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Determination of the Chapman-Jouguet Pressure of a High Explosive from One Single Test

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ABSTRACT

Instead of evaluating the data of the surface velocities of adjacent metal foils of different thicknesses with reference to the high explosive charge, the shock wave velocity in a plexiglass block from one firing for one charge type was measured as a function of distance. If the high explosive charge is large enough, for example 64 mm diameter and 100 mm long, then the shock wave induced in the plexiglass gives, over the first 15 mm, a shock velocity which correlates with the detonation pressure or Chapman-Jouguet pressure. With the resolution inherent in this technique, an enhanced velocity over the first few millimeters, which would correspond to a von Neumann spike, could not be detected.

1. INTRODUCTION

According to a paper by Duff & Houston the Chapman-Jouguet pressure can be determined from the straight line fitted by least squares through the free surface velocities attained by materials of different thickness and in contact with the high explosive charge. This least squares line, which is unaffected by the von Neumann spike, must be extrapolated to material thickness zero. Therefore, Duff & Houston had determined the free surface velocity with electrical pin contacts. The velocities of many plates having different thicknesses must be determined in order that a good least squares line can be obtained. The Chapman-Jouguet pressure of the detonating high explosive charge can then be calculated from the hydrodynamic shock equations, considering the shock impedance of both the high explosive and the adjacent materials.

Deal[2,3] determined the free surface velocity not by means of electrical pins but used the streak technique instead, in particular the so-called time-of-arrival technique.

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Jameson & Hawkins[4] also worked with the time-of-arrival streak technique, achieving high resolution with rather thin plates and very thin plexiglass covers. Recently, Davis & Ramsay[5] had reported on the determination of the detonation pressure of PBX 9404, Composition B, PBX 9502, and nitro methane by this very method.

A disadvantage of this time-of-arrival method is that, in order to ascertain the Chapman-Jouguet pressure of a high explosive, one has to establish the free surface velocity line as a function of plate thickness, and this requires a relatively large number of trials. It will be shown below that the shock velocity as a function of the thickness of the material layer can be obtained in one single trial by using a transparent medium, such as plexiglass, with distance gauges embedded in its middle. In this way, the Chapman-Jouguet pressure can also be determined from one single trial. Plexiglass has the advantage of having a shock impedance which is not much different from that of the high explosives, so there will be little interference from shock reflections to the reaction mechanism in the reaction zone.

2. TEST ARRANGEMENTS

For the purpose of measuring the shock velocity in plexiglass with a high resolution in space, 0.1 mm thick copper grating was embedded through liquid plexiglass into the centre plane of a 70 ×70 mm square and 100 mm long block of plexiglass (Fig. 1). Two types of grating were used (i) A grid was used with a regular 2.0 mm spacing, but with every 5th spacing only 1 mm wide for better coordination, and with the ribs 0.5 mm wide. (ii) The second type grid had 5 lines spaced at 2 mm, 5 more lines spaced at 10 mm, and 3 more lines spaced at 20 mm. The accuracy of the grid marks in the plexiglass block was thus ±0.01 mm.

The shock velocities were recorded with a Model 200 Beckman & Whitley rotating mirror streak and framing camera. The streak speed was only 3.45 mm/μs in order to obtain a sufficient length of recording.

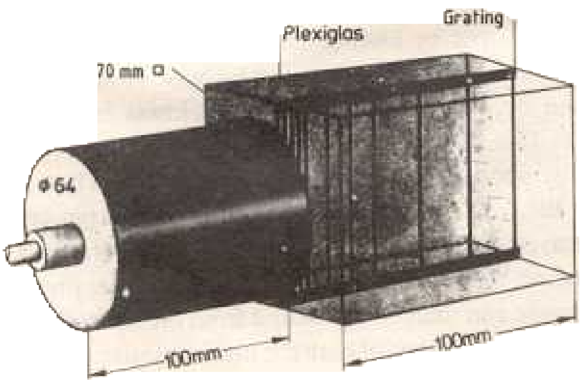

Figure 1. Aquarium test set-up.

