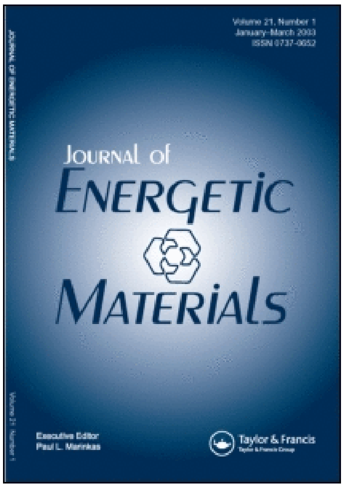

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Empirical estimate of detonation parameters in condensed explosives

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EMPIRICAL ESTIMATE OF DETONATION PARAMETERS IN CONDENSED EXPLOSIVES*

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ABSTRACT

Based on the available data base on the detonation parameters of existing explosives, an observation was made that by proper normalization with the dynamic pressure - $\rho_0 D^2$ the Chapman-Jouguet states of all explosives converge to a single generic point in the pressure-specific volume plane. With the exception of very few explosives, this point in P-V plane has a variance of less than 1%. The pressure-particle velocity (P-Up) plot of all Chapman-Jouguet states revealed a simple quadratic relationship between P and Up which, together with the nondimensional identities of the generic point, led to a simple relationship between the initial density (ρ_0) of an explosive and its detonation velocity (D).

Thus, having the values of ρ_0 and D of any explosive, one can easily estimate all of its detonation parameters (P_{CJ}, U_{CJ}, V_{CJ}, and Γ_{CJ}) with an accuracy of less than 3%. However, if the detonation velocity is also not known, it too can be estimated quite accurately, increasing the margin of uncertainty to about 10%.

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INTRODUCTION

For some applications exact values of the detonation parameters of explosives are not mandatory, and empirical estimates appear to be quite sufficient. This is especially true with new explosives, where one would like to calculate their performance and how much work can one expect from them. This need for a quick and easy calculation has resulted in several good empirical relations which are described in the literature.(1-4)

Most of the empirical relations are concerned only with the detonation velocity as the most important parameter. Only Kamlet and Jacobs(1) have derived a simple empirical expression for the Chapman-Jouguet pressure. In order to use all these empirical relations, one has to know the chemical composition of the products as well as the total chemical energy of the reaction taking place in a detonation wave. While all this information may readily be available in the handbooks, the process of evaluating the parameters may still be quite tedious.

Without diminishing the importance and value of existing empirical formulae, the intent of this communication is to point out an, as yet undescribed, observation which may simplify the estimating procedure and at the same time may lead to a better understanding of the detonation phenomenon.

The Detonation Wave Theoretical Model

In our present understanding the detonation wave consists of a shock wave followed by a reaction zone which in turn is followed by a zone in which the reaction products are relaxing to normal conditions. The whole detonation-wave complex is illustrated in Fig. 1a, where various dimensions are exaggerated for clarity. The shock wave raises the pressure and temperature of the initial explosive, causing it to undergo a chemical reaction either instantaneously or after a certain induction period, τ, which may be negligible or significant depending on the HE.

This reaction takes place in the reaction zone which is associated with either a pressure drop or a drop preceded by a slight rise. Attached to the reaction zone is a region where the products, usually in gaseous form, will expand, cool down and, with time, bring everything back to normal pressures. This region is known as the expansion region and, since it propagates as a wave, it is called a "release wave," known also as the "Taylor wave." The reaction zone is usually very thin and, depending on the explosive, it varies between several millimeters for some insensitive high explosives and only fractions of a millimeter for other more sensitive ones. The end of the reaction zone is known as the Chapman-Jouguet (CJ) state, which for each explosive has characteristic values of pressure (P_{CJ}), temperature (T_{CJ}), energy (E_{CJ}), specific volume (V_{CJ}), and particle velocity (U_{PCJ}). Also characteristic of a particular explosive is the detonation velocity (a phase front wave speed-D) at which the whole detonation complex propagates into the undisturbed medium.

In contrast to the nonsteady Taylor wave expansion region, the shock wave with the reaction zone is a steady complex; i.e., it does not vary with time and is governed by the usual conservation equations:

mass $$\rho_o D = \rho_{CJ}(D-U_{PCJ}), \qquad (1a)$$

momentum $$P_{CJ} - P_o = \rho_o U_{PCJ} D, \qquad (1b)$$

energy $$E_{CJ} - E_o = \rho_o \ (P_{CJ} + P_o)(1/\rho_o - 1/\rho_{CJ})/2, \qquad (1c)$$

where P, E, ρ, D and Up represent pressure, energy density, detonation (phase) velocity, and particle (mass) velocity respectively. The subscripts o and CJ correspond to the initial undisturbed state and the Chapman-Jouguet state respectively. Here P_o represents the initial pressure of the system, which in comparison to CJ pressures of any explosive is very small and can easily be neglected. The density ρ is the inverse of the specific volume V.

