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Ratio of detonation pressure and critical pressure of high explosives with different compounds

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The experimental data that describe explosive performance (detonation velocity and pressure) are compared with the critical pressure – the value which characterizes the shock sensitivity of explosives, one of criteria for explosive security. Presented values are the result of extensive experimental work and consider explosives with different composition and structure. The aim of this paper is to establish grounds for evaluating the critical pressure value of new explosive compound based on the detonation velocity, the parameter which is measured primarily, for the purpose of future application in warheads.

Key words: **high explosives, detonation velocity, explosive sensitivity, detonation pressure, critical pressure.**

Used marks and symbols

P_{CJ}	– Detonation pressure
D	– Detonation velocity
TATB	– 1,3,5 – triamino 2,4,6 – trinitrobenzene
ρ_0	– Explosive charege density
u_{CJ}	– particle velocity
P_{cr}	– critical pressure
HMX	– octogen, cyclotetramethylene tetranitramine
RDX	– hexogen, cyclotrimethylene trinitramine
TNT	– trinitrotoluene
PETN	– pentaerythritoltetranitrate
PBX	– plastic bonded explosive
PB	– polyurethane binder
K1, K2	– normalization coefficients, “characteristics” for explosive performance
K3	– normalization coefficient, security “characteristic” for explosive

Introduction

LICHT H. underlined the connection between brisance and sensitivity of an explosive to mechanical impulse or shock in his paper [1]. He used detonation velocity and Gurney energy experimental data obtained during examination of explosive charges with different compositions as parameters which describe brisance. Impact and shock sensitivity, as well as thermo-chemical stability data were used for determining full sensitivity of explosive materials. As a result, a dependence of brisance/sensitivity was obtained with the observed boundary line with almost all data for the examined explosive compositions under it. The author underlined that there was no theoretical evidence that enhanced brisance was connected with higher sensitivity of high explosives even when there was a practical proof.

The aim of this paper is to prove or deny Licht's thesis. The extensive data base of experimental data for detonation pressure and critical pressure of initiation of cylindrical explosive charges obtained at the Military Technical Institute was used to evaluate the connection between the detonation pressure and the critical pressure of explosive, which would result in useful data for preliminary theoretical estimation of its values for new explosive compounds assigned to warheads.

Basic parameters which define the brisance are detonation velocity and pressure of detonation; the shock sensitivity is relevant for security.

Theory

An important problem in the theory of high explosives is the relationship between the chemical structure of an explosive and its performance under different conditions. The performance can be determined by various methods of impulse measurement: by relative brisance according to Kast (brisance is one of the forms of performance), by ballistic pendulum, by measuring of the charge shell velocity or velocity of metal plate rejected with detonation products, by determination of the degree of deformation of the material in contact with the charge or just near it.

It was considered [2] that it would be necessary to emphsdizr two well known factors when discussing the relationship between brisance and chemical structure of CHNO explosives:

- There is a strong dependence of composition and properties of detonation products on the chemical structure of an explosive, which directly determines the detonation pressure P_{CJ}, in other words brisance. A change of the relationship and the arrangement of C, H, N and O atoms in an explosive molecule (crystal explosive density), as well as an enthalpy of formation of a molecule, in a

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rather wide range exchanges the ratio and oxidation forms amount of C and H in detonation conditions and, consequently, the explosive energy. These reactions are finally the only source of detonation energy for CHNO explosives, which is distributed between various forms of work of detonation products. For example, the detonation pressure value for octogen with more complex chemical structure compared with nitro methane is more than three times higher, but the detonation velocity is only 1.5 times higher.

- The character of isentropic expansion of detonation products depends much less on the ratio of an explosive molecule's atoms, because detonation products of various CHNO explosives consist of the same molecules of gases (N_2, H_2O, CO, CO_2, O_2). Therefore isentropes of large number of CHNO explosives are similar.

In spite of relatively weak dependence of isentropic expansion of detonation products on the ratio of C, H, N and O atoms in the explosive molecule, brisance experimental data as well as data for detonation velocity are the most relevant and often the only source of information of detonation process chemism. Also, when talking about nonsensitive explosives (such as 1, 3, 5-triamino 2, 4, 6-trinitrobenzene, TATB), whose parameters P_{CJ} and detonation velocity are high, but the brisance is low, the experimental determination of brisance is needed. It is also necesery to determine which parameters are responsible for such behaviour.

