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Measurements of Detonation Pressure*

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The "aquarium technique" is applied in the experimental determination of the equation of state for water and Lucite. Results for water are compared with similar results obtained by other methods. Measurements of the peak pressures in the detonation waves are presented for explosives of various types and rates of reaction. The peak pressures were found to be the Chapman-Jouguet or "detonation" pressures of the thermohydrodynamic theory. There was no evidence whatever for the "spike" of the Zeldovich–von Neumann model even though conditions were such that this spike would have been detected by the method employed if it were actually present, at least in the large diameter, nonideal explosives of maximum reaction zone length.

INTRODUCTION

WHEN a shock wave propagates through an undisturbed medium of density ρ_1, all the remaining shock wave parameters may be expressed uniquely in terms of any one chosen parameter if the equation of state is known. For example, pressure, temperature, and particle velocity may each be expressed uniquely in terms of the velocity of the shock wave. The fact that disturbances, even of relatively low pressure, propagate in water as shocks, coupled with the fact that water is transparent, thereby permitting convenient and continuous observation of the shock wave by a streak or framing camera, suggested that water might be used as a "pressure gauge" for measuring transient pressures, including the peak pressures in detonation waves of condensed explosives.

The Rankine-Hugoniot curves for water have been derived by a number of investigators including Kirkwood and Montrall,[1] Kirkwood and Richardson,[2] Richardson, Arons, and Halverson,[3] Arons and Halverson,[4] and Doering and Burkhardt.[5] In these treatments systematic extrapolations of Bridgman's[6,7] PVT data for water were made. Probably the most comprehensive extrapolation of Bridgman's PVT data, however, was carried out by Snay and Rosenbaum[8] who used more recent data of Bridgman[9,10] which for water extended to 36 500 kg/cm² and for ice VII to 50 000 kg/cm².

A different approach was used in a later study by Rice and Walsh.[11] In their method an intense plane shock wave was generated in an aluminum plate by the detonation of a slab of composition B in contact on one side of the plate. The shock through a portion of the plate was then transmitted into water. Higher pressures in the aluminum plate were reported by "slapping" the aluminum plate with a thin, high velocity, explosively driven plate rather than detonating the charge directly in contact with the test plate. By application of a special streak camera technique pioneered by Walsh and co-workers and through use of a previously derived equation of state for aluminum the shock velocity in water was determined as a function of the corresponding shock pressure in the aluminum at the interface. Continuity conditions of pressure and particle velocity across the interface between the aluminum and water were then applied to determine the Hugoniot curves for water.

In determining shock parameters for water a factor which should be considered is the possibility of a phase change of the medium within the shock wave. This possibility was investigated by Snay and Rosenbaum[8] and by Rice and Walsh.[11] According to Snay and Rosenbaum the Rankine-Hugoniot curve for supercooled water and the Rankine-Hugoniot curve for partially frozen water are never far apart, and thus the shock velocity would not be materially affected if freezing did occur. Since partial freezing of a liquid should lead to reduce transparency because of differences in indices of refraction of water and ice, Rice and Walsh carried out some transparency experiments of water being traversed by a shock wave in the pressure range of 30 to 100 kbars. No sign of opacity due to freezing was observed. They concluded therefore that even though p, T conditions might be proper for freezing under static conditions, the time the liquid was under the correct conditions within the shock was apparently too short for freezing to occur.

In using water as a pressure gauge (by observing the transmission of the shock into it) one must calculate from the measured shock pressure in water the pressure in the adjacent medium of interest from which the

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[1] J. G. Kirkwood and E. W. Montrall, OSRD No. 670, June 1942.

[2] J. G. Kirkwood and J. M. Richardson, OSRD No. 813, August 1942.

[3] J. M. Richardson, J. M. Arons, and R. R. Halverson, J. Chem. Phys. **15**, 785 (1947).

[4] A. B. Arons and R. R. Halverson, OSRD No. 6577, March 1946.

[5] W. Doering and G. Burkhardt, HEC Accession List No. 60, p. 4, Bias Group.

[6] P. W. Bridgman, Proc. Am. Acad. Arts Sci. **47**, 441 (1912).

[7] P. W. Bridgman, J. Chem. Phys. **5**, 964 (1937).

[8] H. G. Snay and J. H. Rosenbaum, NAVORD Report 2383, U. S. Naval Ordnance Laboratory, White Oak, Maryland, April 1952.

[9] P. W. Bridgman, J. Chem. Phys. **9**, 794 (1941).

[10] P. W. Bridgman, Proc. Am. Acad. Arts Sci. **74**, 399 (1942).

[11] M. H. Rice and J. M. Walsh, J. Chem. Phys. **26**, 824 (1957).

water shock is transmitted. In the initial application by Holton[12] of the "aquarium technique" for the measurement of pressure, two procedures were used to perform this calculation. The first method, which was considered the more exact one, was patterned after a treatment given by Riemann for a shock propagating across a boundary into a medium of lower impedance. The second method utilized the shock "impedance mismatch" equation

$$p_i = p_t(\rho_t V_t + \rho_i V_i)/2\rho_t V_t, \tag{1}$$

where p is pressure, ρ is initial density of the medium before being traversed by a shock, V is the velocity of the shock, and subscripts i and t designate the incident medium and the transmitting medium, respectively. Although the impedance mismatch equation was expected on theoretical grounds to be accurate only when the wave reflected at the interface is a weak shock, in the investigations of Holton, where the reflected wave was a rarefaction, Eq. (1) was found to yield results in very good agreement with the first method. Therefore, the method appears reliable whether the reflected wave is a release or a shock wave.