Fig. 2 shows the streak record of a shock wave as obtained with the fine grid. The high resolution in space and time is readily recognized.

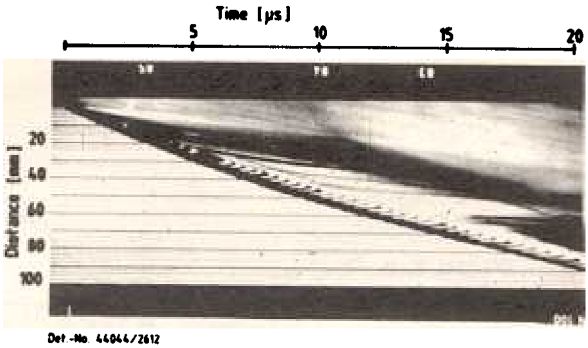

Figure 2. Streak registration (TNT/RDX 35/65).

3. TEST RESULTS

The distance-versus-time records were taken of different size high explosive charges. In this, the high explosive TNT/HMX 15/85 was used. Fig. 3 shows the distance-versus-time records for 32 mm diameter charges having various lengths. It was found that tne behaviour of distance with time is almost constant with the given diameter from a length of 50 mm on; at least along the initial ranges, across a distance of 20 mm.

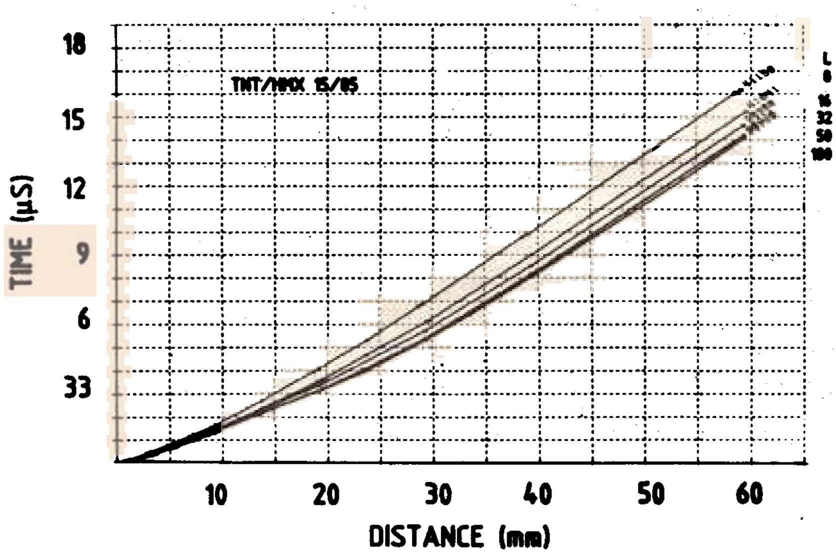

Figure 3. HE-Charges of 32 mm dia. and variable length.

When the charge diameter is varied from 16 to 32 and 64 mm, with a constant length of 100 mm, the distance-versus-time records are distinctly different, also beyond the range of 20 mm (Fig. 4). In this distance-versus-time diagram there is an almost straight section in the range from 0 to 20 mm, and another straight section is around the range from 20 to 40 mm, but the latter exhibits a somewhat greater slope, i.e. it corresponds to a lower shock wave velocity.