The great progress in the detonation process phenomena research was attained over last decades. Thanks to the technical achievements and a great number of the measuring methods it is possible nowadays to measure processes with extreme by small duration (even to picosecond extent) and to obtain important qualitative and quantitative data from the detonation physics field. Table 1 shows measuring problems encountered in detonation physics. Brisance has been introduced as a measuring parameter because the user is principally interested in the effect of expanding products on specific targets.

Table 1. Review of measurement procedures in detonation physics

Detonation - physical field	Measuring quanrtity	Measurement procedure
Effect of explosion	Relative brisance	Compression of metal slabs (according to Kast or Hess), Trauzl test, Plate dent test.
	Gurney energy	Flying plate test, Cylinder test.
Material behaviour caused by explosion	State of material (U_S, u_{CJ} - relationship)	Flying plate test
	Elast./plast. quantities	Plate dent test, Manganin method.
Detonation products expansion	Isentropic P-V plot	Cylinder test
Starting point of expansion (Chapman-Jouguet, CJ, point)	Detonation velocity	Path/time measurement: with electrical pins, with optical methods. Laser interferometry
	Particle velocity	Electromagnetic method
	Detonation pressure	Manganin method, Plate dent test, Flying plate test, Aquarium test, Cylinder test.
	Detonation heat	Caloric measurement, Cylinder test

Brisance is expressed by the ratio between the work capacity of detonation products and the total duration of the detonation process [3]. Brisance can not be determined, nor satisfactorily nor be measured in absolute values, regardless of the measurement method. Also, the definition of brisance is extremely arbitrary. However, there is an abundance of different mathematical expressions for its calculation in references. Nevertheless, many of them are reduced to P_{CJ} value, which is further considered as a measuring parameter for brisance.

Methods frequently used, and the most promising, for measuring the performance of explosives are (see Table 1): plate dent test, flying plate test, aquarium test and cylinder test. Whereas the plate dent test is based on measuring relative brisance; path/time progression is measured directly in other cases, from which velocity is determined indirectly through differentiation of the analytical curve obtained.

The security when handling and storing explosive materials is determined by parameters such as impact, friction and shock sensitivity and thermo-chemical stability. Therefore the initiation mechanism of explosive materials: light, thermal, mechanical, electrical pulse, atomic particles and the so called "spontaneous" processes is well explained and experimentally confirmed in references.

It is characteristic that the research in an explosive initiation field has been carried out mostly on systems with detonation initiated by shock waves. The reason for this was the increasing development of complex warheads in which explosive charges were initiated by shock waves. In spite of the most contemporary methods of measurement (laser interferometry, pulse X-ray, numerous solutions of measuring gages for the precise shock wave parameters measurements etc.) the experimental research of complex, non-stationary initiation process and detonation development gave poor results with direct mechanism study, particularly the kinetics of chemical decomposition of explosives in the conditions of impact compression.

According to contemporary notions, the initiation of an explosion by external pulse, regardless of incentive energy form, is reduced to the formation of hot spots which stimulate thermal decomposition of the surrounding material. According to thermal explosion theory, the reaction of thermal decomposition of the material's molecule begins in local sites of different deformities, impurities and other heterogeneities in explosive material structure (porosity, presence of cavities , voids and air holes, shape and size of crystals have an important role). The sensitivity of explosives depends primarily on the nature, concentration and placement of hot spots in an explosive charge.

The common condition for shock initiation of detonation is the formation of the compression zone in an explosive under shock loading, in which the exotherm chemical reaction of decomposition can start. When talking about homogeneous explosives, this reaction takes place in the whole compressed volume.

The decomposition reaction initiates immediately behind the shock wave front in local "hearths" – hot spots, so when the shock pressure intensity is higher than the critical value, its decay is rarely registered. Namely, the energy released at the beginning of local decomposition compensates for the pressure drop caused by a rarefaction wave behind the shock wave front, which supports exceeding of shock into detonation wave front which accomplishes additional compressions and new hot spots formation, local compression waves. All these lead to progressive increasing of primary shock wave until the level of detonation parameters is reached, i.e. until the process reaches the steady-state. Therefore, the effect of hot spot acting must depend on the explosive's thermal content (energy): the

higher its thermal content, the higher its sensitivity.

