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Critical Shock Energy and Shock and Detonation Parameters of an Explosive

H.S. Yadav, S.N. Asthana, and A. Subhananda Rao

High Energy Materials Research Laboratory, Pune-411 021

ABSTRACT

The present study deals with the connection between critical shock energy and detonation properties of an explosive. A relation for critical shock energy has been derived in terms of detonation velocity, width of reaction zone, initial density of the explosive, specific heat ratio of detonation products and either constants of linear relation between shock and particle velocity of the explosive or the constants of the Murnaghan's type of equation of state of the explosive. These relations have been used to calculate the critical shock energy of RDX, HMX, RDX/TNT (60/40) and TNT explosives. The values of critical shock energies obtained in this study are in close agreement with those reported in the literature.

Keywords: Critical shock energy, shock, detonation, explosives, RDX, HMX, RDX/TNT

1. INTRODUCTION

The shock wave is an effective stimulus to cause initiation of detonation in an explosive because it not only compresses the explosive but also imparts kinetic energy to it and raises its temperature**.** If a time-dependent shock wave of pressure $P(t)$ and particle velocity $U(t)$ is produced in an explosive, then the shock energy (E_s) that enters per unit area of the explosive in time ts is obtained from the relation.

$$E_s = \int_0^{ts} P(t)U(t)dt \tag{1}$$

If mean values of pressure and particle velocity are denoted by $\overline{P}$ and $\overline{U}$, then eqn (1) is readily integrated to give

$$E_s = \overline{P}\,\overline{U}\,ts \tag{2}$$

Similarly if the shock wave of uniform pressure (P) and particle velocity (U) propagates in the explosive, then integration of eqn (1) gives,

$$E_s = \text{Puts} \tag{3}$$

Walker and Wasley[1] proposed that a uniform shock wave initiates a bare heterogeneous explosive only if the shock energy E_s becomes equal to a critical energy E_c which is a characteristic value of shock energy for each explosive. If shock energy E_s builds up in explosive to energy E_c in time τ, then eqn (3) gives,

$$E_c = PU\tau \tag{4}$$

This critical shock energy criterion has been studied experimentally by Longuiville, *et al*[2] and Moulard[3]. These authors produced shock wave in explosive by impact of flyers plates and kinetic energy projectiles respectively. The results of flyer plate impact[2] were found in agreement with the critical energy criterion for some explosives but the results of kinetic energy projectile gave critical velocity of impact for initiation always higher than what is predicted by the critical energy criterion.

To extend the application of critical energy criterion to the explosive initiation by impact of kinetic energy projectiles, *James*[4] suggested that the shock duration τ in eqn (3) should be replaced by the time of maximum energy of uniform shock wave T in the explosive. With this modification, the energy criterion for shock initiation is obtained as

$$E_c = PUT \tag{5}$$

In addition to critical energy, the sensitivity of an explosive to shock wave was also obtained from Pop-plots[5] and gap test[6] methods.

In all these sensitivity tests, since the nature of shock-profile was different, therefore different shock sensitivity results were obtained as pointed out by Souers and Vitello[7]. Yadav[8] has earlier pointed out the comparison of heights of inert barrier in gap tests may lead to erroneous comparison of sensitivity of the test explosives, if the shock-impedances of the explosive and barrier differ widely. Clement and Rudolf[9], have used small scale gap test method for measuring shock initiation thresholds of HNS explosive as a function of its density.

It is obvious that the experimental setups commonly used for measuring shock sensitivity of explosives give different results. Also the measurement of shock-sensitivity by these three methods involves conduction of a large number of controlled shock wave experiments. Attempt, has been made to derive a relation for critical shock energy of an explosive in terms of its detonation properties which can be easily measured.

The basic concepts that suggest the present approach

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lie in the fact that a shock wave energy in front of *C-J* plane of reaction zone produces a steady detonation wave in the explosive. Therefore, this shock wave energy can be considered as critical shock energy of the explosive.

2. THEORETICAL

The present theoretical approach for determination of critical shock energy of an explosive is based on the ZND model of detonation wave as shown in Fig.1. According to this model, the detonation wave in an explosive has a shock discontinuity in the front and a *C-J* plane at the rear. The exothermic chemical reaction starts at the shock front and gets completed at the *C-J* plane. In between these two boundaries lies the reaction zone where chemical reaction proceeds non-linearly. Infact, maximum mass of explosive in between shock front and *C-J* plane, undergoes chemical reaction in the vicinity of the *C-J* plane only. In view of this, one can assume that the explosive undergoes chemical reaction almost instantaneously at the *C-J* plane due to shock energy available in between shock front and *C-J* plane of a detonation wave and chemical energy released in the reaction in between shock front and *C-J* plane does not influence the process of initiation of detonation.

