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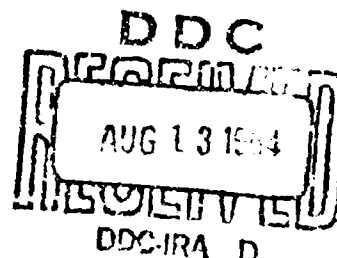
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## CHAPMAN-JOUGUET PRESSURES OF SEVERAL PURE AND MIXED EXPLOSIVES

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 ( $PV^k = \text{constant}$ ).

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<sup>3</sup>, PETN at 1.568 g/cm<sup>3</sup>, and Teteryl at 1.614 g/cm<sup>3</sup> gave detonation pressures of 283.7 kilobars, 239.9 kilobars, and 226.4 kilobars respectively.

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Chapman-Jouquet 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/P008-08-11 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. E. 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.

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By direction

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LIST OF SYMBOLS

P - final pressure  
 $V_0$  - 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  
 $\rho$  - density  
k - isentropic exponent  
U - shock wave velocity  
 $\alpha$  - 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<sup>1</sup>,

$$P_1 = \frac{1}{V_0} Du_1, \quad (1) \text{ Momentum}$$

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

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

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

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

(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<sup>2,3,4</sup>, the C-J density<sup>5</sup> and pressure<sup>6,7,8,9,10</sup> with somewhat greater difficulty and less precision. (C-J temperature measurements<sup>11,12</sup> 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

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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<sup>13,14,15,16,17</sup> 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<sup>18</sup> and used by Cook, Keyes and Ursenbach<sup>19</sup>, and Coleburn, Drimmer and Liddiard<sup>20</sup>, 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,  $u_2$ , of the product gases is obtained from the Riemann relation,

$$u_2 - u_1 = - \int_{p_1}^{p_2} \frac{c}{\rho_1} dp \quad (5)$$

An evaluation of this integral will give a value for  $u_2 - u_1$ . Then, if  $u_2$  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,

$$c_1^2 = v_1^2 \left( - \frac{\partial P}{\partial V} \right)_s \quad (6)$$

with

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

so that

$$\frac{c_1^2}{v_1^2} = \frac{P_1}{V_0 - V_1}, \quad (7)$$

and since from equations (1) and (2)  $D^2 = \frac{v_0^2 P_1}{V_0 - V_1}$ , one obtains

$$D = \frac{v_0}{v_1} \quad c_1 = \frac{v_0}{v_1} \quad c_1 \quad (8)$$

From the isentropic equation of state

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

one obtains

$$c_1^2 = k P_1 v_1^{k-1} = A k v_1^{k-2} \quad (10)$$

where  $A$  and  $k$  are constants. Since  $P_1 = D u_1 \rho_0$  substituting for  $D$  its equivalent,  $(\rho_1/\rho_0) c_1$ , and combining the result with equation (10) gives

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

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

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

and

$$c_1 = k D/(k+1). \quad (13)$$

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

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



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),

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

and the isentropic law,

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

it follows that

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

and thus

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

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

$$P_1 = P_{H_2O} \left[ 1 - \frac{(k^2-1)u_{H_2O} - (k-1)D_1}{2kD_1} \right] - \frac{2k}{k-1} \quad (19)$$

( $P_{H_2O}$  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,

$$P_1 = \frac{\rho_0 D^2}{k+1} \quad (20)$$

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<sup>8,9,10</sup>

$$P = P_{H_2O} \frac{(\rho_0 u)_{H_2O} + (\rho_0 D)_E}{2(\rho_0 u)_{H_2O}}, \quad (21)$$

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<sup>2,4</sup> which have established for  $\rho_0 > 1 \text{ g/cm}^3$ ,

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

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,  $x = b_0 + b_1 t + b_2 t^2 + \dots + b_n t^n$ , 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<sup>20</sup> to the Rankine-Hugoniot data of Walsh and Rice<sup>16</sup>, and the static compressibility measurements of Kennedy<sup>14</sup> and others.  $P_{C-J}$  was then obtained by use of equation (19). With the exception of PETN (pentaerythritol tetranitrate), EDNA (N, N'-dinicro-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.