Experimental results and discussion

The detonation velocity was measured in the steady-state detonation zone according to SNO 1475 method [4] using the short-circuit pins.

The detonation pressure was determined in two ways, by using the electromagnetic method with pulse magnetic field [5], and manganin method [6]. The particle velocity of detonation products, u_{CJ}, was determined based on the registered electromagnetic gage record. The detonation pressure was calculated based on hydrodynamic theory relation:

$$P_{CJ} = \rho_0 \cdot D \cdot u_{CJ} \,. \tag{1}$$

The shock sensitivity of explosive compounds was determined by GAP test [7], using the following experimental configuration:

- donor charge: FH-5 booster (1.60 g/cm^3 density), 30 mm diameter,
- attenuator: polyamide cylinder, 32 mm diameter, with the known shock adiabat,
- acceptor charge, 30 mm diameter and width,
- aluminium or copper cylinder, 35 mm diameter, whose deformation is used for critical conditions of initiation estimation.

The shock sensitivity is expressed by the critical pressure value, P_{cr}, which is calculated by using the width of metal cylinder under critical initiation conditions.

The results of the detonation velocity and pressure measurements for octolites, hexolites [9, 10, 11] (with [12] or without addition of aluminium) and pentolites [11] are presented in Table 2. Also, Table 2 contains the results obtained for pressed mixtures of octoles and hexotoles [13] and granular explosive mixtures with 5 % wax (SVIT-A) and Al [9], with adopted charge porosity of 6 %. In Table 3 the results of performance (measured detonation velocity and pressure) for PBX with or without Al [12, 14] are presented. All data were normalised with respect to the maximum value of detonation velocity obtained for explosive compound HMX/TNT 89/11. Normalized coefficients K1 and K2 in the columns are as follows:

$$K_1 = \frac{D_i}{D_{\max}} \,, \tag{2}$$

$$K_2 = \frac{(P_{CJ})_i}{(P_{CJ})_{\max}} \,. \tag{3}$$

Table 2. Results of detonation velocity and CJ pressure determination for some examined explosive compounds

Explosive (mas. %)	ρ_0 (g/cm^3)	D (m/s)	K1	P_{CJ} kbar	K2
octolite 70/30	1.77	8192	0.933	295	0.838
octolite 80/20	1.82	8523	0.971	331	0.940
octolite 89/11	1.84	8778	1.000	352	1.000
hexolite 50/50	1.65	7540	0.859	251.3	0.714
hexolite 60/40	1.79	8130	0.926	309	0.878
TNT pressed	1.59	6950	0.792	187	0.531
	1.47	6490	0.739	154.7	0.439
TNT	1.67	7500	0.854	241.3	0.685
octolite 90/10 pressed	1.75	8320	0.948	303	0.861
hexolite 90/10 pressed	1.61	7910	0.901	256	0.727
octolite 80/20 pressed	1.71	8050	0.917	278	0.789
hexolite 80/20 pressed	1.60	7745	0.882	242	0.687
octolite 70/30 pressed	1.70	7900	0.899	267	0.758
hexolite 70/30 pressed	1.59	7580	0.864	216	0.614
octolite 60/40 pressed	1.70	7680	0.875	253	0.719
hexolite 60/40 pressed	1.59	7415	0.845	219	0.622
PETN/TNT 60/40	1.67	7525	0.857	231	0.656
	1.68	7610	0.867	248	0.704
PETN/TNT 60/40 pressed	1.65	7530	0.858	242	0.687
PETN/TNT 20/80	1.59	6980	0.795	180	0.511
PETN/TNT/RDX 20/30/50	1.71	7890	0.899	266.5	0.757
RDX/TNT/Al 40/40/20	1.82	7560	0.861	182.7	0.519
RDX/TNT/Al 35/30/35	1.93	7320	0.834	163.4	0.464
RDX/TNT/Al 45/30/25	1.87	7440	0.847	201.0	0.571
RDX/Al/wax 90/5/5	1.685	8198	0.934	308.1	0.875
RDX/Al/wax 85/10/5	1.712	8100	0.923	289.7	0.823
RDX/Al/wax 80/15/5	1.740	8098	0.922	299.4	0.850
RDX/Al/wax 75/20/5	1.805	8233	0.938	283.8	0.806
RDX/Al/wax 70/25/5	1.800	7920	0.902	280.3	0.796
RDX/Al/wax 65/30/5	1.830	7811	0.890	321.6	0.914
HMX/Al/wax 80/15/5	1.820	8293	0.945	327.1	0.929
HMX/Al/wax 75/20/5	1.860	8370	0.953	321.3	0.913
HMX/Al/wax 65/30/5	1.930	8219	0.936	346.8	0.985

