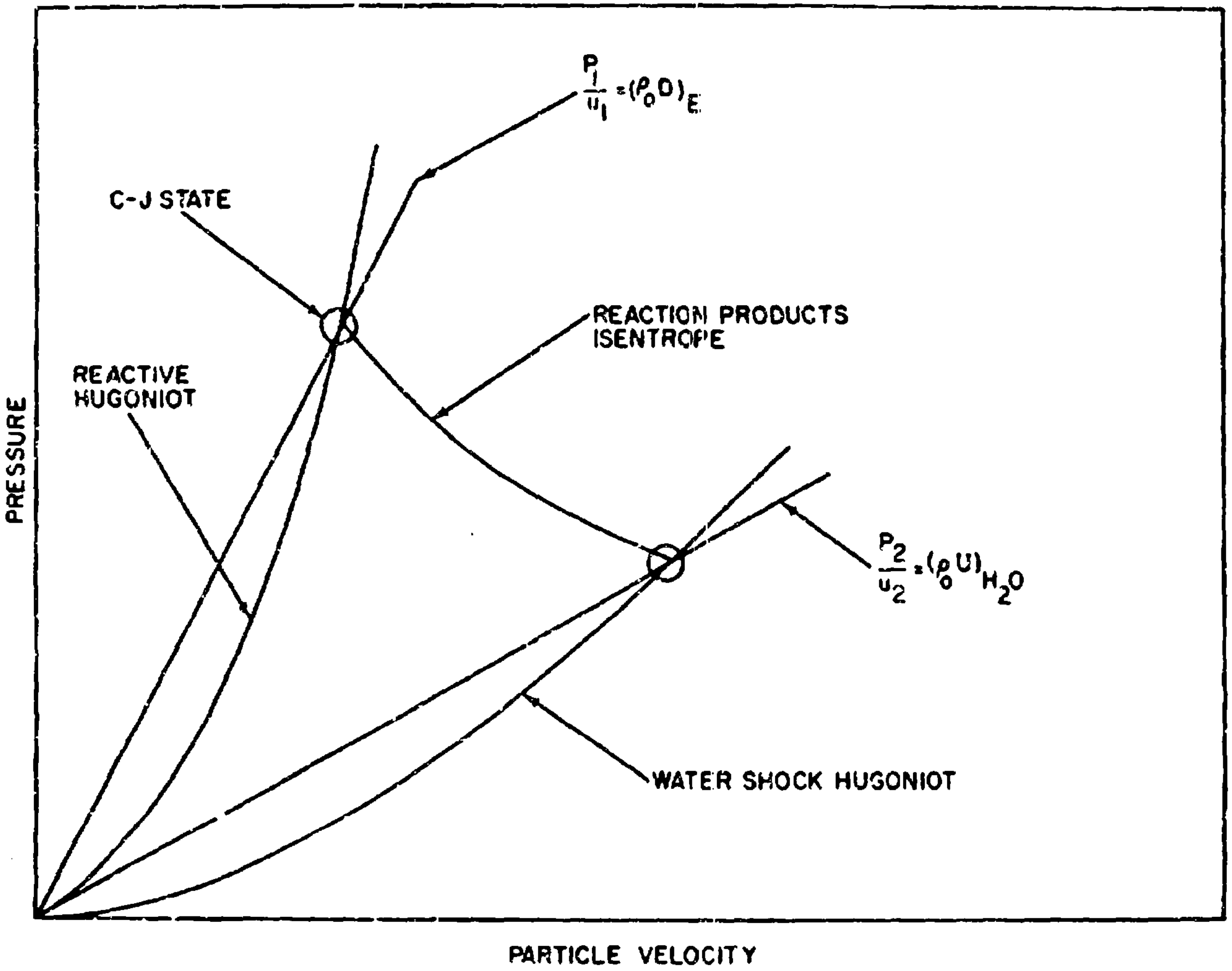

FIG. 3 PRESSURE-VELOCITY DIAGRAM