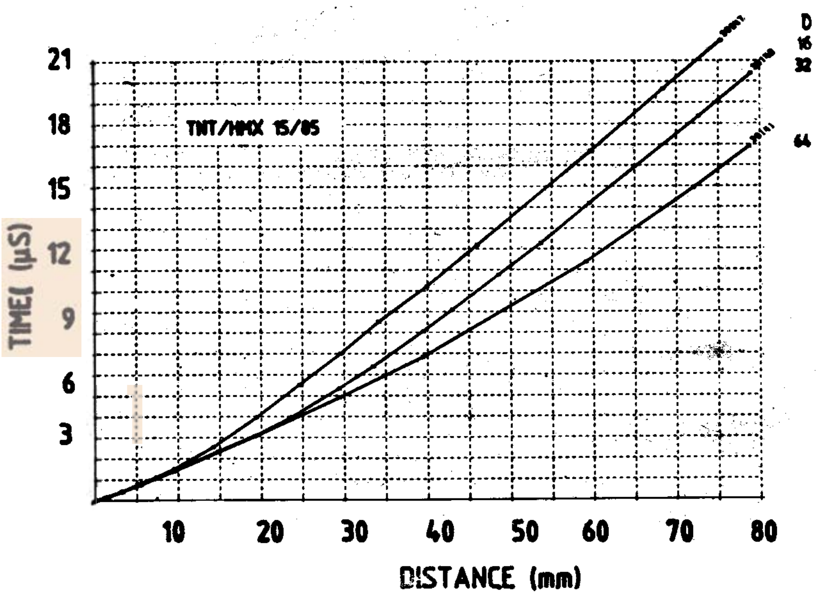

Figure 4. **HE-Charges of 100 mm length and variable diameter.**

To demonstrate this behaviour, the streak record with the fine grating of Fig. 2 shall be analyzed more closely. For the first section of the distance-versus-time record, between 0 and 20 mm, this record discloses a velocity of 6.094 mm/μs in the plexiglass; the points in this record correspond to a correlation coefficient of 0.99985 (Fig. 5).

The measured points between 20 and 40 mm again fit quite well to a straight line, which corresponds to a shock velocity of 5.089 mm/μs with a correlation coefficient of 0.99974. After this follows, a transition range which then again runs into a straight line from about 75 to 90 mm. This last straight line corresponds to a shock velocity of 3.396 mm/μs with a correlation coefficient of 0.99987.

This means that the distance-versus-time history for a sufficiently large charge (64 mm in diameter and 150 mm long in this case) and correspondingly large block of plexiglass (70 $\times$70 $\times$100 mm in this case) can be divided into the three regions A, B and D in which the shock velocities are virtually constant.

The distance-versus-time records from ,high explosive charges of various TNT/HMX and TNT/RDX compositions, each 64 mm in diameter and 100 mm long,

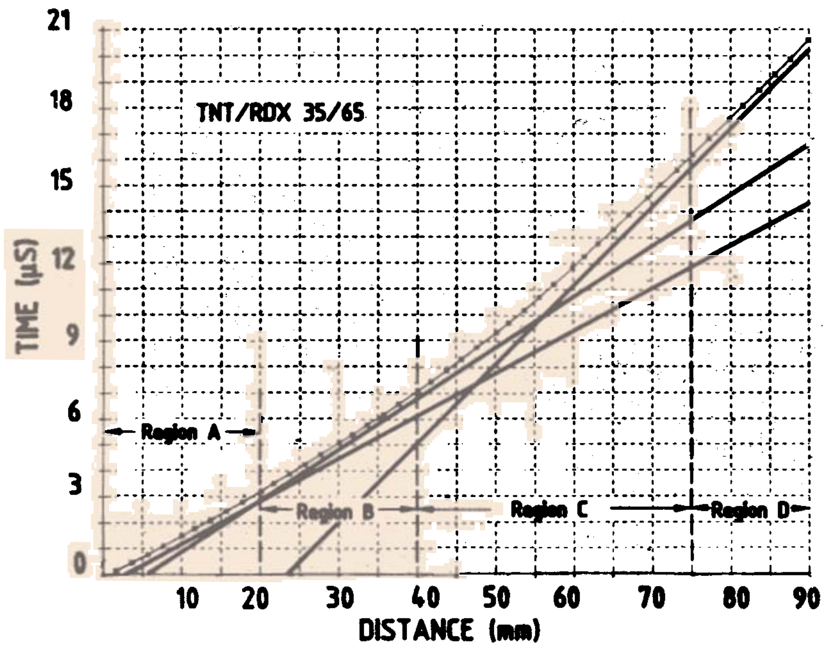

Figure 5. Detailed evaluation of Fig. 2.