A third more direct method was used in this investigation in which the equations of state for water and Lucite were obtained by direct simultaneous observation of the shock velocity and the free surface velocity. This method while developed in this investigation was referred to and summarized by Cook, Pack, and McEwan.[13] Therefore, only essential points not outlined there are presented in this article. The application of the aquarium technique in the measurement of detonation pressures for various ideal and nonideal explosives is then presented and results discussed.

EXPERIMENTAL

(a) Shock Parameter Determinations

The shock parameters which are of interest in this study are related by the familiar hydrodynamic equations

$$p - p_i = \rho_i V W \doteq p \tag{2a}$$

$$W/V = (1 - \rho_i/\rho) \tag{2b}$$

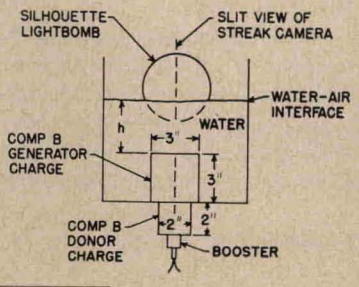

FIG. 1. Aquarium setup for measuring velocity of water shock along the charge axis and free surface velocity.

and the approximate relation

$$W \doteq V_{fs}/2, \tag{3}$$

where V_{fs} is the free surface velocity, and W is the particle velocity, the subscript i indicating initial conditions in the undisturbed medium. Equation (3) expresses the basic, now well-established, postulate of the Goranson theory that free surface velocity is approximately twice the particle velocity in the shock in the medium immediately beneath the free surface.

The method used for determining the shock-parameter data for water and some of the data for Lucite consisted of simultaneous measurements of the shock velocity immediately inside the free surface and the free surface velocity as the shock emerged from the water or Lucite. Observations of the shock and free surface velocities were made with a rotating mirror

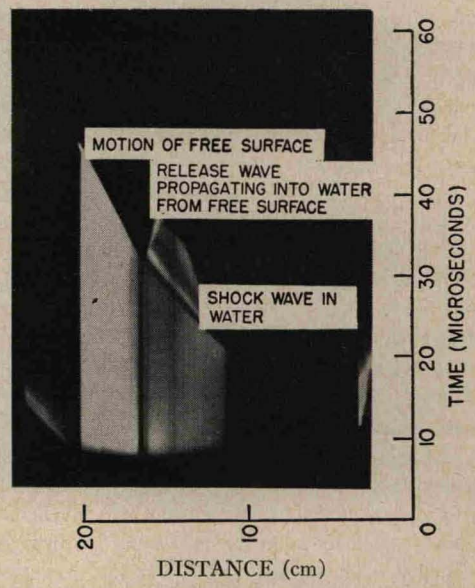

FIG. 2. Typical streak camera trace obtained using the arrangement of Fig. 1 (shock parameter determination for water).

streak camera using diffuse backlighting from an explosive flash bomb. This method is illustrated in Fig. 1. Because point-initiated charges were used it was necessary that the slit view of the streak camera lie along the charge axis in order to obtain the correct values of shock velocity and the corresponding free surface velocity. Care was taken also to ensure that the free surface was coincident with the optic axis of the system, i.e., that the view of the camera was flush with the free surface.

Two sizes of aquaria were used, namely 6×6×6 in. and 12×12×8 in., the size being dictated by the height h of water above the receptor charge. As h was increased above a certain limit, the dimensions of the aquarium had to be increased because generally shattering of the glass propagates at higher velocity than the shock in the liquid.

[12] W. C. Holton, NAVORD 3968, U. S. Naval Ordnance Laboratory, White Oak, Maryland, December 1, 1954.

[13] M. A. Cook, D. H. Pack, and W. S. McEwan, Trans. Faraday Soc. **56**, No. 451, Part 7 (July 1960).

The velocity (and therefore the pressure) of the shock wave at the air surface was varied either by varying h or the detonation pressure of the shock-generator charge.

Figure 2 presents a typical streak camera trace showing the attenuating shock wave, the release wave, and the free surface "wave." Note that in this case conditions were such that the free surface velocity was constant over a relatively long distance, thus assuring its accurate evaluation. Both the shock and the free surface velocities were obtained from the slopes of the traces at the interface through application of the proper magnification factor and camera writing speed.

While some shock-parameter determinations for Lucite were made in the same manner as those for water, i.e., by simultaneous measurements of shock velocity at the free surface and the free surface velocity, for convenience most measurements for Lucite were made by observing the transmission from Lucite into water, measuring the final velocity of the shock in Lucite and the initial velocity of the shock in water by means of a streak camera (utilizing a silhouette backlight bomb to render the shocks visible), and applying the Goranson shock transmission equations to calculate the shock pressure in Lucite immediately inside the Lucite-water interface. The two methods gave consistent results. The strength of the shock in Lucite at the Lucite-water interface was varied by varying the thickness of Lucite between the charge and the water using a constant shock generator system. The diameter of the Lucite was in all cases sufficiently large to shield the detonation products from the region where the motion of the shock wave was observed.