All the important parameters can be represented visually on the physical pressure-specific volume plane as illustrated in Fig. 1b. Here the jump conditions across the shock wave are represented by the Rankine-Hugoniot curve (RH), sometimes called simply a shock adiabat. This line represents the locus of states across the shock wave and does not include any energy terms from the chemical reaction; i.e., λ, the fraction of material reacted, equals zero. The locus of states across a shock wave with a completed reaction ($\lambda = 1$) is described by the Hugoniot curve (H), sometimes referred to as the reacted Hugoniot. The H line is offset from the RH line by the amount of energy Q that is released during the chemical reaction within the reaction zone. The steadiness of the shock front and the reaction zone is manifested by the Rayleigh line (R), whose slope on that plane represents the velocity of the wave. Thus, the pressure and specific volume of the material attained by the jump condition may be found at the intersection of the RH and R lines, indicated as the von Neumann point (VN). The end of the reaction zone must simultaneously be on the H line to indicate a complete reaction and on the R line to represent a steady wave. Additional constraints, namely that the wave be self-sustained and unaffected by the flow behind the reaction zone, force the Rayleigh line to be tangent with the Hugoniot curve and the CJ state to be at the point of tangancy. It can be shown that at this point we also have a tangancy of the isentrope (I) along which the expansion of the detonation products takes place. The energy of the process is represented on that plane as the triangular area under the Rayleigh line. All this is textbook material and has been described earlier in much greater detail by others.(5)

The Generic Explosive

The model described above was based on theoretical grounds and has proven to be extremely accurate. As mentioned earlier, most, if not all, important physical parameters of the detonation wave have values which are characteristic of the particular type and nature of the explosive material. Thus, in order to characterize an unknown explosive, one must subject it to various types of tests to determine its characteristic parameters. This has been done for many explosives whose parameters were measured and correlated by various sources and are now listed in various handbooks(6,7) and reports.(8,9) A list of such explosives from Ref. 6 is given in Table 1. Also shown in that table are the corresponding detonation parameters.

Most interesting observations are made when the parameters are normalized or expressed in a nondimensional form. In our case the most convenient normalization parameters are the initial density, ρ_o, and the detonation velocity, D, which are the most readily available and for most cases are very accurately measurable quantities. With $\rho_o D^2$, the "dynamic pressure," as the normalizing parameter, our set of conservation equations may be rewritten in the following form for

mass:

$$\tilde{U}_{CJ} \equiv U_{CJ}/D = 1 - \rho_o/\rho_{CJ} = 1 - V_{CJ}/V_o, \qquad (2a)$$

momentum:

$$\tilde{P}_{CJ} \equiv P_{CJ}/\rho_o D^2 = U_{CJ}/D, \qquad (2b)$$

and energy:

$$\tilde{E}_{CJ} - \tilde{E}_o \equiv E_{CJ}/\rho_o D^2 - E_o/\rho_o D^2 = [P_{CJ}/\rho_o D^2](1 - V_{CJ}/V_o)/2. \qquad (2c)$$

Here the value of P_o has been neglected, and the tilde (~) has been used to identify the non-dimensional form.

Comparing all these equations, one can write the following identities.

$$\tilde{P}_{CJ} = \tilde{U}_{CJ} = 1 - \tilde{V}_{CJ} \qquad (3)$$

and

$$\tilde{E}_{CJ} - \tilde{E}_o = \tilde{U}^2_{CJ}/2. \qquad (4)$$

An interesting observation is made when the values of $\tilde{P}_{CJ}$ and $\tilde{E}_0$ are evaluated for all the explosives that are listed in Table 1. These are listed in Table 2 and plotted against the initial density ρ_0 in Fig. 2. Looking at Fig. 2, one immediately observes that while the normalized pressure $\tilde{P}_{CJ}$ converges to a single value of 0.265, the normalized energy term $\tilde{E}_0$ shows a linear dependency on the initial density with an intercept of 0.204 and a slope of -0.0734, so that

$$\tilde{E}_0 = 0.204 - 0.0734\,\rho_0. \qquad (5)$$

The standard deviation of $\tilde{P}_{CJ}$ from its average value is only 3%, which can further be reduced if some of the low-density explosives are not taken into account. The standard deviation of $\tilde{E}_0$, on the other hand, shows also a strong dependence on the initial density, decreasing rapidly to zero at or near $\rho_0 = 2.1$.

Thus, looking at the above identities in (3), one should note that if $\tilde{P}_{CJ}$ is very nearly a constant for all known explosives then so are $\tilde{U}_{CJ}$ and $\tilde{V}_{CJ}$ with a very small variance. At the same time if $\tilde{E}_0$ has a linear dependence on ρ_0 then so does $\tilde{E}_{CJ}$, since it differs from $\tilde{E}_0$ by nearly a constant value of $\tilde{U}^2{}_{CJ}/2$.

Furthermore the detonic system gamma, defined as

$$\Gamma \equiv -d\ln P/d\ln V, \qquad (6)$$

represents the rate of pressure release in the expansion of the explosion products, can also be normalized and evaluated at the CJ state,

$$\Gamma_{CJ} = -\tilde{V}_{CJ}/\tilde{P}_{CJ}\ (d\tilde{P}/d\tilde{V})_{CJ} = [\tilde{V}_{CJ}{}^{-1} - 1]^{-1} = \tilde{U}_{CJ}{}^{-1} - 1. \qquad (7)$$

Here we applied the identity that at the CJ point dP/dV = -1 (Ref. 10). This identity again leads to an observation that the value of Γ_{CJ} is also nearly constant for all the explosives, with a small variance.