resemble one another quite much (Fig. 6). They show a more or less material-dependent but constant shock velocity in the region from 0 to 10 and 20 to 40 mm. A scrutinous analysis and evaluation of the data shows slightly different slopes and, hence, different shock velocities in plexiglass for the various high explosives. Table 1 shows a compilation of the high explosive charges examined, their densities, the shock velocities U_{Pl} in the region A together with their correlation coefficients, and the shock velocities U_x in the region B, also together with their correlation coefficients, as well as the intersections of the U_{pl} and the U_x lines in terms of Δs and Δt.

The correlation coefficients clearly indicate that the measured points really lie on a straight line, and that neither in the region A for U_{Pl} nor in the range B for U_x there is a curved-line. The values of Δs and Δt definitely have a somewhat greater dispersion because the two straight lines intersect at a very flat angle.

The shock velocity in plexiglass can be represented as a function of the density of the high explosive charge (Fig. 7). Apart from 2 stray values, namely, TNT/RDX 25/75 and TNT/HMX 25/75, all points fit very well to a straight line. With all of the 8 values considered, the relationship between the shock velocity and the density of the high explosive charge is

$$U_{Pl} = 3.43 \, \rho^{o}_{HE} + 0.17$$

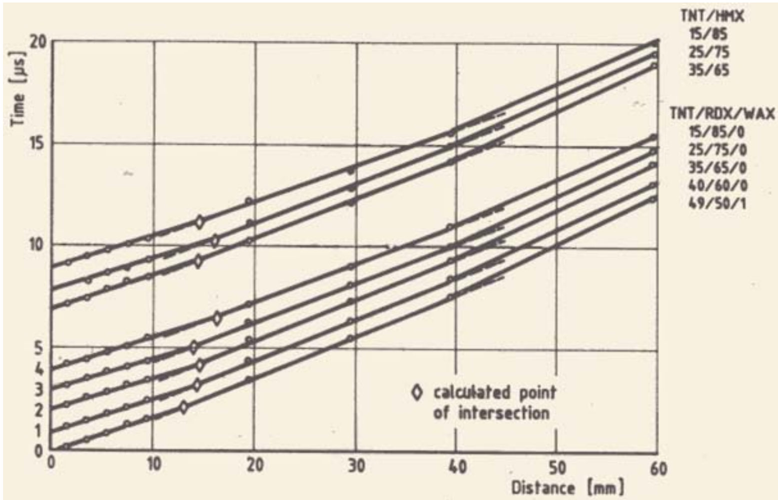

Figure 6. HE-Charges of 100 mm length and 64 mm diameter.

Table 1. Evaluation of shock wave of Fig. 6.

HE-Types TNT/RDX/WAX	$\overset{0}{\rho}_{HE}$ [g/cm³]	U_{Pl} [mm/µs]	X_{01} [mm]	Corr	U_x [mm/µs]	X_{02} [mm]	Corr	Intersection Δs [mm]	Intersection Δt [µs]
49/50/1	1.667	5.835	0.804	0.9993	4.833	2.901	0.9999	13.015	2.093
40/60/0	1.722	6.087	0.746	0.9991	4.955	3.249	0.9999	14.205	2.211
35/65/0	1.728	6.094	0.576	0.9997	4.986	3.089	0.9999	14.40	2.268
25/75/0	1.747	6.434	0.580	0.9991	5.225	3.099	0.9999	13.98	2.083
15/85/0	1.771	6.209	0.743	0.9999	5.346	2.878	0.9999	16.10	2.474
TNT/HMX									
35/65	1.721	6.075	0.655	0.9999	5.130	2.750	0.9999	14.123	2.217
25/75	1.790	6.079	1.834	0.9999	5.067	4.181	0.9998	15.930	2.319
15/85	1.847	6.573	0.707	0.9995	5.469	3.036	0.9999	14.570	2.110

with a correlation coefficient of 0.80. On the other hand, with only the 6 values fitting well to the straight line considered, the equation is

$$U_{Pl} = 3.96\,\overset{\bullet}{\rho}_{HE} - 0.76$$

with a correlation coefficient of 0.99.