(b) Detonation Pressure Determinations

Figure 3 illustrates the application of the aquarium technique for measuring the initial velocity of the shock (and pressure) in water transmitted directly from the detonating explosive. As in the previous cases the assembly was aligned such that the streak camera observations were made along the charge axis, the height and tilt of the assembly being such that the bottom face of the charge in this case was coincident with (and parallel) to the optical axis of the camera. The streak camera viewed the charge upward through a periscope in which the line of sight was reflected to a horizontal direction by a front surface mirror. The camera was mounted on a turntable and three supporting casters, permitting rotation of the camera about its optic axis. Thus the slit view of the camera could conveniently be adjusted to either the horizontal or vertical direction or to any position between them simply by rotation of the turntable, thus easily permitting proper alignment.

The cast charges were detonated with the bare end immersed in the aquarium. In cases where there existed the possibility of absorption of water or solution of some of the charge components the charges were sprayed with Krylon for waterproofing. Charges made

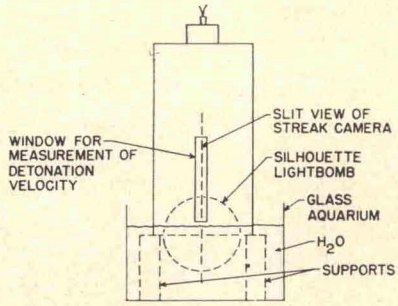

FIG. 3. Aquarium assembly for measurement of velocity along the axis (and pressure) of the transmitted shock in water from a detonation wave.

up from granular or loose material were vibrator-packed in thin-walled (approximately 0.16 cm thick) cardboard tubes and waterproofed with a 3-mil thick sheet of Polyethylene.

The explosives included in this study were pelleted TNT of standard Tyler mesh sizes $-4+6$, $-6+8$ and $-8+10$; granular $-48+65$ mesh TNT; cast 65/35 baratol; cast 50/50 amatol; granular 50/50 AN/TNT; granular RDX; granular RDX-salt; HBX-1; and a classified explosive X. Results obtained in this investigation for 50/50 cast pentolite, composition B, TNT, and tetryl were summarized previously.[13] Similar measurements have been made by Bauer and Cook[14] for commercial "blasting agents", including 94/6 ammonium nitrate/fuel oil, and the "slurry" explosives.[15] The blasting agents are of interest because their reaction zones are among the longest possible in detonating explosives since they remain nonideal even in very large diameter charges.

Except for a study with composition B and the classified explosive X where charge length was varied to observe transient effects of pressure against charge length, the charges were at least four charge diameters in length insuring a constant velocity and steady detonation head before the detonation front reached the end of the charge. In the case of the pelleted TNT, charge diameter was varied from the critical diameter to a diameter sufficiently large for the detonation to be ideal, thus covering the entire nonideal region. An ideal explosive is defined as one which detonates at its theoretical maximum or hydrodynamic velocity, i.e., $D=D^*$, and a nonideal one has a lower velocity, $D<D^*$ (reference 16, Chapter 3).

RESULTS

(a) Shock Parameter Determinations

In Fig. 4 are plotted the experimental results for water with pressure as the ordinate and shock velocity as the abscissa. Figure 5 presents a similar plot in which the low pressure part of the curve of Fig. 4 has been

[14] A. Bauer and M. A. Cook, Can. Min. and Met. Bulletin, January 1961; Trans. Can. Inst. Mining Met. **61**, 62 (1961).

[15] M. A. Cook and H. E. Farnam, U. S. Patent No. 2,930,685, March 29, 1960.

[16] M. A. Cook, *The Science of High Explosives* (Reinhold Publishing Corporation, New York, 1958).

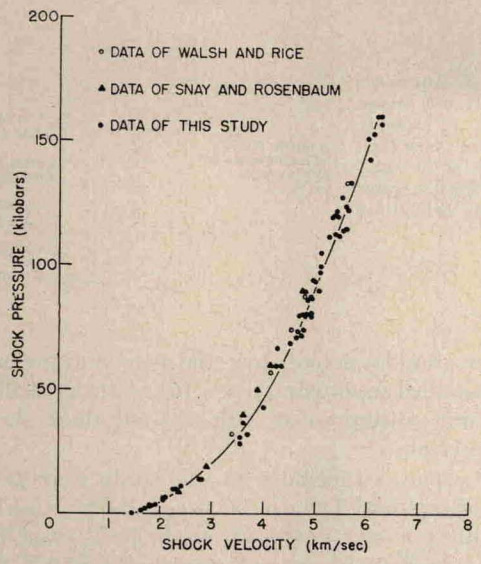

FIG. 4. Experimental shock velocity vs pressure data for water.

expanded to a larger scale. On both figures the smooth curve through the points represents an approximate best fit as "drawn by eye" to the data. Velocity-pressure values from this curve of best fit are given in Table I. Results of Snay and Rosenbaum,[8] and Rice and Walsh[11] also are plotted in Fig. 4 for comparison. Note that Snay and Rosenbaum's results agree with the results of the present study at pressures up to about 10 kbars, and from thence there is a tendency for their data to show greater compressibility. The results of Rice and Walsh fall about midway between those of Snay and Rosenbaum and this study. The differences in compression between the results of Rice and Walsh, which should be more comprehensive than Snay and Rosenbaum's data, and the data of this study were 3.2% for a shock velocity in water of 3.5 km/sec and 2.8% for a shock velocity of 5.5 km/sec, corresponding to pressures to 31 and 125 kbars, respectively. The disagreement in measured pressures at these two velocities amounted to 9.7% at the lower velocity and 4.2% at the higher one.