When Chapman-Jouguet state parameters of all the explosives listed in Table 1 are viewed in the normalized $\widetilde{P}$-$\widetilde{V}$-$\widetilde{E}$ space, as shown in Fig. 3, one can immediately notice that the internal energy of an explosive has very little effect, if any, on the CJ values of pressure, particle velocity, specific volume, or even gamma. With the exception of energy, the CJ parameters of all the explosives listed in Table 1 converge to a point with a very small variance in both $\widetilde{P}$ and $\widetilde{V}$ directions. This point in the $\widetilde{P}$-$\widetilde{V}$ plane may therefore be viewed as the C-J state of a generic explosive. Thus, knowing the initial density of an explosive and its detonation velocity, one can easily estimate all the CJ parameters of that explosive including the value of its internal energy (E_0) and, by virtue of a kinetic energy term common to all explosives ($\widetilde{U}^2{}_{CJ}/2$), also the CJ energy (E_{CJ}).

Another interesting observation is made when all the CJ states are plotted on the pressure-particle velocity plane as shown in Fig. 4. With only very few exceptions, all the points fall within a narrow band, and can be fitted with a quadratic expression

$$P_{CJ} = A + BU_{CJ} + C\,U_{CJ}{}^2 \ , \qquad (8)$$

where the constants A, B, and C are equal to -6.749, -4.749, and 10.27 respectively.

On the same plane a straight line through the origin represents a well-known Rayleigh line of the form

$$P/U_p = \rho_0 D. \qquad (9)$$

Thus, knowledge of both ρ_0 and D can immediately determine both P_{CJ} and U_{CJ} of that explosive.

However, by nondimensionalizing Eqn. 8 and using identities in (3) we can get the quadratic equation

$$aD^2 + bD + c = 0, \qquad (10)$$

where both b and c are constants $\tilde{P}_{CJ}B$ and A, respectively, and

$$a = \tilde{P}_{CJ}{}^2C - \tilde{P}_{CJ}\rho_o \qquad (11)$$

contains the variable ρ_o, giving us still another empirical link but this time between ρ_o and D. Indeed, comparing the D-ρ_o relationship as calculated from this empirical formula with the values listed in Table 1 one sees a very good correlation. This is illustrated in Fig. 5. Although there appears to be a certain scatter in the listed data, the correlation is evident and one can use the empirical formula for making estimates with great confidence.

The Effect of Initial Charge Density

One of the important relationships in the detonic field, the detonation velocity with the initial charge density, has been the subject of many earlier investigations.(2,3,11,12) Most of these earlier studies were devoted to the effect of initial charge density of one particular pure or composite explosive with additives. The object was to determine not only the expected linear relationship of D(ρ_o) but also the local deviations from that linearity and the probable cause for such deviations.(11,12) In our study we have looked at the general problem and have uncovered a relationship that is based on the data base of explosives available in the open literature,(6) including some which have been listed several times but with different initial charge densities.

Among the earlier studies, one in particular(3) is of interest because it offers an interesting correlation with our results.

Assuming that $D(\rho_o)$ relationship is linear,

$$D = A + B\rho_o, \tag{12}$$

the authors of Ref. 3 determined and listed both constants A and B for nineteen explosives and their various mixtures. Then, for each particular explosive or mixture they derived a generalized expression

$$D/D_o = (1-\alpha) + \alpha\, \rho_{oo}/\rho_o, \tag{13}$$

which provides the $D(\rho_{oo})$ relationship for a particular explosive relative to the maximum detonation velocity (D_o) that can be obtained with the maximum charge density (ρ_o). The best fit for all the explosives and their mixtures resulted in $\alpha = 0.74$ and $(1-\alpha) = 0.26$ with a variance of 0.0011 and a standard deviation of 0.03. These two constants are remarkably close to our nondimensional values of $\tilde{V}_{CJ}$ and P_{CJ}, respectively, which as shown in Eqn. 3 are related as $\tilde{P}_{CJ} = 1-\tilde{V}_{CJ}$. Thus, within a maximum error of 5% one can rewrite the above expression to read

$$D/D_o = \tilde{P}_{CJ} + \tilde{V}_{CJ}\ \rho_{oo}/\rho_o. \tag{14}$$

It is not immediately obvious whether this is merely a remarkable coincidence or is yet another bonus feature of normalization, but it can be shown that with

$$A = D\,\tilde{P}_{CJ} \text{ and } B = D/\rho_{CJ} \tag{15}$$

Eqns. 12 and 14 are in full agreement with the experimental data discussed in Ref. 3.

For the purpose of correlating these results with our findings, Eqn. 14 may be rewritten as

$$d(D)/d(\rho_{oo}) = \tilde{V}_{CJ}\, Do/\rho_o \qquad (16)$$

to show that the slope of the $D(\rho_{oo})$ line is constant and that its value depends on both ρ_o and D_o, which represent the maxima of initial charge density and the corresponding detonation velocity of a particular explosive in question.