The shock velocities U_x in the region B are dispersed somewhat more about the least-squares line given by the following equation with a correlation coefficient for 0.76:

$$U_x = 3.30\,\overset{\bullet}{\rho}_{HE} - 0.64.$$

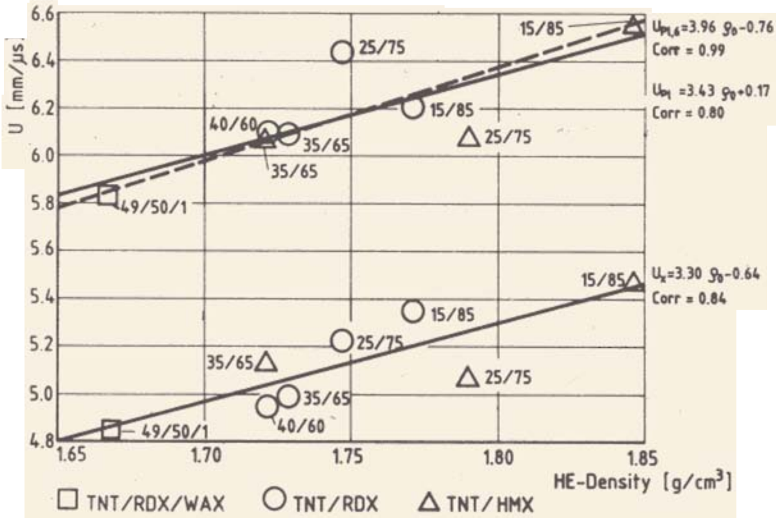

Figure 7. $U_{P_1} = f\ (\rho^0_{HE})$ for region A and B.

4. EVALUATION

The pressure P_{pl} in the plexiglass can be determined by means of the Hugoniot data of the plexiglass and the measured shock velocities in the plexiglass. To a first, acoustic approximation, the detonation pressure P_{HE} can be calculated from the density ρ^0_{HE} of the high explosive charge and from its detonation velocity, using the shock impedances (Fig. 8). The values obtained in this way are compiled in the Table 2.

This Chapman-Jouguet pressure, or the detonation pressure, can in turn be represented as a function of the density of the high explosive charge (Fig. 9). These values are in line with those given in publications[1-5] for comparable high explosives.

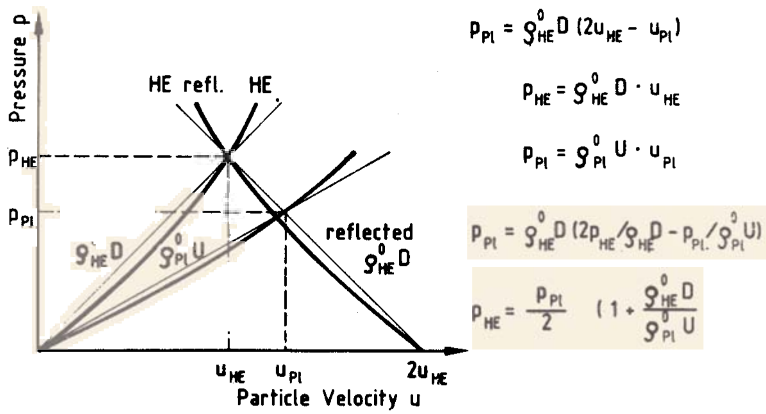

Figure 8. Shock impedance in acoustic approach.

Table 2. Summary of evaluated data.