The agreement between the shock parameter data for water obtained by Rice and Walsh and the data of this investigation is reasonably good. One may conclude therefore that the Rankine–Hugoniot curves for water are now known with sufficient accuracy that water may reliably be used as the transmission medium for the measurement of pressures in shock and detonation waves. The agreement also demonstrates the general reliability of the aquarium technique.

The essential shock-parameter results for Lucite are portrayed graphically in Fig. 6. No differentiation was made as to which of the two methods mentioned above was used to obtain a given $p(V)$ point in this case because the results of the two methods were indistinguishable within the limits of experimental error. The smoothed results representing the most reliable values are given in Table II. The curve of Fig. 6 was not extended to the sonic velocity because there is some uncertainty in available values of the sonic velocity for Lucite.

TABLE I. Smoothed shock parameter results for water (20°±5°C).

Shock velocity (m/sec)	Shock pressure (kilobars)	Shock velocity (m/sec)	Shock pressure (kilobars)
1450	Sonic	3450	30.0
1620	1.0	3820	40.0
1740	2.0	4120	50.0
1840	3.0	4350	60.0
1940	4.0	4570	70.0
2020	5.0	4780	80.0
2100	6.0	4980	90.0
2170	7.0	5170	100.0
2240	8.0	5350	110.0
2310	9.0	5530	120.0
2380	10.0	5700	130.0
2680	15.0	5870	140.0
2980	20.0	6040	150.0
		6200	160.0

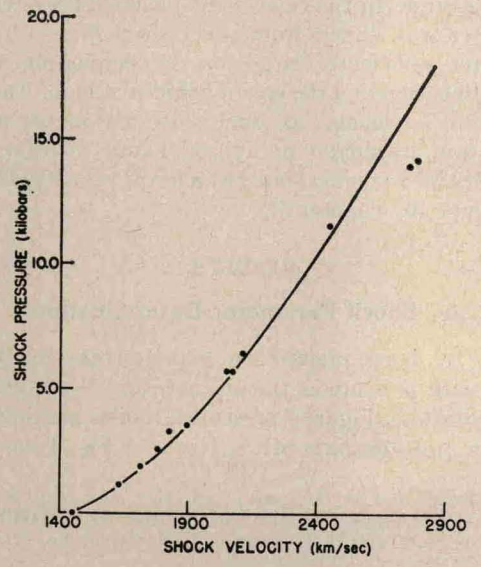

FIG. 5. Experimental shock velocity vs pressure data for water (low pressures).

(b) Detonation Pressure Measurements

Results obtained for ideal explosives (i.e., where $D=D^*$) in which the charge length was maintained at approximately four diameters to assure that the detonation wave was steady are listed in Table III. All the charges in this case may be considered to be effectively unconfined, the cast charges being bare and the loose charges being contained in only 0.16-cm-thick pasteboard tubing. In Table III are listed the type explosive, the charge density, the charge diameter, the measured detonation velocity, the initial pressure of the shock front in water p_t as determined from the measured initial shock velocity V_t in the water and the calibration

TABLE II. Smoothed shock parameter data for Lucite.

Shock velocity (m/sec)	Shock pressure (kilobars)	Shock velocity (m/sec)	Shock pressure (kilobars)
3350	20	5410	100
3820	30	5560	110
4160	40	5700	120
4430	50	5840	130
4670	60	5960	140
4880	70	6100	150
5070	80	6210	160
5250	90	6330	170

curves of Fig. 4 and Table I, the pressure in the detonation wave or incident wave p_i calculated through application of Eq. (1) (the impedance mismatch equation), and finally p_i/p_2^* or the ratio of the measured pressure to the calculated Chapman–Jouguet value of the detonation pressure.

Table IV presents similar data for nonideal explosives (i.e., $D/D^* < 1.0$). Also listed in this table are the ratios $(D/D^*)^2$ which should be equal to p_i/p_2^* if the measured pressure is the Chapman–Jouguet pressure, but much lower (about half) if the measured pressure is the "spike pressure." The results show that the measured pressure is definitely the Chapman–Jouguet pressure and that there is no evidence for an over-pressure of the type required by the Zeldovich–von Neumann model.

