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An approach to determining the TNT equivalent of high explosives

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Effective explosive weight (EEW) is one of the basic parameters for estimating the pyrotechnic safety in manufacturing, storing and manipulation processes with explosive ordnance. For its resolving the values of TNT equivalents for explosives which are in the explosive ordnance must be known. Since there are many approaches to this problem, a unique TNT equivalent based on detonation parameters obtained from thermo-chemical calculations are proposed in this paper. Methods are confirmed comparing the obtained results with the results available in references and also experimentally.

Key words: **explosives, pyrotechnic safety, effective explosive weight (EEW), TNT equivalent (TNT), safety distances.**

Introduction

IN the manufacturing and storage processes of explosive ordnance (XO), among many other procedures, all regulations of pyrotechnical safety must be strictly applied. One of the most important things that must be considered is determining the safety distances. Safety distances are determined by the all-inclusive analysis of the possible consequences of potential detonation, where it is necessary to analyze the effects of shockwave overpressure, fragments and fire damage on the surroundings.

Safety distances are considered from two aspects. The first one deals with the possibility of sympathetic detonation, and the second one with causing harmful consequences to people and various objects.

In the first case, for the known conditions, it is to determine, the so called, separation distances between individual storage units of the XO (package, stock, warehouse) which will prevent sympathetic detonation. In the other, the safety distances which are different for a variety of objects (settlements, schools, line of communications, long-distance power lines, hospitals, airports, etc.)

One of the base parameters necessary for reliable determination of safety distances is net explosive weight (NEW), or more exactly, effective explosive weight (EEW) which is contained in the considered storage unit of the XO.

NEW presents the total weight of high explosives and propellants in one storage unit of XO, while EEW stands for the amount of TNT which will give the same value of the selected detonation parameter as the examined explosive.

To determinate EEW, it is quite necessary to know TNT equivalent (TNTe) for various explosives in XO. As long as the TNT equivalent remains an undetermined unilateral for all explosives, NEW is used for calculating safety distances [1].

Shock wave blast effects

Shock wave blast appears as a result of shock wave expanding through the environment where an explosion was (air, water, ground). In many cases, the most dominant influence on the blast effects is the value of the shock wave impulse:

$$I = \int_0^{\tau} p(t)dt \tag{1}$$

where $p(t)$ – is the overpressure at the moment t after passing of the shock wave. Blast impulse value can be determined on the basis of the experimentally determined pressure-time dependence or if the blast overpressure value has been known, Δp :

$$p(t) = \Delta p\left(1-\frac{t}{\tau}\right)e^{-\frac{t}{\tau}} \tag{2}$$

where τ - is the overpressure positive phase duration.

M.A. Sadovski [2] suggested, on the basis of numerous experimental results from detonation of spherical TNT charge in the air, these formulas for shock wave parameters (Δp is in MPa):

$$\Delta p = 0,085\frac{\sqrt[3]{m}}{r} + 0,3\left(\frac{\sqrt[3]{m}}{r}\right)^2 + 0,8\left(\frac{\sqrt[3]{m}}{r}\right)^3 \tag{3}$$

$$\tau = 1,2\sqrt[6]{m}\sqrt{r}\ \text{ms}, \tag{4}$$

$$I = 200\frac{\sqrt[3]{m^2}}{r}\ \text{Pa s}, \tag{5}$$

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where m - is TNT charge weight , and r - distance from explosion.

With certain corrections, the same formulas can be used for the other ideal explosives, but the explosive weight must be recalculated to EEW if the TNT equivalent is known. When semispherical explosion occurs, the explosive weight must be increased for 2η, because explosive weight can not be doubled since an amount of energy is used for the deformation of the base material. Therefore, the coefficient η depends on the used base material; for the absolute hard one, the value of η is 1 (Table 1) [2].

Table 1. Values of the coefficient η for various base materials

Type of the material	Steel plate	Reinforced concrete plate	Concrete; Rock	Compact sandy clay; Clay	Medium compact soil	Water
η	1	0,95-1	0,85-0,9	0,7-0,8	0,6-0,65	0,55-0,6

While moving through the environment where detonation occurred, shock wave causes various consequences on both people and objects, depending on the shock wave intensity and duration (Tables 2 and 3).