Such linear $D(\rho_{oo})$ relationships for four representative explosives are shown in Fig. 6 together with the general nonlinear $D(\rho_o)$ relationship derived above in this communication (Eqns. 10 & 11). Using this figure, one can make reasonable estimates either for the maximum density materials or for their less compact derivatives.

Useful Consequences

Having established that a unique feature of most explosives is within a very small region of variance in $\tilde{P}_{CJ}$, $\tilde{V}_{CJ}$, $\tilde{E}_o$, $\tilde{E}_{CJ}$, and $\tilde{U}_{CJ}$, we can make use of some of the consequences that follow.

One of the most significant benefits of these observations is the reduction in need for many costly experiments to characterize a given explosive material. It seems that knowing only the initial density of an unknown explosive may yield all the information needed with an accuracy of less than 5%.

Another significant outcome of these observations is that no matter how different various explosives are, in a normalized form they all seem to be very similar. Thus, in order to formulate a new, more powerful substance with larger E_{CJ} or P_{CJ} one needs to increase its density and with it the detonation velocity. Of course this notion is not new and has been known for a long time, but here this effect has been more vividly quantified. A small increase in initial density can provide a significant increase in the detonation velocity, which together will provide the desired change in both pressure and energy, raising it by a factor of $(\rho_0 D^2)$new/$(\rho_0 D^2)$old. Although at first glance the distribution of Fig. 2 may suggest that an increase in density will have an adverse effect on the internal energy of an explosive, a closer look will reveal that it is only true in the nondimensional form. In the dimensional form, with D also increasing, the energy of a denser material is also higher.

The detonic system gamma, which is the most sensitive parameter during the analysis of the expanding products behind the Chapman-Jouguet plane, when evaluated at that plane is found to be not only independent of the initial charge density, as suggested earlier,(13) but is also nearly the same for all explosives. This value averages 2.77 with a standard deviation of less than 4% and is about 8.3% lower than the value of 3.0, which, for most earlier calculations, was found to be quite acceptable.

CONCLUSIONS

It is with the extended list of formally investigated materials that the above observations pertaining to primary explosives could be made and useful information about a generic explosive could be extracted. While this information is not intended for fine tuning of a working system it is useful for casual estimates of the performance capability of a new explosive or even for relative comparisons between systems of varying compositions. It should be noted that some of the old explosives do not seem to follow this rule and should be considered as exceptions. A vivid example of such a disobedient substance is Baratol, whose $\rho_0 = 2.6$ g/cc, D = 4.87 mm/μs, and $P_{CJ} = 14$ GPa(6). There may be others, but they should be very few.

Generally, chemical explosives occupy a relatively narrow range on the temperature scale of combustible materials. For this reason it should be expected that their performance is not vastly different when normalized to expose their primary characteristics. This is because the conservation laws of mass, momentum, and energy constrain flow conditions to the point where only a small statistical fluctuation exists among the normalized operating parameters.

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TABLE 1. A Short List of Explosives With Essential Detonation Parameters as Listed in Ref. 6.

Explosive	ρ (g/cc)	D (mm/μs)	P_{CJ} (GPa)	U_{CJ} (mm/μs)	E_0 (GPa-m^3/m^3)	Γ
BTF	1.859	8.480	36.00	2.28364	11.5000	2.717
Comp A-3	1.650	8.300	30.00	2.19058	8.9000	2.790
Comp B	1.717	7.980	29.50	2.15302	8.5000	2.706
Comp C-4	1.601	8.193	28.00	2.13464	9.0000	2.838
Cyclotol	1.754	8.250	32.00	2.21140	9.2000	2.731
DIPAM	1.550	6.700	18.00	1.73327	6.2000	2.842
EL-506A	1.480	7.200	20.50	1.92380	7.0000	2.752
EL-506C	1.480	7.000	19.50	1.88224	6.2000	2.719
Expl. D	1.420	6.500	16.00	1.73348	5.4000	2.750
FEFO	1.590	7.500	25.00	2.09644	8.0000	2.578
H-6	1.760	7.470	24.00	1.82548	10.3000	3.092
HMX	1.891	9.110	42.00	2.43803	10.5000	2.740
HNS	1.000	5.100	7.50	1.47059	4.1000	2.468
HNS	1.400	6.340	14.50	1.63362	6.0000	2.881
HNS	1.650	7.030	21.50	1.85353	7.4500	2.804
LX-01	1.230	6.840	15.50	1.84234	6.1000	2.711
LX-04-1	1.865	8.470	34.00	1.15237	9.5000	2.935
LX-07	1.865	8.640	35.50	2.20311	10.0000	2.921
LX-09-1	1.840	8.840	37.50	2.30548	10.5000	2.834
LX-10-1	1.865	8.820	37.50	2.27973	10.4000	2.868
LX-11	1.875	8.320	33.00	2.11538	9.0000	2.868
LX-14-0	1.835	8.800	37.00	2.29131	10.2000	2.841
LX-17-0	1.900	7.600	30.00	2.07756	6.9000	2.658
NM	1.128	6.280	12.50	1.76458	5.1000	2.538
Octol 78	1.821	8.480	34.20	2.21473	9.6000	2.830
PBX-9010	1.787	8.390	34.00	2.26774	9.0000	2.700
PBX-9011	1.777	8.500	34.00	2.25098	8.9000	2.776
PBX-9404	1.840	8.800	37.00	2.28508	10.2000	2.851
PBX-9407	1.600	7.910	26.50	2.09387	8.6000	2.513
Pentolite	1.700	7.530	25.50	1.99203	8.1000	2.780
PETN	0.880	5.170	6.20	1.36276	5.0200	2.668
PETN	1.260	6.540	14.00	1.69895	7.1900	2.831
PETN	1.500	7.450	22.00	1.96868	8.5600	2.788
PETN	1.770	8.300	33.50	2.28031	10.1000	2.640
Tetryl	1.730	7.910	28.50	2.08268	8.2000	2.798
TNT	1.630	6.930	21.00	1.85908	7.0000	2.727