Figure 7 presents results for special explosive X in 5 cm (d) and composition B in 4.3 cm (d) for which the charge length was varied from 1 to 6 cm to determine if a pressure-buildup effect existed in explosives of very short reaction zone lengths or in explosives with no appreciable detonation velocity transient. These charges were all boostered with identical 1.27×2.54 cm pressed RDX boosters. With such short charges, however, difficulty was encountered in measuring the initial velocity of the shock wave in water because of a rapid

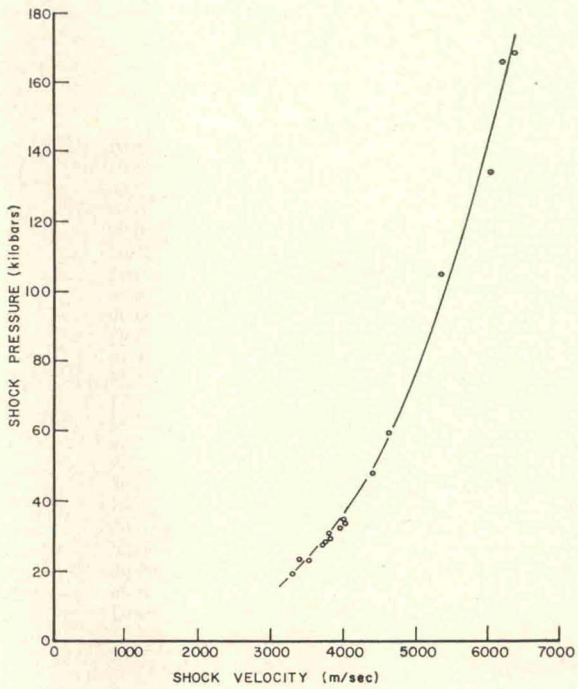

FIG. 6. Experimental shock velocity vs pressure data for Lucite.

attenuation in velocity of the shock in the aquarium. The plot of the results indicates in spite of the observed scatter, a small pickup in detonation pressure as the charge length was increased. Whether or not the detonation velocity increased slightly over this region in order to produce the pressure pickup could not be determined.

Data for the commercial blasting agents were reported by Bauer and Cook.[14] Their results are given both for unconfined charges and charges confined in 0.95-cm thick or 2.44-cm-thick steel tubing. They found that the detonation velocity and pressure of the low density AN/fuel oil mix was very sensitive to confine-

TABLE III. Measured peak pressures in detonation waves of ideal explosives ($D/D^*=1$).

Explosive	No. of shots	Density (g/cc)	Diameter (cm)	Velocity D (km/sec)	p_t[a] (kbars)	p_i[b] (kbars)	p_i/p_2^*[c]
RDX	4	1.21	2.53	6.48	105	134	0.97
	1	1.18	3.77	6.75	89	118	0.91
	1	1.21	4.40	6.67	94	123	0.90
	3	1.18	5.05	6.74	108	135	1.04
	1	1.10	6.30	6.40	94	112	0.98
	1	1.13	7.62	6.62	97	119	0.98
80/20 RDX/salt	1	1.32	2.53	5.79	85	110	0.85
	1	1.30	4.40	6.20	87	115	0.98
	1	1.28	5.00	6.20	92	119	1.01
TNT (−48+65 mesh)	2	0.86	3.80	4.50	51	50	0.98
	4	0.98	5.05	4.56	52	51	0.95
	2	0.84	7.62	4.46	52	49	1.00
(−6+8 mesh)	1	0.97	16.1	4.88	60	63	1.00
(−4+6 mesh)	2	0.99	25.3	5.01	64	68	1.01
HBX−1	1	1.75	5.0	7.16	116	190	1.0

[a] p_t = initial pressure of shock wave in water.
[b] p_i = pressure at detonation wavefront.
[c] *—designates ideal or hydrodynamic value (calculated from hydrodynamic theory). *Note:* The average deviation (correcting for density) for p_t and p_i was ±6.1%.

TABLE IV. Experimental peak pressures in detonation waves of nonideal explosives ($D/D^*<1.0$).

Explosive	No. of shots	Density (g/cc)	Diameter (cm)	Velocity D (km/sec)	p_t (kbars)	p_i (kbars)	$(D/D^*)^2$	p_i/p_2^*
TNT (−4+6 mesh)	1	1.00	7.62	4.41	43	46	0.77	0.69
	2	1.01	10.0	4.65	67	61	0.85	0.87
	1	1.01	12.35	5.00	63	69	0.92	0.90
	1	1.00	15.9	4.80	65	66	0.92	0.88
	4	0.99	20.3	5.01	54	59	1.01	0.97
(−6+8 mesh)	2	0.99	7.62	4.51	55	57	0.81	0.84
	2	1.01	10.0	4.82	62	66	0.91	0.93
(−8+10 mesh)	2	0.95	5.0	3.73	41	40	0.60	0.64
	3	0.99	7.62	4.67	56	58	0.81	0.87
	2	0.99	10.0	4.80	61	64	0.92	0.94
(−48+65 mesh)	2	0.84	2.53	3.86	49	44	0.72	0.89
RDX	1	1.10	1.25	5.83	75	89	0.83	0.78
65/35 baratol	1	2.35	5.0	5.15	62	116	0.85	0.74
50/50 cast amatol[a]	1	1.53	4.8	5.55	72	102	0.74	0.75
	1	1.53	7.6	6.04	85	121	0.94	0.89
50/50 amatol[b]	1	1.58	4.8	5.72	84	120	0.76	0.84
	1	1.58	7.62	6.23	100	145	0.89	1.0
50/50 AN/TNT[c]	3	0.97	2.54	2.95	25	24	0.37	0.35
	3	0.97	3.81	3.64	38	37	0.54	0.55
	5	0.98	5.04	4.08	48	48	0.66	0.67
	7	0.96	10.0	4.57	61	62	0.86	0.91
	6	0.96	15.2	4.76	67	67	0.95	1.00
	2	0.96	20.4	4.80	67	68	0.96	1.00
	4	0.94	25.4	4.88	69	69	1.0	1.08