Table 2. Expected shock wave effects on people [3]

№	Overpressure, kPa	Consequences
1.	20-30	1 % eardrum burst
2.	110	50 % eardrum burst
3.	70(duration 50 ms) 140-200 (duration 3ms)	The limit of lung burst
4.	190 (duration 50 ms) 400-500 (duration 3ms)	1 % mortality

Table 3. Expected shock wave effects on objects [3]

№	Overpressure, kPa	Expected damages
1.	1,0 – 1,5	Window glass cracks
2.	3,5 – 7,6	Minor damages on some buildings
3.	7,6 – 12,4	Metal panels deformity
4.	12,4 – 20	Concrete walls damage
5.	over 35	Wooden construction buildings demolition
6.	27,5 – 48	Major damages on the steel construction objects
7.	40 – 60	Heavy damages on the reinforced concrete buildings
8.	70 – 80	Probable demolition of most buildings

Hopkins-Krantz scaling law (detonation of various explosives at certain distance gives similar shock waves) can be used for safety distances estimation [4]:

$$Z = \frac{R}{m^{1/3}},\ \mathrm{m/kg^{1/3}} \qquad (6)$$

where Z is the scaled distance, R – distance from the center of the explosion (m), m – total explosive weight (kg).

B.D.Hristoforov [2] experimentally tested the influence of density of the spherical detonated explosive charges on the shock wave parameters. It has been shown that while $Z > 0,8$ the influence of the density vanishes.

In Fig.1, blast wave overpressure scaled distance dependence in case of spherical explosion in the air with possible consequences on the surroundings is shown [5].

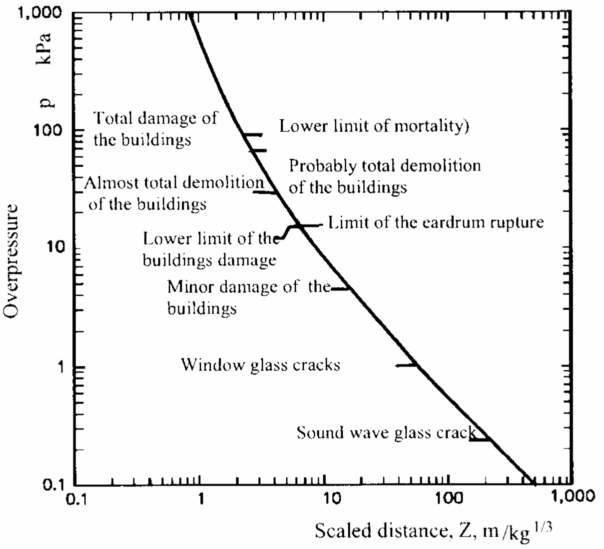

Figure 1. Dependence of the shock wave overpressure from the scaled distance of the TNT explosion [5]

The concept and ways of determining the TNTe

Generally speaking, TNT equivalent presents the weight of TNT which during the explosion yields the same amount of energy as a mass unit of the considered explosive. It is used to express the power of nuclear weapons (kilotons and megatons). More precisely, from pyrotechnics safety determination aspects and blast effects, TNTe presents the amount of pure semispherical shaped charge of TNT which during the detonation on the ground level at precise distance, yields the same blast overpressure or blast impulse as the mass unit of the considered explosive [2].

The main reason for taking TNT as the referent explosive is the fact that there is a great number of experimental data for its blast characteristics. However, the matter of defining and determining of TNTe is not as simple as it may seem. When the effects of sympathetic detonation are considered, blast effect and fragmentation effect dominant influence have the value of the blast wave overpressure, while considering demolition effects, parameters of great importance are positive phase duration and blast impulse.

There are many methods for determining the explosive characteristics of various explosives, but they do not yield the same TNTe values. Also, values of TNTe are different, depending on the blast parameter used, conditions of the experimental testing, charge geometry, distance from the explosive charge, etc., which altogether indicate that the problem of determining the unique value of TNTe is far more complicated. The explanation lies in the energy releasing mechanism during the process of detonation which varies for different explosives.

All explosives are basically made of two components: oxidants and fuel. Pure, or so-called ideal explosives, have both these components bonded at the molecule level, while explosive mixtures or non-ideal explosives have both components mixed (e.g. ammonium nitrate and diesel fuel). Under the effect of the shock wave during detonation, oxidants and fuel undergo mutual reaction in the zone of chemical reactions. The velocity of chemical reaction for ideal explosives and therefore the velocity of detonation, have greater values due to more favorable conditions, resulting in much greater efficiency. The greater velocity of detonation therefore has a larger amount of energy released, which is in direct proportion to the blast impulse and blast overpressure.