\*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<sup>7,8,21</sup> have been made of the C-J pressure of TNT using the free-surface velocity method devised by Goranson<sup>22</sup>. 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<sup>7</sup> measured 188.4 kb as the C-J pressure of pressed TNT at a density of 1.636 g/cm<sup>3</sup> with D = 6932 m/sec. The agreement is apparently good between the value of 187.2 kb for cast TNT at  $\rho_0 = 1.622$  g/cm<sup>3</sup> with D = 6790 m/sec given in Table I, and Deal's measurement. However, if one should use the relation

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

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<sup>23</sup> 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<sup>21</sup> et al give the C-J pressure for cast TNT also at  $\rho_0 = 1.62$  g/cm<sup>3</sup>, as 210 kb, twelve per cent higher than the measurements of this paper.

Cook, Pack and McEwan<sup>24</sup> 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  $230 \pm 10$  kb is significantly lower (13 per cent) than the 264.1 kb measured here. Deal<sup>28</sup> 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.

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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  $1.80 \text{ g/cm}^3$  and  $D = 8754 \text{ m/sec}$ , gave  $P_{C-J} = 341 \text{ kb}$  and  $k = 3.05$ . Using the water shock wave measurements for RDX at  $\rho_0 = 1.63 \text{ g/cm}^3$  and  $D = 8341 \text{ m/sec}$  we obtained  $P_{C-J} = 283 \text{ kb}$  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  $1.8 \text{ g/cm}^3$ , about 1 per cent less than Deal's value. A similar extrapolation of the measurement of Dremine et al, of  $P_{C-J} = 287 \text{ kb}$  for RDX at a density of  $1.59 \text{ g/cm}^3$  indicates their measured detonation pressure of RDX at  $1.63 \text{ g/cm}^3$  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  $D-\rho_0$  curve by the equation

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

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

## 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,  $PV^k = \text{constant}$ , was assumed for the detonation product gases. It may be concluded that this assumption adequately describes the product gas expansion from C-J pressures ( $\sim 300$  kilobars) to pressures somewhat less than 70 kilobars in water.

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TABLE I  
Measured Chapman-Jouguet Parameters

| Explosive                      | $\rho_0$<br>(g/cm <sup>3</sup> ) | D<br>(m/sec) | $\rho_0 \frac{dD}{D d\rho_0}$ | $U_{H_2O}$<br>(m/sec) | $P_2$<br>(kb) | $P_1$<br>(kb) | k     | $\alpha$ |
|--------------------------------|----------------------------------|--------------|-------------------------------|-----------------------|---------------|---------------|-------|----------|
| BARATOL (c)                    | 2.528                            | 4990         | 0.9058                        | 4475 $\pm$ 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 $\pm$ 123        | 185.1         | 283.7         | 3.015 | 0.3491   |
| TNT (c)                        | 1.622                            | 6790         | 0.7704                        | 5532 $\pm$ 17         | 127.6         | 187.2         | 2.994 | 0.2564   |
| 75/25 RDX/TNT                  | 1.648                            | 7952         | 0.6820                        | 6364 $\pm$ 102        | 184.3         | 275.9         | 2.777 | 0.2245   |
| COMP B (c)                     | 1.668                            | 7860         | 0.6706                        | 6226 $\pm$ 28         | 174.1         | 264.1         | 2.801 | 0.2746   |
| 50/50 RDX/TNT (c)              | 1.627                            | 7660         | —                             | 5914 $\pm$ 51         | 152.3         | 231.1         | 3.131 | —        |
| 50/50 PETN/TNT (c)             | 1.682                            | 7662         | 0.6959                        | 6053 $\pm$ 79         | 161.5         | 245.5         | 2.925 | 0.3717   |
| 45/55 PETN/TNT (c)             | 1.677                            | 7420         | —                             | 6026 $\pm$ 31         | 159.8         | 239.6         | 2.853 | —        |
| 40/60 PETN/TNT (c)             | 1.673                            | 7303         | —                             | 6040 $\pm$ 48         | 161.1         | 238.3         | 2.744 | —        |
| 35/65 PETN/TNT (c)             | 1.668                            | 7358         | —                             | 6037 $\pm$ 18         | 160.6         | 238.5         | 2.787 | —        |
| Tetryl                         | 1.614                            | 7581         | 0.6866                        | 5886 $\pm$ 66         | 150.3         | 226.4         | 3.101 | 0.4292   |
| 95/5 Trinitroaniline/<br>Nylon | 1.617                            | 7000         | 0.6588                        | 5245 $\pm$ 38         | 111.2         | 175.2         | 3.580 | 0.7263   |
| Trinitrobenzene                | 1.644                            | 7269         | 0.6450                        | 5935 $\pm$ 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<sub>C-J</sub> Values of This Work Compared with Those of Others