[a] 35 mesh AN. [b] 65 mesh AN. [c] Mechanical mixture.

ment. In 11.7 cm (d) unconfined charges the detonation velocity was only 2.77 km/sec which corresponded to a D/D^* ratio of only 0.66 while with 0.95 cm steel confinement in the same diameter the detonation velocity was 3.93 km/sec corresponding to a D/D^* ratio of 0.94. The series of coarse TNT or composition B "slurries" were much less sensitive to confinement probably because their detonation pressures were much higher.

DISCUSSION OF RESULTS

In comparing the measured values for pressure in the explosive, that is, pressures of the incident waves p_i obtained by the aquarium technique, one will note that in every case where the detonation wave propagated at ideal velocity p_i agreed (with an average deviation of $\pm 6.1\%$) with the Chapman–Jouguet pressure p_2^*, i.e.,

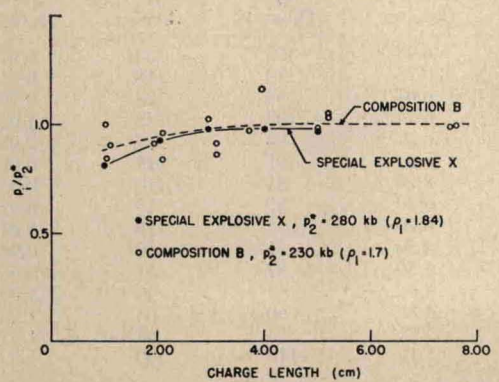

FIG. 7. Pressure of the detonation wave as a function of charge length for 5-cm-diam special explosive X and 4.8-cm-diam composition B boostered with 1.27×2.54-cm pressed RDX.

to the detonation pressure calculated from thermohydrodynamic theory. In most of the loose packed explosives the impedance match between the explosive and water was very good. Therefore, calculations of pressure in the incident medium in terms of pressure in the transmission medium, through applications of the shock impedance mismatch equation, should be quite reliable at least in these cases.

Since the C–J pressure of the detonation wave is given by the relation $p \doteq \rho_1 DW$ in nonideal detonations the Chapman–Jouguet pressure should be given approximately by the relation

$$p_2 = (D/D^*)^2 p_2^*, \tag{4}$$

where asterisks signify ideal values, p_2^* being the ideal detonation pressure. Equation (4) makes use of the approximation that W/D depends only on ρ_1 and not on D/D^* which is well justified by the generality of the covolume-specific volume $[\alpha(v)]$ curve for high explosives.[16] This is consistent also with a frequently used approximation that $W/D=0.25$ for condensed explosive. Comparisons of $(D/D^*)^2$ with p/p_2^* given in Tables III and IV indeed show striking agreement. Judging from reproducibility of results it is estimated that the measured pressures for nonideal explosives was at least as accurate as for the ideal ones, the average deviation of results from the mean being about $\pm 5\%$. This is consistent also with the average deviations of the ratios p_i/p_2^* and $(D/D^*)^2$.

Important information regarding the pressure or particle velocity profiles of detonation waves are also apparent from this study. According to the Zeldovich–von Neumann concept, which is based upon transport

phenomena being negligible in a detonation wave, the pressure at the detonation front should be approximately twice the Chapman–Jouguet pressure. Then as chemical reaction proceeds the pressure decays along the Rayleigh line to the Chapman–Jouguet value at the end of the reaction zone. For explosives of reaction zone length of only a few mm or less, such as composition B, the von Neumann spike might be difficult to detect. Previous experiments to determine the pressure profiles through reaction zones by means of the aluminum free surface velocity technique were devoted primarily to explosives of very short reaction zone length, i.e., composition B. This choice of explosive necessitated the use of very thin plates for which the free surface velocity measurements were in question.[17,18] Since there is no reason to believe that an overpressure would exist in a rapidly reacting explosive and not in a slowly reacting one, it would seem prudent to look for evidence of a spike in slowly reacting explosives. The blasting agents discussed by Bauer and Cook[14] represent a class of explosives known from their persistent nonideal behavior in large diameter charges to possess the longest reaction zones of the detonating type explosives, and according to any published theory, to possess reaction zone lengths sufficiently great that a spike could easily be detected by the aquarium technique. However, no evidence of the spike was observed in these or any of the nonideal explosives included in this investigation. The coarse TNT, especially −4+6 mesh TNT, also should have reaction zone lengths which are ample for easy detection of a spike by the aquarium technique. Moreover, conditions were ideal in this case for its detection, if it were present, owing to a nearly perfect impedance match between the explosive and water. Additionally nonideal behavior persists in some of these, e.g., −4+6 mesh, up to a 25-cm charge diameter. Figure 8 shows a trace for −4+6 mesh spherical TNT in a 25.3-cm-diam charge. One has no difficulty in such a case in obtaining accurately reproducible measurements owing to the relatively slow deceleration of the shock from such a large shock generator. With −4+6 mesh TNT in a 25.3-cm-diam charge, where the detonation velocity was finally in close agreement with the ideal value, and the impedance match was very good, the pressure of the incident wave corresponding to the initial velocity of the transmitted wave was found to be in close agreement with the Chapman–Jouguet value.