The reaction between gaseous products of explosive degradation for non-ideal explosives occurs even beyond the zone of chemical reactions in the extended zone of chemical reactions, so the later energy release does not support the blast wave. For that reason, the blast wave impulse is not in proportion to the yielded detonation energy.

There are different methods for measuring the released energy during the detonation for various explosives. Some of them measure total energy yield, and some only blast wave overpressure which does not include the later energy release of non-ideal explosives. That is why different methods give different values of TNTe. In spite of this, however, the fact that the effects of detonation for both ideal and non-ideal explosives are different because of different values of velocity of detonation and therefore different shock wave velocities must not be disregarded. During the ideal explosives detonation, the damage to the objects is a result of the blast overpressure, while during the non-ideal explosives detonation, the more probable effect would be the throwing of objects. For this reason, for the demolition of firm, but relatively light objects great overpressure is needed, while for the demolition of heavy, but relatively weak objects (brick wall) great impulse is needed. As a consequence of the previously stated, a unique method for TNTe determination has not been established yet and also, the values of EEW which is necessary for reliable estimation of pyrotechnic safety.

According to the DoD standard [1] TNTe are determined by comparison of values of the blast overpressure and impulse of various explosives to TNT. When the needed data are missing values of the heat of detonation is used [4]. However, the approach is not quite accurate because the analysis of the obtained values of TNTe [4] shows they are different, and the standard deviation is great. On the other hand, it must be recognized that the measuring of various blast parameters is quite difficult and there is not much useful data for other explosives, especially for explosive mixtures, in the references.

Since there is no point in having several values of TNTe for estimation of pyrotechnical safety, the question remains whether there is a way to obtain a unique and simple way of its determination. One solution to the problem could be based on the theory of detonation and its mechanism, providing the well known equations expressing the dependence of overpressure, p, and velocity of detonation, D, on the heat of explosion, Q,:

$$p+2(\gamma-1)\rho_0 Q \tag{7}$$

$$D=\sqrt{2(\gamma^2-1)Q} \tag{8}$$

where: γ – adiabatic constant of gaseous products of detonation, and ρ_0 – density of the explosive.