Table 3. Results of detonation velocity and pressure determination for PBX with and without Al

Explosive (mas. %)	ρ_0 (g/cm^3)	D (m/s)	K1	P_{CJ} kbar	K2
HMX/PB 82/18	1.630	8229	0.937	238.3 232*	0.677 0.659*
HMX/PB 80/20	1.607	8250	0.940	258.9 256*	0.735 0.727*
RDX/PB 83/17	1.588	8020	0.914	-	-
RDX/PB 85/15	1.575	8020	0.914	203*	0.577*
RDX/PB 84/16	1.595	8120	0.925	220*	0.625*
RDX/PB 83/17	1.588	8000	0.911	219.4 210*	0.623 0.596*
RDX/PB 80/20	1.568	7900	0.900	216.4 188*	0.615 0.534*
RDX/PB/$Ba(NO_3)_2$ 40/20/40	1.832	6180	0.704	166.4 170*	0.477 0.483*
PETN/PB/$Ba(NO_3)_2$ 20/20/60	2.052	4348	0.495	86.81 108.5*	0.247 0.308*
RDX/PB/Al 6520/15	1.607	7580	0.863	200 199*	0.568 0.565*
RDX/PB/Al 50/20/30	1.695	7130	0.812	154 156*	0.437 0.443*

NOTE:*-the pressure values determined by using manganin method.

The results of critical pressure determination for some cast, pressed and PBX [15, 16] explosive compounds are presented in Table 4. The coefficient of normalization **K3** was determined using the relation:

$$K_3 = \frac{(P_{kr})_i}{(P_{kr})_{\max}} \tag{4}$$

Table 4. The critical pressure values for some explosive compounds

Explosive (mas. %)	ρ_0 (g/cm^3)	P_q kbar	K3
octolite 70/30	1.77	23.06	0.260
octolite 80/20	1.82	20.02	0.226
hexolite 50/50	1.65	25.3	0.286
hexolite 60/40	1.68	23.20	0.262
TNT pressed	1.592	19.4	0.219
TNT	1.586	88.54	1.000
octolite 90/10 pressed	1.75	9.56	0.108
hexolite 90/10 pressed	1.61	11.28	0.127
octolite 80/20 pressed	1.71	10.88	0.123
hexolite 80/20 pressed	1.60	13.04	0.147
octolite 70/30 pressed	1.70	12.85	0.145
hexolite 70/30 pressed	1.59	13.92	0.157
octolite 60/40 pressed	1.70	14.64	0.165
hexolite 60/40 pressed	1.59	15.07	0.170
HMX/PB 83/17	1.588	38.1	0.430

RDX/PB/80/20	1.54	32.41	0.366
RDX/PB/$Ba(NO_3)_2$ 30/20/50	1.963	66.8	0.754
RDX/PB/$Ba(NO_3)_2$ 40/20/40	1.832	49.0	0.553
PETN/PB/$Ba(NO_3)_2$ 20/20/60	2.048	32.9	0.371
PETN/PB 85/15*	1.52	23.00	0.260
RDX/PB/Al 65/20/15	1.607	42.67	0.482
RDX/PB/Al 50/20/30	1.695	46.53	0.525

NOTE:* - plastic explosive [17].

The cast explosive HMX/TNT 89/11 with maximum density has the maximum D and P_{CJ} values. These values are expected because explosive characteristics of octogene are just expressed at higher charge densities. Unfortunately, the data for P_{cr} were not registered.