Published results of measured detonation pressures are not directly comparable to any presented here. Nevertheless an approximate comparison may be made with results for composition B presented by Deal based on two separate methods, namely the free surface velocity method[19] and another type of aquarium

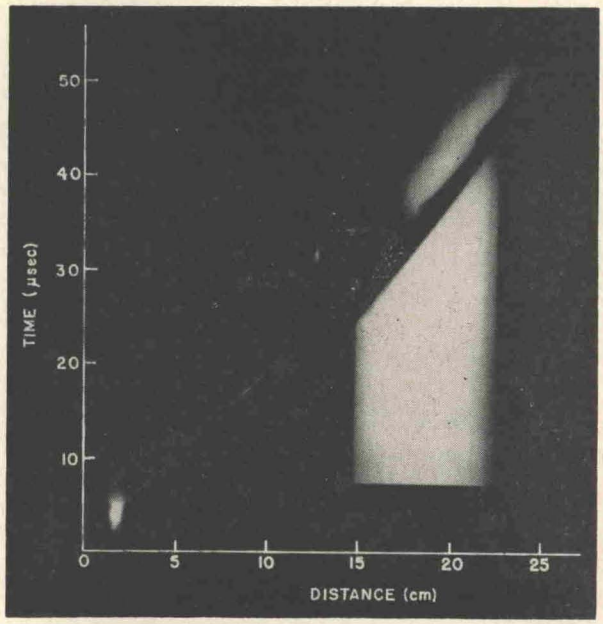

FIG. 8. Streak camera trace illustrating the aquarium technique for measurement of detonation pressure (explosive −4+6 mesh TNT at $d=25.3$ cm).

method.[20] Deal employed 65/35/1 composition B of density 1.714 g/cc and velocity 7.991 km/sec whereas the explosive used here was 60/40/1 composition B of $\rho_1=1.68$ g/cc and $D=7.80$ km/sec. Deal obtained 292.2 and 290.4 kbars by his free surface and aquarium methods, respectively, with a probable error in the aquarium method of only about 2.5 kbars. This is to be compared with the value 230±10 kbars reported by Cook, Pack, and McEwan.[13] The two explosives are closely enough related that the results may be placed on a common basis by the approximation

$$p_2'/p_2''\doteq\rho_1'D'^2/\rho_1''D''^2, \tag{5}$$

which predicts that Deal's results should have been about 1.07 times higher than those measured here. After applying this correction to our results there remains a discrepancy of about 42 kbars which is 30 kbars outside the combined limits of experimental error.

Funk reinvestigated 60/40/1 composition B by the aquarium method using charges of larger diameter than in reference 13. The results are given in Table V and were 19.5 kbars higher than those obtained with the 2-in. charges used earlier. Moreover, the reproductibility was better due to the much lower rate of attenuation of the shock wave in water from the charges of nearly four times greater cross section. Still there remains a discrepancy of about 23 kbars between the results obtained by the aquarium method used here and those obtained by Deal. Since Funk's charges were large enough that nonideal effects should have been completely eliminated, apparently there remains a funda-

[17] R. E. Duff and E. Houston, *Second ONR Symposium on Detonation, Washington, D. C., February 9–11 (1955)*, p. 225.
[18] H. D. Mallory and S. J. Jacobs, *Second ONR Symposium on Detonation, Washington, D. C., February 9–11 (1955)*, p. 240.
[19] W. E. Deal, J. Chem. Phys. **27**, 796 (1957).
[20] W. E. Deal, Phys. Fluids **1**, 1523 (1958).

TABLE V. Detonation of composition B measured by Dr. A. G. Funk by IMER aquarium method.

Charge size	Density (g/cc)	p_2 (kilobars)	p_2 [corrected to 1.68 g/cc by approx. Eq. (5)]
3.94 in. (d)×12.13 in. (L)	1.70	256	249
3.89 in. (d)×15.98 in. (L)	1.69	255	251
3.63×3.32 in. (rectangular)×10.3 in (L)	1.67	243	247
3.62×3.24 in. (rectangular)×9.8 in. (L)	1.69	255	251
			249.5±1.5 kbars

mental discrepancy between the aquarium method employed here and that employed by Deal.