Suppose the velocity of C-J plane and shock front of a detonation wave are denoted by D_j and U_s respectively. If the detonation wave is one-dimensional, plane and steady, then both *C-J* plane and shock front propagate in the explosive with equal velocity. As is shown in Fig. 2, the shock velocity and detonation velocity are given by the slope of same Raleigh line AB. Therefore, for a steady and plane detonation wave, one gets

$$D_j = U_s \tag{6}$$

In a solid explosive, the shock velocity U_s has a linear relation with its particle velocity behind the shock front U_p as

$$U_s = a_x + b_x U_p \tag{7}$$

where a_x and b_x are constants of the explosive. Combining Eqn (6) with Eqn (7), one gets

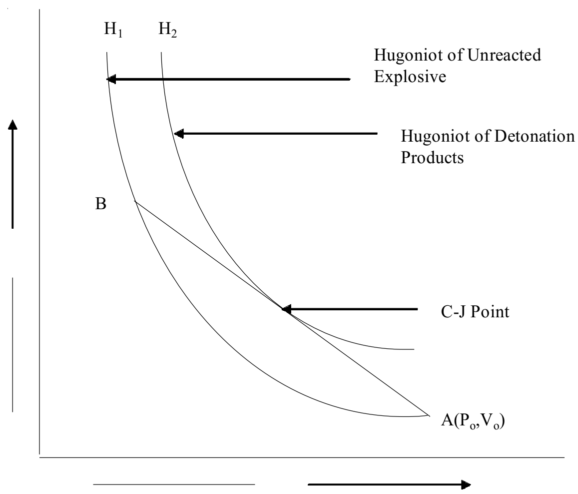

Figure 1. Hugoniots of explosive (H_1) detonation-products (H_2) with R-line AB. Slope of AB ($\sim U_s$) = Slope of AC (D_j).

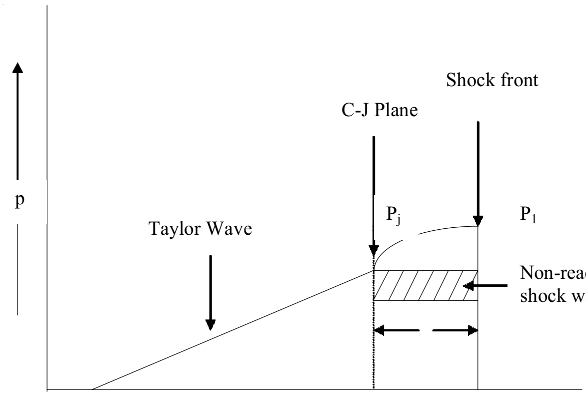

Figure 2. ZND model of detonation wave with non-reactive shock wave.

$$U_p = \frac{D_j - a_x}{b_x} \tag{8}$$

Applying the law of conservation of mass across the shock front, one obtains an average density of explosive ρ behind the shock front as

$$\rho_o D_j = \rho(D_j - U) \tag{9}$$

where ρ_o is the initial density of the explosive and U is the average particle velocity between shock front and *C-J* plane. If U_j is the particle velocity at *C-J* plane and U_p is the particle velocity behind the shock front, then average particle velocity in small width of reaction zone is obtained as

$$U = \frac{U_j + U_p}{2} \tag{10}$$

Combining Eqns (8) and (10), one gets

$$U = \frac{U_j}{2} + \frac{1}{2}\left(\frac{D_j - a_x}{b_x}\right) \tag{11}$$

where U_j is obtained from simple theory of detonation wave as

$$U_j = \frac{D_j}{r+1} \tag{12}$$

Here, *r* is the specific heat ratio of detonation products. If δ in the distance between shock front and *C-J* plane, then the energy of the shock wave per unit area of the explosive between shock front and the *C-J* plane is readily obtained as

$$E_s = \rho u^2 \delta \tag{13}$$

Obtaining the value of density from Eqn (9) as

$$\rho = \rho_o D_j / (D_j - u) \tag{14}$$

and substituting this value in Eqn (13), one gets

$$E_s = E_c = \frac{\rho_o D_j U^2 \delta}{(D_j - U)} \tag{15}$$

Also, substituting U from Eqn (11) in eqn, one gets

$$E_c = \frac{\rho_o D_j \delta \left[\frac{D_j - a_x}{2b_x} + \frac{D_j}{2(r+1)} \right]^2}{D_j - \left(\frac{D_j - a_x}{2b_x} + \frac{D_j}{2(r+1)} \right)} \quad (16)$$