HE-Types TNT/RDX/WAX	$\overset{0}{\rho}_{HE}$ [g/cm³]	D [m/s]	U_{Pl} [mm/µs]	p_{Pl} *1 [kbar]	p_{Pl} *2 [kbar]
49/50/1	1.667	7380	5.835	179.8	249.6
40/60/0	1.722	7840	6.087	199.2	285.7
35/65/0	1.728	7600	6.094	199.8	281.3
25/75/0	1.747	8010	6.434	227.5	322.77
15/85/0	1.771	(8630)	6.209	209.0	(321.21)
TNT/HMX					
35/65	1.721	7330	6.075	198.3	272.5
25/75	1.790	8420	6.079	198.6	306.7
15/85	1.847	8500	6.573	239.4	360.6

*1 $p_{Pl} = 1.187 \cdot U_S \cdot u_P$
$U_S = 2.12 + 1.56 \cdot u_P$

*2 $p_{CJ} = \frac{p_{Pl}}{2}\left(1 + \frac{\rho_{HE} \cdot D}{\rho_{Pl} \cdot U_{Pl}}\right)$
$\rho_{Pl} = 1.187\ g/cm^3$

Here, the straight line in the middle corresponds to the following equation :

$$P_{CJ} = 60.3\ \overset{\bullet}{\rho}_{HE} - 74.4$$

with a correlation coefficient of 0.93.

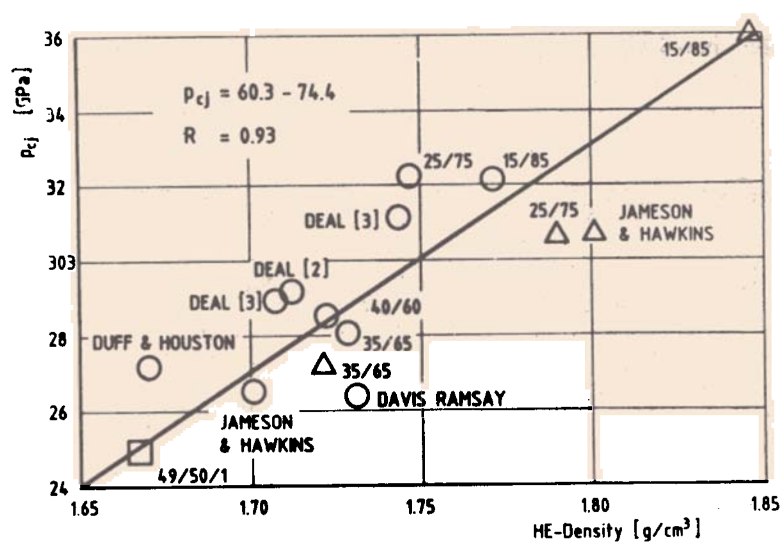

Figure 9. $P_{CJ} = f(\overset{\bullet}{\rho}HE)$ in comparison with values from literature.

5. SUMMARY

Larger high explosive charges, for example 64 mm diameter and 100 mm long, will induce shock waves in plexiglass which can be divided into 3 domains of ranges :

(i) Region A from 0 to 15 (or 20) mm, which can be associated with the detonation pressure and/or Chapman-Jouguet pressure.

(ii) Region B from 20 to 40 mm, for which there is no explanation at present.

(iii) Region D from 60 mm on, which with such size charges corresponds to the acoustic approximation, i.e. to the velocity of sound in the plexiglass.

The Chapman-Jouguet or detonation pressure of a high explosive charge can thus be determined by 'one' trial from analysis of the first range.

The advantage of plexiglass as a transparent medium is that its shock impedance is not too much different from that of the high explosives, i.e. a calculation of the detonation pressure from the pressure in the plexiglass does not involve any large errors. On the other hand, the reaction behaviour in the detonation zone, or reaction zone in general, will not be disturbed too much by the reflected pressure from the plexiglass.

A constant shock occurs in the range from 20 to 40 mm. This means that there is a constant pressure for which there is no explanation at present. This pressure is then reduced by the rarefactions coming in from the side and from the high explosive charge.

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