Table 3. Results of TNTe calculations for various explosives

Explosive	**Density,** ρ_0 **(g/cm^3)**	**Number of moles.** n	**Heat of ex.,** Q **(kJ/kg)**	p **(kbar)**	D **(m/s)**	**TNT$_e$** (n)	**TNT$_e$** (Q)	**TNT$_e$** (p)	**TNT$_e$ (D)**	**TNT$_e$ mean**	**Average deviation (%)**
TNT	1.64	25.9	5569	190	6950	1.00	1.00	1.00	1.00	1.00	0.00
Hexogen	1.8	33.8	6334	347	8754	1.31	1.14	1.83	1.26	1.38	15.94
Hexotol											
90/10	1.61	33.1	6232	256	7910	1.28	1.12	1.35	1.14	1.22	7.58
80/20	1.6	32.3	6150	242	7745	1.25	1.10	1.27	1.11	1.18	6.57
70/30	1.59	31.6	6070	227	7580	1.22	1.09	1.19	1.09	1.15	5.00
60/40	1.59	30.8	6003	219	7415	1.19	1.08	1.15	1.07	1.12	4.24
Octogen	1.9	33.8	6538	393	9100	1.31	1.17	2.07	1.31	1.46	20.55
Octol											
90/10	1.75	33	6438	303	8320	1.27	1.16	1.59	1.20	1.31	11.07
80/20	1.71	32.2	6342	278	8050	1.24	1.14	1.46	1.16	1.25	8.40
70/30	1.7	31.3	6242	267	7900	1.21	1.12	1.41	1.14	1.22	7.79
60/40	1.7	30.6	6156	253	7680	1.18	1.11	1.33	1.11	1.18	6.14
Pentrite	1.77	32	6400	335	8300	1.24	1.15	1.76	1.19	1.34	16.04
Tetryl	1.68	27.5	5920	245	7560	1.06	1.06	1.29	1.09	1.13	7.52
PBX-9011	1.77	33.2	6168	299	8700	1.28	1.11	1.57	1.25	1.30	10.19
HMX/PU											
80/20	1.43	34.1	5856	193	7334	1.32	1.05	1.02	1.06	1.11	9.23
70/30	1.4	33.8	5566	182	7200	1.31	1.00	0.96	1.04	1.07	10.51
RDX/PU											
80/20	1.57	33.8	5735	234	7778	1.31	1.03	1.23	1.12	1.17	8.33
70/30	1.38	33.7	5436	167	6961	1.30	0.98	0.88	1.00	1.04	12.50
NM	1.13	38.6	6435	125	6523	1.49	1.16	0.66	0.94	1.06	24.76
NGL	1.59	32	6606	246	7580	1.24	1.19	1.29	1.09	1.20	5.21
DATB	1.79	28.9	5498	259	7520	1.12	0.99	1.36	1.08	1.14	9.87
PETN/PU											
90/10	1.65	31.9	6406	263	7950	1.23	1.15	1.38	1.14	1.23	6.50
80/20	1.50	32.4	6034	215	7465	1.25	1.08	1.13	1.07	1.14	5.48
70/30	1.39	32.7	5682	165	6957	1.26	1.02	0.87	1.00	1.04	10.82
PEP (85/15)	1.50	32.40	6186	215	7600	1.25	1.11	1.13	1.09	1.15	4.78
SEMTEX	1.40	33.80	6372	198	7220	1.31	1.14	1.04	1.04	1.13	8.19
COMP. A-3	1.67	33.4	6780	286	8470	1.29	1.22	1.51	1.22	1.31	7.63
C-4	1.66	33.8	6650	257	8370	1.31	1.19	1.35	1.20	1.26	1.24
COMP. B	1.72	30.6	6000	281	8052	1.18	1.08	1.48	1.16	1.22	10.41
LX-17	1.91	29.1	4407	316	7630	1.12	0.79	1.66	1.10	1.17	21.14
LX-14	1.83	33.6	6452	363	8958	1.30	1.16	1.91	1.29	1.41	17.57
LX-04	1.86	33.7	5940	330	8460	1.30	1.07	1.74	1.22	1.33	15.27

Taking any equation of gaseous product of detonation state, it can be concluded that the effects of detonation are influenced by these basic detonation parameters: velocity of detonation, detonation overpressure, the heat of detonation and number of moles of gaseous products of detonation. Comparing these values of various explosives to TNT, which can be quite easily obtained from thermo-chemical calculations, it is possible to get the mean value of the TNTe.

Accordingly, on the bases of the results of thermo-chemical calculations of detonation parameters [6] mean values of TNTe for several explosives and explosive mixtures has been determined (Table 3). From the pyrotechnic safety aspect it is necessary to know the distance for sympathetic detonation from active to passive charge; also for evaluating the calculated values of TNTe, passive cylinder shaped charge of TNT weighting 100g in front of the active pentrite spherical charge and active TNT charge of the same weight has been activated. The experiment took place on the ground level, on the steel plate. The obtained results showed that pentrite activates passive TNT charge at 82 mm, and TNT charge at 59 mm. So for the aspect of sympathetic detonation TNTe of pentrite is 1,39 which is very close to the calculated value. (1,34).

In Table 4, comparative review of the calculated and taken from references values of TNTe has been given for some explosives. Values taken from references express the values of blast overpressure (NUT) and experimentally obtained specific blast impulse (Is).

Table 4. Comparative review of the calculated and taken from references values of TNTe

Explosive	Density, ρ_0 (g/cm^3)	TNTe calculated	TNTe (NUT)	TNTe (*Is*)	Average deviation (NUT) (%)	Average deviation (*Is*) (%)
Pentrite	1.77	1.34	1.27[a]	1.39[c]	5.6	3.6
Tetryl	1.68	1.13	1.07[a]	1.20[c]	5.6	5.8
RDX	1.8	1.38	-	1.42[c]	-	2.8
HMX	1.903	1.46	-	1.52[c]	-	3.9
Octol 70/30	1.70	1.22	1.06[a]	-	15.1	-
COMP. A-3	1.67	1.31	1.1[a]	-	27.3	-
C-4	1.66	1.26	1.37[a]	-	9.5	-
Octol 90/10	1.75	1.31	1.32[b]	-	0.8	-
COMP. B	1.72	1.22	1.1[b]	-	10	-
LX-17	1.91	1.17	1.0[b]	-	17	-
LX-14	1.83	1.41	1.32[b]	-	6.8	-
LX-04	1.86	1.33	1.23[b]	-	8.1	-