This relation expresses the critical shock energy of an explosive in terms of its basic properties like, its initial density ρ_0, velocity of detonation D_j, thickness of reaction zone ä , specific heat ratio of detonation products r and its Hugoniot constants a_x and b_x. The later two constants are determined by measuring shock and particle velocity in the explosive. These measurements, however, can be avoided if the constants a_x and b_x are obtained alternatively. In order to accomplish this, one first obtain the eqn of Hugoniot of the explosive by combining Eqn (7) with equations of conservation of mass and momentum which are given as

$$\rho_o U_s = \rho(U_s - U_p) \quad (17)$$

$$P = \rho_o U_s U_p \quad (18)$$

Where ρ_o is the initial density of the explosive and P, ρ, and U_p denote the pressure, density and particle velocity behind the shock front moving in explosive with velocity U_s. Combining eqn (7) with eqn (17) and (18), one readily obtains the relation for Hugoniot of the explosive as

$$P = \frac{\rho_o a_x^2 \eta}{(1 - b_x \eta)^2} \quad (19)$$

where $\eta = \left(1 - \frac{\rho_o}{\rho}\right)$. If Murnaghan's type of eqn of state[10] of the explosive is given by the relation,

$$P = A\left[\left(\frac{\rho}{\rho_o}\right)^n - 1\right] \quad (20)$$

then, the condition, $\left(\frac{d^2P}{d\rho^2}\right)_H = \left(\frac{d^2P}{d\rho^2}\right)_s$ at initial state ($P_o V_o$), which is the centre for both curves given by eqn (19) and (20), gives[11]

$$b_x = \frac{n+1}{4} \quad (21)$$

$$a_x = \left(\frac{An}{\rho_o}\right)^{1/2} \quad (22)$$

Substituting eqns (21) and (22) in eqn (16), one gets the expression for critical shock energy of an explosive as

$$E_c = \frac{\rho_o D_j \delta \left[\frac{2\left(D_j - \sqrt{An/\rho_o}\right)}{n+1} + \frac{D_j}{2(r+1)} \right]^2}{D_j - \left[\frac{2\left(D_j - \sqrt{An/\rho_o}\right)}{n+1} + \frac{D_j}{2(r+1)} \right]} \quad (23)$$

This relation shows that the critical shock energy of an explosive can be computed from the knowledge of velocity of detonation wave and the constants of the explosive, ρ_0, δ, r, A and η.

3. RESULTS AND DISCUSSION

The critical shock energies of RDX/TNT (60/40), TNT, HMX and RDX explosives have been computed from relation Eqn (16). The detonation properties like D_j, δ, r and ρ_0 and shock parameters like a_x and b_x of these explosives are enlisted in Table 1. Substituting these parameters in Eqn (16), one can directly calculate the values of critical shock energy E_c. To simplify the calculations, however, the calculations of E_c of different explosives have been performed in the following steps :

Step 1. $U_j = \frac{D_j}{r+1}$

Step 2. $U_p = \frac{D_j - a_x}{b_x}$

Step 3. $U = \frac{U_j + U_p}{2}$

Step 4. $E_c = \frac{\rho_o D_j \delta U^2}{D_j - U}$

where U_j, U_p and U denote the particle velocities in *C-J* plane, at shock front and average particle velocity between shock front and *C-J* plane. The constants of above eqns like D_j, δ, r, a_x and b_x have been taken from Table 1. The values of E_c obtained from these calculations are shown in Table 3. where corresponding values of E_c reported in literature[4] are also shown.

If shock parameters of the explosive a_x, and b_x are not available for some explosives, then these constants are expressed in terms of constants (A, n) of Murnaghan's type of equation of state. The values of these constants have been obtained by using eqns (21) and (22) and are shown in Table 2. The value of critical shock energy of different explosives have been computed by substituting the constants of Table 2. in eqn (23). These values of E_c are similar to those shown in Table 3.