|                             | TNT                 |                       |                        | RDX<br>(pressed)       |           |          | Comp B<br>(cant) |                     |           |
|-----------------------------|---------------------|-----------------------|------------------------|------------------------|-----------|----------|------------------|---------------------|-----------|
|                             | This Work<br>(cast) | Deal (7)<br>(pressed) | Dremlin (21)<br>(cast) | Deal (23)<br>(pressed) | This Work | Deal (7) | This Work        | Cook, et al<br>(24) | Deal (25) |
| $\rho$ (g/cm <sup>3</sup> ) | 1.622               | 1.636                 | 1.62                   | ---                    | 1.63      | 1.80     | 1.59             | 1.68                | 1.714     |
| D (m/sec)                   | 6790                | 6932                  | ---                    | ---                    | 8341      | 8754     | 8200             | 7800                | 7991      |
| P <sub>C-J</sub> (kb)       | 187.2               | 188.4                 | 210                    | 209.4(b)               | 283       | 341      | 287              | 230±10              | 290.4     |
|                             | ---                 | 194(a)                | ---                    | ---                    | 335(c)    | ---      | 303(d)           | ---                 | 272(e)    |

(a) Corrected to  $\rho = 1.622$  g/cm<sup>3</sup> by Eq. (23) page 6.

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

(c) Corrected to  $\rho = 1.80$  g/cm<sup>3</sup> by Eq. (23).

(d) Corrected to  $\rho = 1.63$  g/cm<sup>3</sup> by Eq. (23).

(e) Corrected to  $\rho = 1.668$  g/cm<sup>3</sup> by Eq. (23).