It has been noticed that cast explosives have higher D and P_{CJ} values when comparing the results for cast and pressed octolite 70/30 with approximately the same density; this compound also has higher P_{cr} value. Different structure of these charges reflects on the initiation process flow because of different behaviour under dynamic compression conditions. Higher shock sensitivity for the pressed octolite is distinct in consideration of high hot spots concentration for the pressed charge. The critical pressure value for the pressed octolite is smaller because of higher porosity of the pressed charge than of the cast one (D and P_{CJ} values are higher for cast octolite due to smaller porosity).

Pressed octolite 90/10 is the most sensitive one; it also has high D and P_{CJ} values.

It was expected that the critical pressure for cast TNT is much higher than for cast TNT (see Table 4). Namely, initiation process flow for cast TNT is specific [7]. It has longer "ignition" phase – about 40 mm – in which the shock wave amplitude decreases, followed by attenuation of the process until the steady-state detonation is reached.

Although PBX with 40 % of inert additive $Ba(NO_3)_2$ has higher density, the detonation velocity (and P_{CJ}) is considerably smaller compared to the compounds based on RDX with the same mass. content of binder, Table 3, which is caused by smaller percent of energetic component. D and P_{CJ} values decrease with increasing of mass content of aluminium. P_{cr} values are higher for PBX with Al addition, with the exception of RDX/PU/$Ba(NO_3)_2$ 40/20/40 and 30/20/50 explosive compounds, which have the highest critical pressures after cast TNT.

There is a trend of D and P_{CJ} values increasing and P_{cr} decreasing with mass content of JMX (RDX) increasing. From the detonation parameters' aspect, the same trend follow PBXs with mass content of RDX increasing, but also with critical pressure increasing. However, when adding Al, P_{cr} decreases with increasing of Al mass content. This points to the strong influence of metal addition on the shock sensitivity of explosives, which concurs with the data given in references [18].

Based on the critical pressure values, the examined explosive compounds can be classified as:

1. Distinctly sensitive explosive compounds with P_{cr} value from 0 to 20 kbar; cast octolites and hexolites and pressed TNT belong to this group.
2. Considerably sensitive explosive compounds with P_{cr} value from 20 to 25 kbar, where cast explosives based on TNT belong.
3. Average sensitive explosive compounds with P_{cr} value from 30 to 50 kbar, where PBXs with or without aluminium belong.
4. Non-sensitive explosive compounds with P_{cr} value higher than 50 kbar, where cast TNT falls.

The graph in Fig.1 shows the performance of explosives' dependence, on the shock seinsitivity (K3) expressed by coefficient $K'(K'=K1\times K2)$ and based on the results presented in Table 5.

Table 5. The review of normalization coefficients

Explosive (mas. %)	ρ_0 (g/cm^3)	K1	K2	K'	K3
octolite 70/30	1.77	0.933	0.838	0.782	0.260
octolite 80/20	1.82	0.971	0.940	0.912	0.226
hexolite 50/50	1.65	0.859	0.714	0.613	0.286
TNT pressed	1.592	0.792	0.531	0.420	0.219
octolite 90/10 pressed	1.75	0.948	0.861	0.816	0.108
hexolite 90/10 pressed	1.61	0.901	0.727	0.655	0.127
octolite 80/20 pressed	1.71	0.917	0.789	0.723	0.123
hexolite 80/20 pressed	1.60	0.882	0.687	0.606	0.147
octolite 70/30 pressed	1.70	0.899	0.758	0.681	0.145
hexolite 70/30 pressed	1.59	0.864	0.614	0.530	0.157
octolite 60/40 pressed	1.70	0.875	0.719	0.630	0.165
hexolite 60/40 pressed	1.59	0.845	0.622	0.525	0.170
RDX/PB 83/17	1.588	0.914	0.623 0.596*	0.570 0.569*	0.430
RDX/PB/$Ba(NO_3)_2$ 40/20/40	1.832	0.704	0.477 0.483*	0.336 0.340*	0.553
RDX/PB/Al 65/20/15	1.607	0.863	0.568 0.565*	0.490 0.487*	0.482
RDX/PB/Al 50/20/30	1.695	0.812	0.437 0.443*	0.355 0.360*	0.525