The critical shock energies obtained in the present work for RDX/TNT, HMX and RDX are reasonably in good agreement with those reported in the literature. In case of TNT, however, the present values of 83.5 J/cm^2 is close to the upper value of reported TNT range of values from (64–77) J/cm^2. The main uncertainty in these calculations lies in the values of width of reaction zone. In the present work, only those standard values of reaction zone width (δ) are used which have been reported in the literature.

4. CONCLUSION

This study concludes that the relation for critical energy, given by Eqn (16), gives values of critical energy which compare with reported values within a variation of maximum

Table 1. Detonation and shock wave parameters of different explosives

Explosive	Density (g/cc) ρ_o	Detonation parameters			Shock Wave Parameters		Ref. No.
		VOD, (mm/µs) D_j	Specific heat ratio, (γ)	Width of reaction zone, (δ) cm	a_x (mm/µs)	b_x (mm/µs)	
RDX/TNT (60/40)	1.72	7.98	2.711	0.013	2.71	1.86	4
Pressed TNT	1.54	6.93	2.725	0.01	2.08	2.33	4
HMX	1.77	9.03	3.013	0.01	2.40	2.40	2
RDX	1.60	8.30	2.98	0.01	2.30	1.80	2

Table 2. Detonation parameters and equation of state constants of various explosives

Explosive	Density(g/cc) ρ_o	Detonation velocity, (mm/µs) D_j	Specific heat ratio (γ)	Width of reaction zone, Δcm	Equation of state constants	
					A kbar/cm^2	*N*
RDX/TNT (60/40)	1.72	7.98	2.711	0.013	19.629	6.44
Pressed TNT	1.54	6.93	2.725	0.01	8.0	8.32
HMX	1.77	9.03	3.013	0.01	11.85	8.60
RDX	1.60	8.30	2.98	0.01	13.65	6.20

Table 3. Comparison of calculated and reported values of critical shock energies of different explosives

S.No.	Explosive	Density g/cc	Critical shock energy Ec, J/cm^2		Reference No.
			Calculated	Reported	
1.	RDX/TNT (60/40)	1.72	201.80	190.0	4
2.	TNT	1.54	83.50	77.0	4
3.	HMX	1.77	153.89	150.0	2
4.	RDX	1.60	174.30	175.0	2

8.4% for TNT and a minimum of -0.57% for RDX, as is shown in Table 2.

The present relation for critical energy given by Eqn (16) is easily transformed to a new relation for critical energy given by Eqn (23). This relation avoids use of shock parameters and make use of equation of state parameters of the explosive. With these relations, one can now calculate the critical shock energy by knowing conveniently measurable parameters like, the detonation velocity D_j, initial density ρ_0, and equation of state constants A and n of the explosive.

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Contributors

Dr S.N. Asthana obtained his PhD from University of Pune. Presently, he is Associate Director at HEMRL, Pune. He is involved in the technology development of explosives for advanced class of warheads and projectiles. He was also actively involved in R&D work in the area of modern and novel HEMs like CL-20. He was system manager of new class of nitramine propellants for third–generation antitank missile Nag. Currently, he is recognized guide of Pune University for PhD and M Sc. Eight students have completed their PhD and post graduation under his guidance. He has more than 100 publications to his credit. He is recipient of DRDO *Scientists of the year Award (2003)* for his outstanding contributions in the area of high energy materials.

Dr A. Subhananda Rao is an Outstanding Scientist & Director of HEMRL. He is a gold medallist in Mechanical Engineering from National Institute of Technology, Warangal. He continued his academic excellence during his ME (Aeronautics) from IISc, Bangalore and received *Roll of Honour*. He completed his doctorate from Osmania University, Hyderabad. He is an acclaimed propulsion designer. He has designed, developed, realised and productionised more than 30 indigenous propulsion systems for strategic and tactical missiles. He is associated with the development of advanced propellant and explosive systems including insensitive munitions. He is actively involved with establishment of propellant processing plants of various capacities in the country. He is recipient of many awards for outstanding contribution including *Scientists of the Year Award-2005, DRDO Spin-off Technology Award-2006* and *Titanium Trophy-2007* (as Head of establishment), *DRDO performance excellence Award-2007* and *Path Breaking Research Award* for two years in succession in 2006 and in 2007. He is member of professional bodies and is president of High Energy Materials Society of India (HEMSI) and Chairman, Aeronautical Society of India (AeSI)- Pune Branch. He has over 50 technical publications to his credit in national and international journals and seminar/conference proceedings.