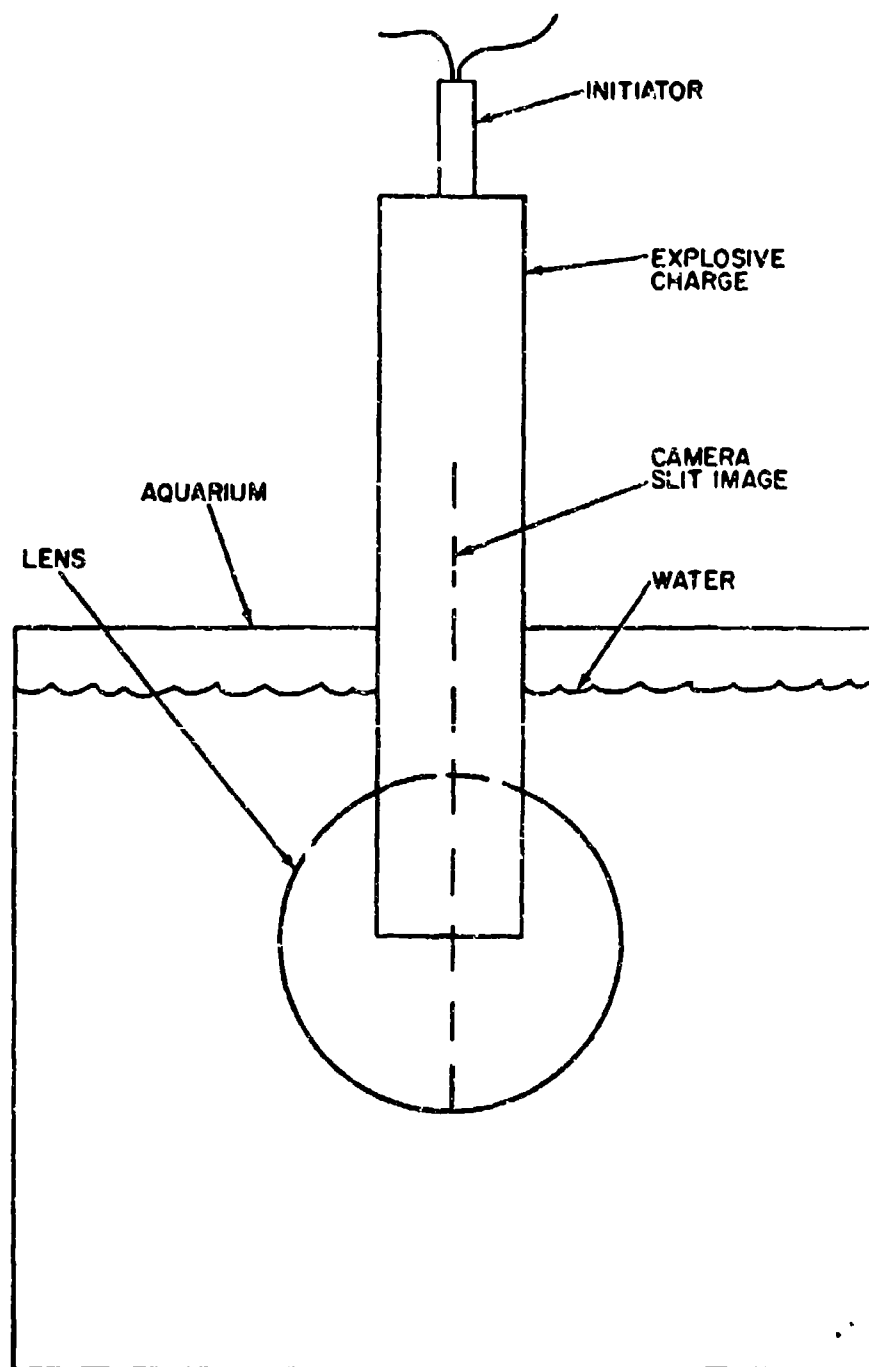


FIG.1 ARRANGEMENT FOR MEASURING THE VELOCITY OF THE SHOCK WAVE TRANSMITTED IN WATER BY THE DETONATION OF A CYLINDRICAL EXPLOSIVE CHARGE.