TABLE 2. Normalized Detonation Parameters for the Explosives Listed in Table 1.

Explosive	ρ (g/cc)	D (mm/μs)	$\tilde{P}_{CJ} = \tilde{U}_{CJ}$	$\tilde{V}_{CJ}$	$\tilde{E}_0$	$\tilde{E}_{CJ}$	Γ_{CJ}
BTF	1.859	8.480	0.26930	0.73070	0.08603	0.12229	2.713
Comp A-3	1.650	8.300	0.26393	0.73607	0.07830	0.11313	2.789
Comp B	1.717	7.980	0.26980	0.73020	0.07774	0.11414	2.706
Comp C-4	1.601	8.193	0.26054	0.73946	0.08375	0.11769	2.838
Cyclotol	1.754	8.250	0.26805	0.73195	0.07706	0.11299	2.731
DIPAM	1.550	6.700	0.25870	0.74130	0.08911	0.12257	2.866
EL-506A	1.480	7.200	0.26719	0.73281	0.09124	0.12693	2.743
EL-506C	1.480	7.000	0.26889	0.73111	0.08549	0.12164	2.719
Expl. D	1.420	6.500	0.26669	0.73331	0.09001	0.12557	2.750
FEFO	1.590	7.500	0.27952	0.72048	0.08945	0.12851	2.578
H-6	1.760	7.470	0.24438	0.75562	0.10488	0.13474	3.092
HMX	1.891	9.110	0.26762	0.73238	0.06691	0.10272	2.737
HNS	1.000	5.100	0.28835	0.71165	0.15763	0.19920	2.468
HNS	1.400	6.340	0.25767	0.74233	0.10662	0.13982	2.881
HNS	1.650	7.030	0.26366	0.73634	0.09136	0.12612	2.793
LX-01	1.230	6.840	0.26935	0.73065	0.10600	0.14228	2.713
LX-04-1	1.865	8.470	0.25412	0.74588	0.07100	0.10329	2.935
LX-07	1.865	8.640	0.25499	0.74501	0.07183	0.10434	2.922
LX-09-1	1.840	8.840	0.26080	0.73920	0.07302	0.10703	2.834
LX-10-1	1.865	8.820	0.25847	0.74153	0.07168	0.10509	2.869
LX-11	1.875	8.320	0.25425	0.74575	0.06934	0.10166	2.933
LX-14-0	1.835	8.800	0.26038	0.73962	0.07178	0.10568	2.841
LX-17-0	1.900	7.600	0.27336	0.72664	0.06287	0.10024	2.658
NM	1.128	6.280	0.28098	0.71902	0.11464	0.15412	2.559
Octol 78	1.821	8.480	0.26117	0.73883	0.07331	0.10742	2.829
PBX-9010	1.787	8.390	0.27029	0.72971	0.07155	0.10808	2.700
PBX-9011	1.777	8.500	0.26482	0.73518	0.06932	0.10439	2.776
PBX-9404	1.840	8.800	0.25967	0.74033	0.07158	0.10530	2.851
PBX-9407	1.600	7.910	0.26471	0.73529	0.08591	0.12094	2.778
Pentolite	1.700	7.530	0.26455	0.73545	0.08403	0.11902	2.780
PETN	0.880	5.170	0.26359	0.73641	0.21342	0.24816	2.794
PETN	1.260	6.540	0.25978	0.74022	0.13341	0.16716	2.849
PETN	1.500	7.450	0.26425	0.73575	0.10282	0.13773	2.784
PETN	1.770	8.300	0.27474	0.72526	0.08283	0.12057	2.640
Tetryl	1.730	7.910	0.26330	0.73670	0.07576	0.11042	2.798
TNT	1.630	6.930	0.26827	0.73173	0.08942	0.12541	2.728
average			0.26500	0.73500	0.09003	0.12518	2.777010
variance			0.00007	0.00007	0.00080	0.00083	0.013022
			0.02%	0.01%	0.89%	0.66%	0.47%
std. dev.			0.00808	0.00808	0.02828	0.02882	0.11411
			3.05%	1.10%	31.41%	23.03%	4.11%