[a] According to reference [4]
[b] According to reference [7]
[c] According to reference [2]

Comparing the calculated and experimental values leads to the conclusion that the standard deviation is within the limit of deviation for TNTe values obtained on the bases of various detonation parameters, indicating that it is correct to use this method for determining TNTe.

This method can be improved by means of determining the actual contribution of some explosive for each detonation parameter; there is a semi-empirical equation as one solution to the problem:

$$TNT_E = k_1\frac{n_{EM}}{n_{TNT}} + k_2\frac{Q_{EM}}{Q_{TNT}} + k_3\frac{p_{EM}}{p_{TNT}} + k_4\frac{D_{EM}}{D_{TNT}} \qquad (9)$$

where: k_1, k_2, k_3 and k_4 are empiric coefficients obtained experimentally from the examined explosive and TNT at the same conditions.

Conclusion

For reliable estimation of pyrotechnic safety, it is necessary to know EEW in XO. To determine EEW the procedure for obtaining TNTe for various explosives has to be known.

Due to the existence of a variety of different approaches of TNTe determination, it is necessary to develop a unique and simple method. The method given in this paper shows the easiest, quite reliable and most accurate way to obtain TNTe on the bases of thermo-chemical calculations.

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Pristup određivanju TNT ekvivalenta različitih eksplozivnih materija

Kao osnovni parametar za procenu pirotehničke bezbednosti u procesu proizvodnje, skladištenja i manipulacije sa ubojnim sredstvima služi efektivna količina eksploziva. Za njeno određivanje neophodno je poznavanje vrednosti TNT ekvivalenta za eksplozivne materije kojima su laborisana ubojna sredstva. S obzirom na različite pristupe u rešavanju ovog problema, u radu je predložena metoda za jednoznačno određivanje TNT ekvivalenta na osnovu parametara detonacije dobijenih termohemijskim proračunom Ispravnost metode potvrđena je poređenjem dobijenih rezultata sa dostupnim literaturnim vrednostima i eksperimentalnom proverom.

Ključne reči: **eksplozivne materije, pirotehnička bezbednost, efektivna količina eksploziva, TNT ekvivalent, zona bezbednosti.**

Подход к определению ТНТ эквивалента различных взрывчатых веществ

В роли основного параметра для оценки пиротехнической надёжности в процессе производства, складывания и манипулирования боевым средством является эффективное количество врзывчатой смеси. Ради её определиния необходимо знать стоимость (величины) ТНТ эквивалента для взрывчатых веществ, которыми обрабатываны боевые средства. Учитывая различные подходы к решению этой проблемы, в настоящей работе предложен метод для однозначного определения ТНТ эквивалентов на основе параметров детонации, полученых термохимическим предварительным расчётом. Достоверность метода потверждена сравнением полученых результатов с величинами в доступной литературе и путём экспериментальной проверки.

Ключевые слова: взрывчатые вещества, пиротехническая надёжность, эффективное количество взрывчатой смеси, ТНТ эквивалент, зона безопасности.

Une approche à la détermination de l’équivalent TNT de différentes matières explosives

La quantité effective d’explosif représente le paramètre principal pour estimer la sécurité pyrotechnique dans la production, le dépôt et la manipulation des moyens meurtriers.Pour sa détermination il est nécessaire de connaitre les valeurs de l’équivalent TNT pour les matières explosives avec lesquelles sont élaborés les moyens meurtriers. Considérant les différentes approches dans la résolution de ce problème, dans ce travail on a proposé la méthode pour la détermination unique de l’équivalent TNT basée sur les paramètres de détonation, obtenus à l’aide du calcul technochimique. L’exactitude de la méthode était confirmée par la comparaison des résultats obtenus et les valeurs linéaires accessibles ainsi que par la vérification expérimentale.

Mots clés: **matière explosive, sécurité pyrotechnique, quantité effective d’explosif, équivalent TNT, zone de sécurité.**