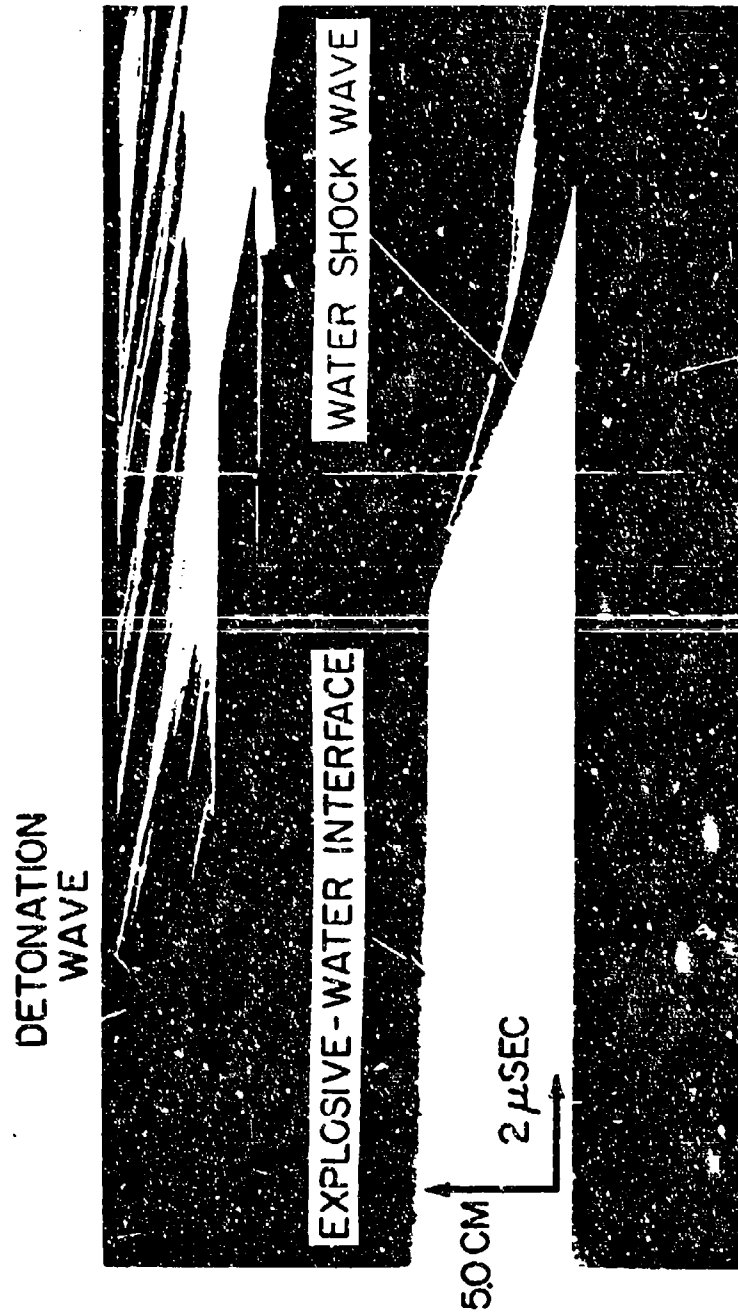
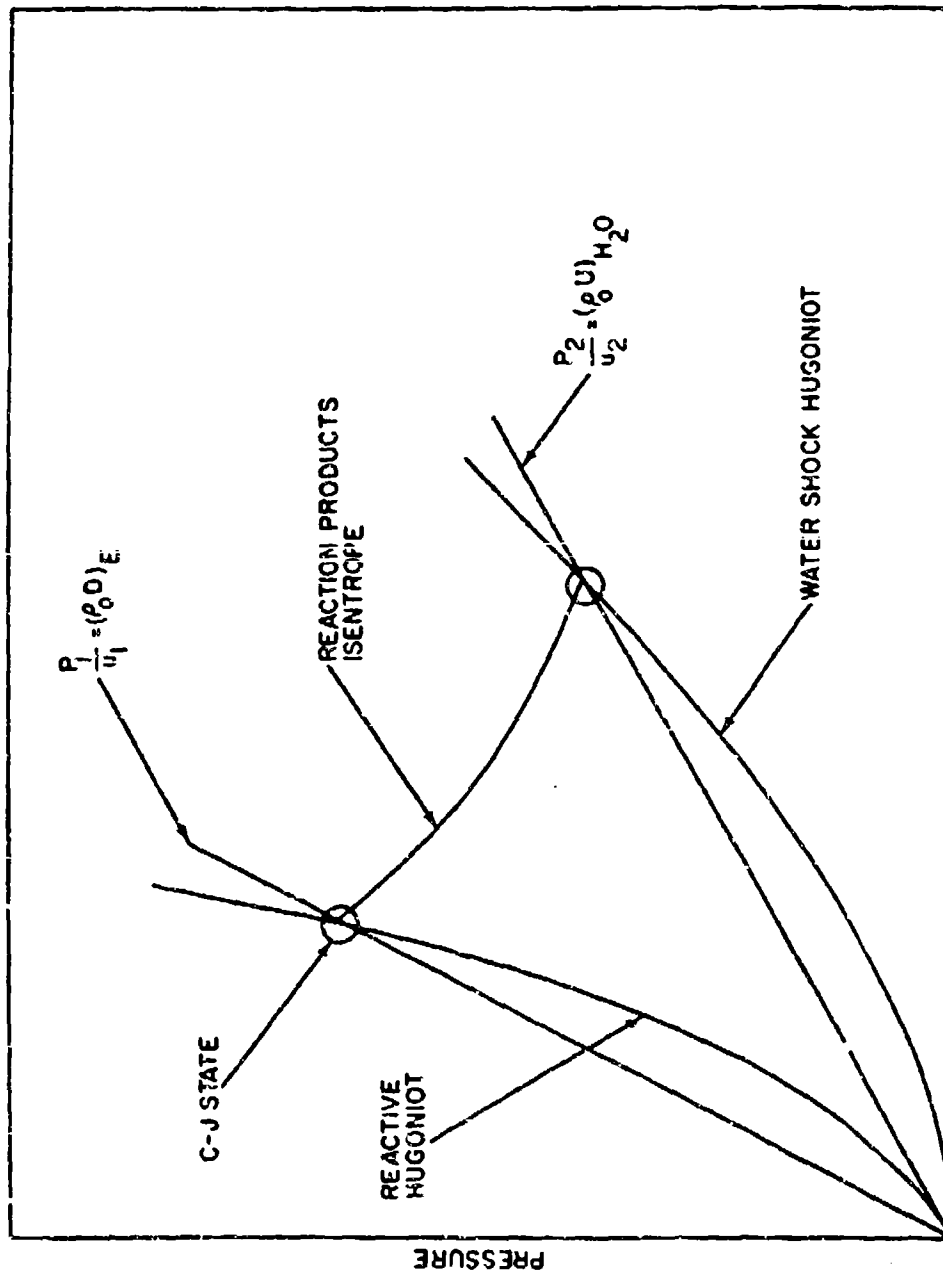


FIG.2 SMEAR CAMERA SHADOWGRAPH OF THE SHOCK WAVE  
TRANSMITTED IN TO WATER WHEN THE DETONATION  
WAVE REACHED THE END OF A CYLINDER OF  
TRINITROBENZENE



PARTICLE VELOCITY

FIG. 3 PRESSURE-VELOCITY DIAGRAM