One of us has criticized the measurements of the "spike" in the detonation front by the use of very thin plates and the free surface velocity method.[16] This criticism, however, does not apply to Deal's measurements since he extrapolated to C–J conditions from free surface velocity measurements with adequately thick plates. Furthermore, the criticism should not be construed as a rejection of the Goranson theory of impedance mismatch which certainly has been adequately confirmed when applied to media of sufficient extent. More recent studies by Clay[21] seem to confirm, however, the suggested limitations of the shock wave reflection-transmission theory for very thin plates. Using microsecond framing camera sequences of the transmission-reflection characteristics of shock waves through brass plates of different thickness, Clay showed that ordinary laws of transmission-reflection at an interface apparently break down for thin plates of thickness below a certain critical value. Clay employed 3-in.²×2-in. thick Plexiglas–x thick brass–3-in².×1-in. thick Plexiglas sandwiches shock loaded by 1-in.-diam ×2-in.-long 50/50 cast Pentolite. Intimate contact between the Plexiglas and the brass plate was achieved by fluidizing the surface of the Plexiglas with a thin film of ethylene dichloride. Clay observed that the ratio of the relative intensities of the transmitted to the reflected (shock) waves from the brass plates decreased from a very large (almost infinite) value at $x=0.05$ mm, through approximately unity at 0.3 mm, to a constant (normal) value at about 1.5 mm. Figure 9 shows four successive frames each of three framing camera sequences obtained by Clay at $x=0.05$ mm, $x=1.55$ mm and by Funk at $x=0.25$ mm. These results show that shock transmission-reflection conditions at an interface involve a type of "uncertainty principle" wherein ordinary shock wave theory for interactions at an interface breaks down if the dimension of the medium on either side of the interface in the direction normal to the wave front is below a certain critical value.

The discrepancy between the results of the aquarium method applied here and the free surface and aquarium methods employed by Deal may possibly be due to a fundamental difference between steady and nonsteady detonation waves. A steady detonation wave is not only one having a constant velocity but also one with a steady "detonation head" and a steady (spherical) wave front of constant radius of curvature.[16,22] In composition B the detonation head and wave front both require a run-up distance of about 3.5 to 4.0 charge

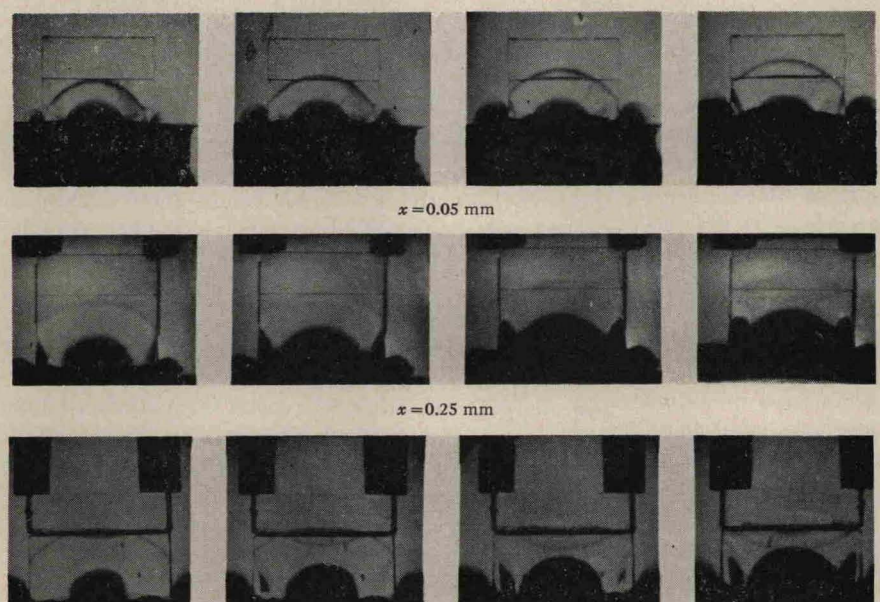

FIG. 9. Shock transmission and reflection by brass sandwiched between Plexiglas blocks showing effect of plate thickness on effective impedance of brass.

[21] R. B. Clay, Ph.D thesis, "Formation and Behavior of Shock Waves in Solids," University of Utah (June 1960).
[22] M. A. Cook, G. S. Horsley, R. T. Keyes, W. S. Partridge, and W. O. Ursenbach, J. Appl. Phys. 27, 269 (1956).

diameters to become steady, and the radius of curvature of the steady-state wave front in composition B is also about 3.5 to 4.0 charge diameters. Moreover, during any wave shape transient the shape of the wave front tends to revert rapidly to the normal wave front irrespective of the (abnormal) wave shape built into the detonation front during formation of the detonation wave. For instance, when detonation is initiated as a reentrant wave, the wave front undergoes a rapid transition into a normal spherical form and in doing so it exerts an *overdrive* that increases toward the axis of the charge or center of the wave. This overdrive effect has been used to accelerate pellets to higher velocities than is possible with a normal wave.[23]

A plane detonation wave may be regarded as a special case of a reentrant wave relative to the steady, spherical detonation wave, or unsteady, but stable spherical wave that would exist during formation of the detonation head in a case of symmetrical point initiation. A plane detonation wave may, therefore, itself tend to overdrive the detonation. The nonsteady and overdrive character of the plane wave lens system may, in fact, be inferred by the pick-up in velocity of the wave in water (from the 8-in.-diam charge) indicated by the nonlinearity of the "wedge trace" of Fig. 1, reference 20 over the very small (less than 3 mm) distance involved. In contrast to this effect, note that there was no appreciable change in velocity of the transmitted wave in water in the case of the 10-in. diameter, low density, coarse TNT charge shown in Fig. 8 for a distance of at least 2 in. Whether or not this is the true explanation for the discrepancy between the results of this investigation and those of Deal for composition B, Deal's methods involves nonsteady detonation waves, whereas the present investigation pertains to steady detonation waves.

[23] M. A. Cook and R. T. Keyes, J. Appl. Phys. **29**, 1651 (1958).