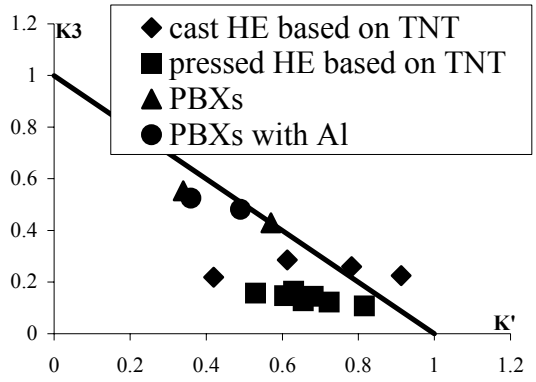

Figure 1. Dependence of explosive performance on sensitivity

There is a virtual border line in Fig.1 above which data for octolites 70/30 and 80/20 (the most brisant K' = 0.912, Table 2) are shown almost on the line the data for PBX RDX/PU 83/17 and RDX/PU/Al 65/20/15 are shown.

Conclusion

The relationship between the performance of explosive, expressed by detonation velocity and pressure, and the critical pressure was examined in this paper by analyzing experimental data base for various explosive compounds. The thesis that more brisant explosives are also more sensitive is confirmed. Naturally, this relationship cannot be considered a strong correlation which many authors dedicated to exploring this field insist on in their papers. However, the described procedure can be applied to test future explosive mixtures with regards to new compounds, less sensitive but with attractive performances.

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Odnos pritiska detonacije i kritičnog pritiska brizantnih eksploziva različitog sastava

Analizirani su eksperimentalni podaci koji definišu brizantnost eksploziva (brzina i pritisak detonacije) i kritični pritisak – parametar koji karakteriše osetljivost eksploziva na inicijaciju udarnim talasom. Prikazane vrednosti su rezultat obimnog eksperimentalnog rada i razmatraju eksplozive različitog sastava i strukture. Cilj rada je mogućnost procene vrednosti kritičnog pritiska na inicijaciju udarnim talasom novog eksplozivnog sastava na osnovu detonacione brzine, parametra koji se prvenstveno odredjuje, radi buduće primene ovog sastava u ubojnim sredstvima.

Ključne reči: **brizantni eksplozivi, brzina detonacije, osetljivost eksploziva, detonacioni pritisak, kritični pritisak.**

Соотношение давления детонации и критического давления быстродействующих взрывчатых веществ различного састава

В настоящей работе анализированы экспериментальные данные, определяющие быстрое действие взрывчатого вещества (скорость и давление детонации) и критический диаметр - параметр характеризующий чувствительность взрывчатого вещества на инициирование (возбуждение) детонационной волной. Здесь показаные значения представляют результаты объёмных работ и рассматривают взрывчатые вещества различного состава и структуры. Цель этой работы - возможность оценки значения критического давления на инициирование (возбуждение) детонационной волной нового взрывчатого состава на основе скорости детонации, параметра прежде всего определяющегося с целью будущего применения этого состава в боевых головках и средствах.

Ключевые слова: **быстродействующее взрывчатое вещество, скорость детонации, чувствительность взрывчатых веществ, детонационное давление, критическое давление.**

Relation entre la pression de détonation et la pression critique chez les explosifs brisants de différente composition

On a analysé les données expérimentales qui définissent la brisance des explosifs (vitesse et pression de détonation) et le diamètre critique – paramètre qui caractérise la sensibilité des explosifs à l'initiation par l'onde de choc. Les paramètres présents sont le résultat d'un grand travail expérimental et considèrent les explosifs dont la structure et la composition sont différentes. Le but de ce travail met l'accent sur la possibilité d'évaluer la pression critique à l'initiation par l'onde de choc chez la nouvelle composition explosive en partant de la vitesse de détonation, paramètre qui est déterminé, avant tout, à cause de la future application de cette composition chez les ogives.

Mots clés: **explosifs brisants, vitesse de détonation, sensibilité des explosifs, pression de détonation, pression critique**