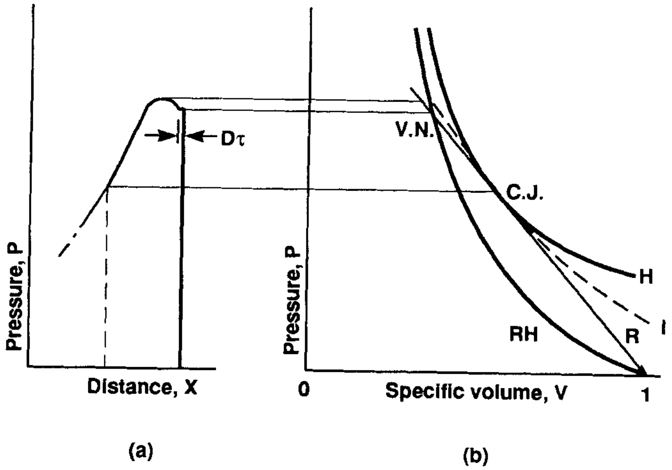

FIGURE 1

Detonation-wave profile as viewed on (a) pressure-distance (or time) and (b) pressure-specific volume planes.

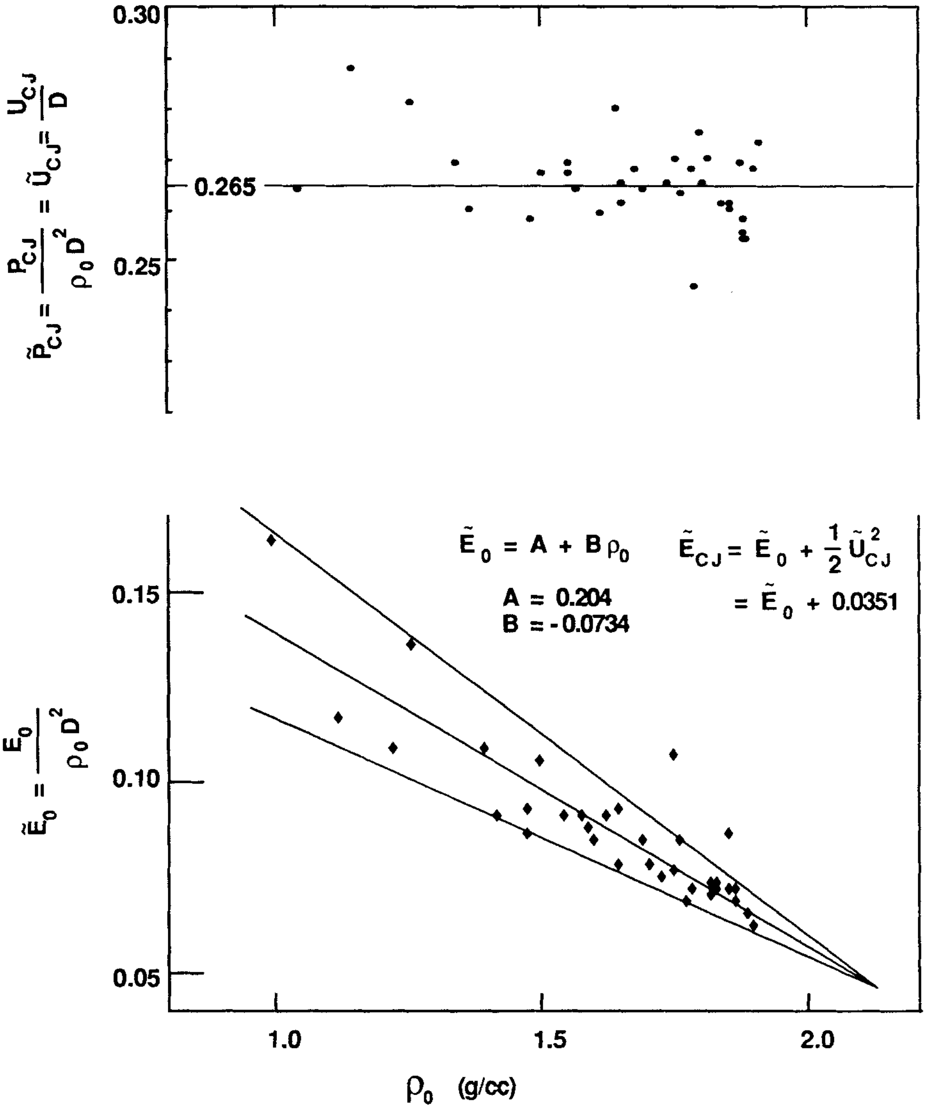

FIGURE 2

Normalized values of (a) pressure and (b) internal energy plotted against initial density of all explosives listed in Table 1.

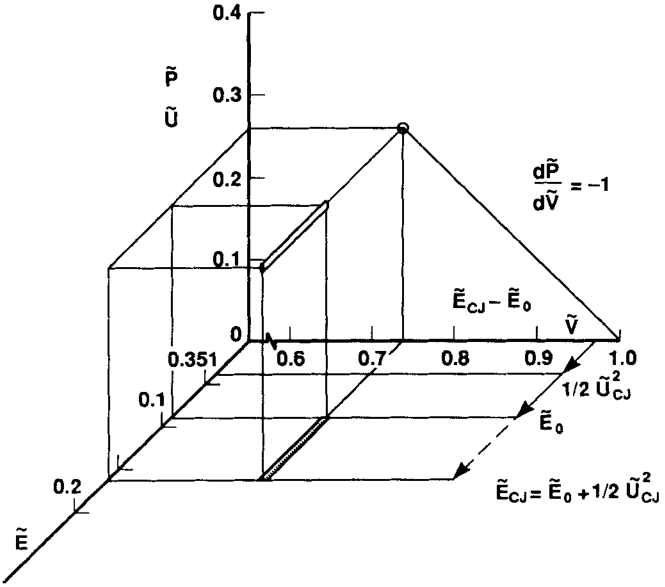

FIGURE 3

Normalized pressure-specific volume-energy space where on the $\tilde{P}$-$\tilde{V}$ plane all explosives listed in Table 1 converge to a single point with a small variance.

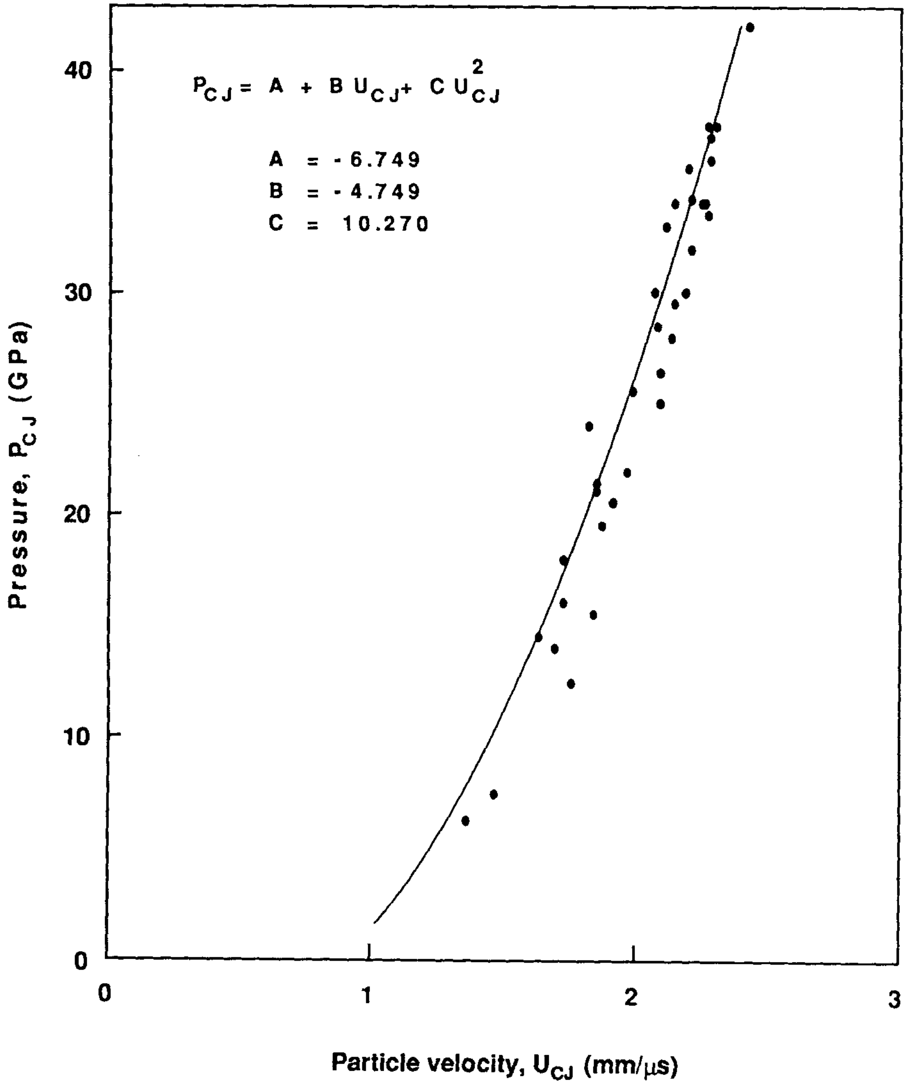

FIGURE 4

Pressure-particle velocity plane with the Chapman-Jouguet values of all explosives listed in Table 1. The solid line represents the best quadratic fit through the data points.

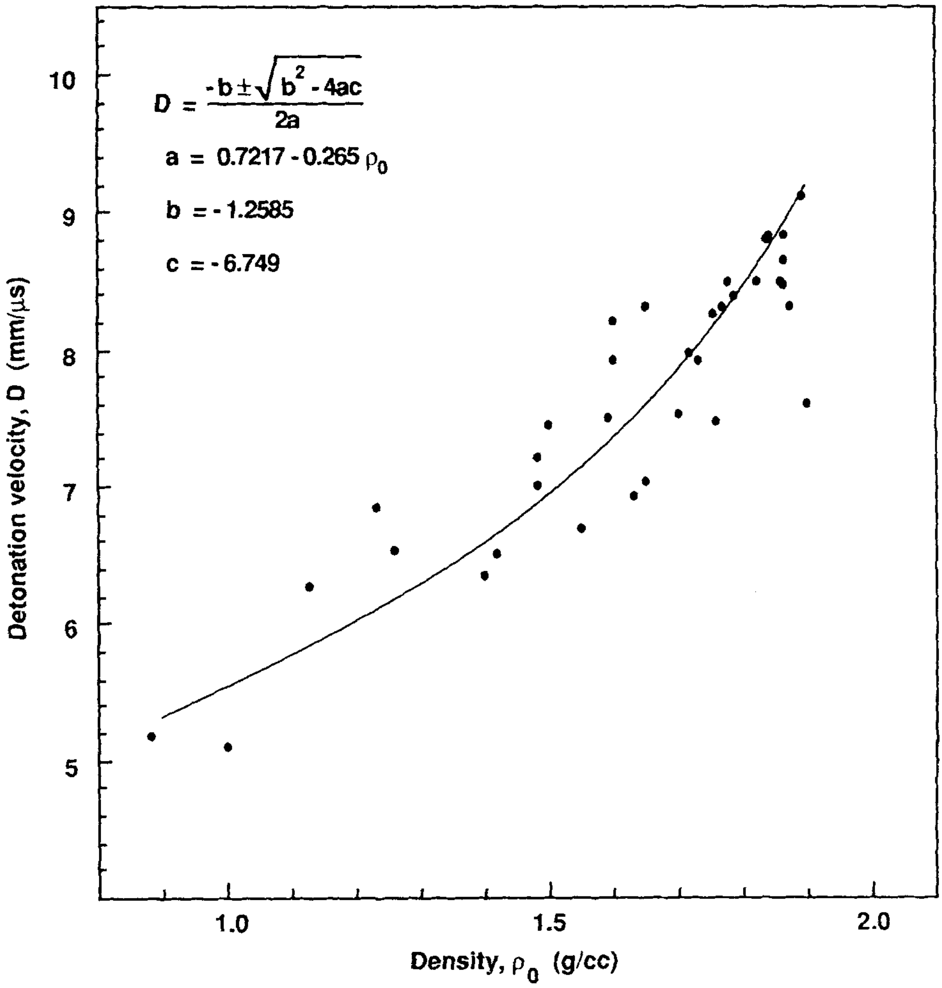

FIGURE 5

Detonation velocity-initial density plane with the points corresponding to the explosives listed in Table 1 and the line derived from the quadratic fit in Fig. 4 and the average normalized CJ pressure, which turned out to be unique for all explosives listed in Table 1.

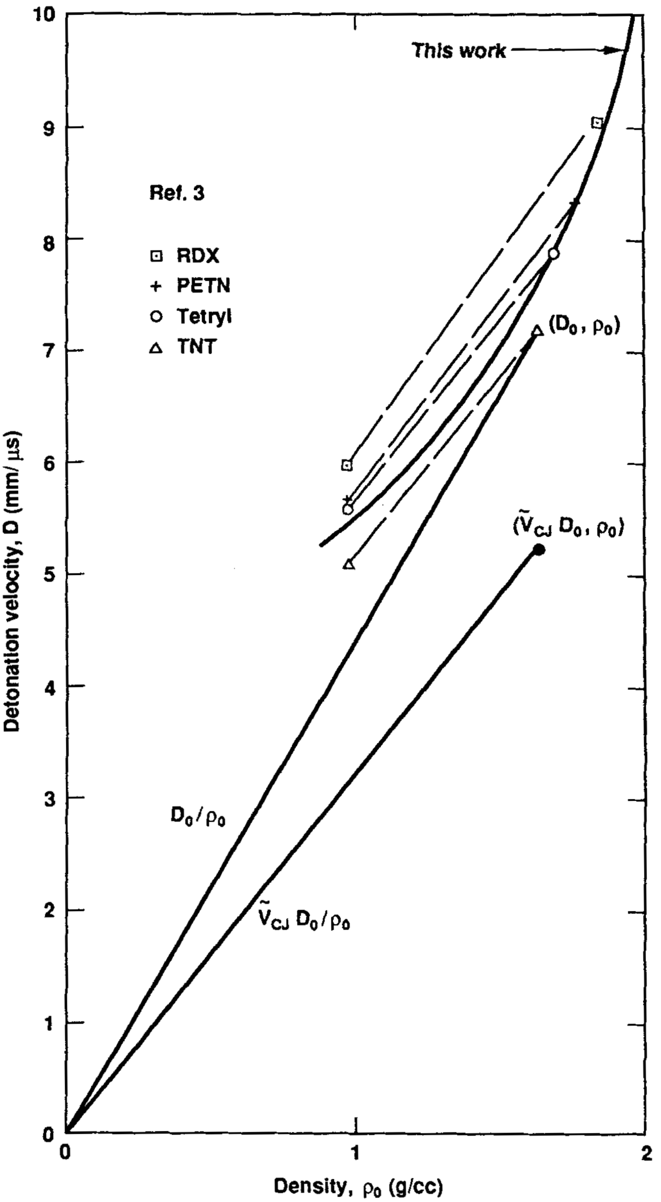

FIGURE 6
Comparison of linear $D(\rho_{oo})$ relationships for four representative explosives discussed in Ref. 3 with the general nonlinear $D(\rho_o)$ relationship of this work.