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Research paper / Praca badawcza

Theoretical assessment of the response of an explosive charge to the impact of a tungsten subprojectile *Teoretyczna ocena odpowiedzi ładunku materiału wybuchowego na uderzenie podpocisku wolframowego*

Waldemar A. Trzciniński

Military University of Technology, Faculty of Chemistry, 2 gen. S. Kaliskiego Street, 00-908 Warsaw, Poland

E-mail: waldemar.trzcinski@wat.edu.pl

Abstract: *The criteria for initiation of detonation in an explosive encased in a metal envelope following impact by a projectile are discussed in the paper. Methods for estimating the pressure in the explosive after impact by a high-speed projectile are presented. The methods and criteria were used to investigate the response of explosives encased in steel shells after tungsten projectile impact. Based on the results obtained, the ability of AHEAD ammunition to destroy missiles and artillery shells was assessed.*

Streszczenie: *W pracy omówiono kryteria inicjowania detonacji po uderzeniu pocisku w materiał wybuchowy zamknięty w metalowej otoczce. Przedstawiono metody szacowania wartości ciśnienia w materiale wybuchowym po uderzeniu pocisku napędzonego do wysokiej prędkości. Metody i kryteria zastosowano do zbadania odpowiedzi materiałów wybuchowych zamkniętych w stalowych skorupach po uderzeniu podpocisku wolframowego. Na podstawie uzyskanych wyników oceniono zdolność amunicji AHEAD do niszczenia pocisków raketowych i artyleryjskich.*

Keywords: *explosives, projectile impact sensitivity, threat of tungsten subprojectile for encased explosives*

Słowa kluczowe: *materiały wybuchowe, wrażliwość na uderzenie pocisku, zagrożenie podpocisków wolframowych dla zamkniętych materiałów wybuchowych*

Symbols

a	parameter in the equation of empirical shock adiabat of the medium $D_s(u)$ [m/s]
c	speed of sound in the medium [m/s]
d_c	diameter of a rod section not weakened by the unloading wave [m]
d_0	diameter of the impacting rod [m]
D_1	shock wave velocity in the impacting plate (rod) [m/s]
D_i	shock wave velocity in the envelope of an explosive charge [m/s]
D_s	shock wave velocity in the medium [m/s]
E	total energy per medium surface area unit [J/m ²]
E_c	critical energy for detonation initiation [J/m ²]
E_{\max}	maximum energy transferred to the explosive [J/m ²]
h	explosive shock wave penetration depth [m]
L	impacting plate thickness or rod length [m]

p	pressure [Pa]
P	constant pressure downstream of the shock wave front [Pa]
P_u	shock wave pressure at the rod-charge envelope interface [Pa]
t	time [s]
T	time of the maximum energy transfer to the explosive [s]
u	mass velocity of the medium [m/s]
up	projectile velocity [m/s]
U	mass velocity of the medium compressed under the constant pressure shock wave pulse [m/s]
V_{\max}	maximum volume of the explosive compressed by the shock wave [m ³]
x	linear coordinate [m]
α	constant of proportionality [m/N s]
λ	parameter in the equation of empirical shock adiabat of the medium $D_s(u)$ [-]
ρ_0	initial medium density [kg/m ³]
τ	duration of load [s]

1. Introduction

The development of AHEAD (*Advanced Hit Efficiency And Destruction*) technology has increased the capability of anti-aircraft artillery to combat aerial targets from large planes to artillery rounds. Programmable AHEAD ammunition was developed to combat rocket missiles, artillery and mortar projectiles but can also be used to destroy precision delivery vehicles (airplanes, helicopters, unmanned aerial vehicles) by a very short range anti-aircraft artillery. The most common anti-aircraft projectile contains 152 tungsten subprojectiles weighing 3.3 g each. The probability of hitting an aerial target by AHEAD ammunition (delivery) has been analysed in many studies [1, 2]. A key issue when considering the effectiveness of AHEAD ammunition in combating small targets, including rocket missiles, artillery and mortar projectiles is the need to evaluate the response of an explosive encased in a metal shell to the impact of a tungsten subprojectile at velocities of 800 to 1200 m/s. This paper attempts a theoretical evaluation of the response of the encased explosive to the impact of a tungsten subprojectile. The criteria for explosive initiation following projectile impact are presented, the methods of evaluating pressure in the explosive are discussed and the response of explosive encased in mortar and artillery projectiles to the impact of a tungsten subprojectile, is analysed.

2. Detonation initiation criteria

Following projectile impact, a strong shock wave is generated in an explosive, the material is compressed, heated and propelled at the front of the shock wave. If the energy accumulated in a specific volume of the explosive exceeds a critical level, chemical reactions and explosion are initiated in the explosive. All the initiation criteria of the explosive by the shock wave contribute to the transfer of energy to the material, thus, the amount of energy must be estimated as a first step of the analysis. The detonation initiation criteria for the encased and non-encased explosive following impact of a cylindrical projectile, will be presented.

2.1. Shock wave energy in the medium

In a study [3] a model problem of estimating the total energy of a shock wave in a medium following impact by a flyer plate was discussed. The criterion was that the transverse dimension of the flyer plate is significantly higher than its thickness and so the flyer plate can be considered a one-dimensional problem. Using the law of conservation of energy, it has been shown that an increase in total energy (internal and kinetic) in the medium affected by the shock wave, can be described using the Equation 1 [3]:

$$E = \int_0^\tau (up)_{|h=0} dt \quad (1)$$

where E – total energy for the surface area unit of the medium, τ – duration of load, u – medium mass velocity, p – pressure, t – time, h – shock wave penetration depth (at the medium surface $h = 0$).

If the pressure pulse is rectangular with a duration of τ , after flyer plate impact the energy transferred to the medium is:

$$E = U \cdot P \cdot \tau \quad (2)$$

where P , U are constant pressure and mass velocity at the medium interface.

The pressure at the shock wave front propagated in the undisturbed medium is related to the mass velocity:

$$p = \rho_0 \cdot u \cdot D_s \quad (3)$$

where D_s is shock wave velocity and ρ_0 is medium density.

By substituting u from Equation 3 in Equation 2 and assuming the shock wave propagation rate is not highly dependent on its pressure, an expression for the energy transmitted to the medium after flyer plate impact, is as follows:

$$E = \frac{P^2 \tau}{\rho_0 D_s} \approx \alpha P^2 \tau \quad (4)$$

where α is the constant of proportionality.

The duration of load τ is estimated by the thickness L of the flyer plate (liner) and shock wave velocity D_l in the flyer plate material as follows:

$$\tau = \frac{2L}{D_l} \quad (5)$$

2.2. Detonation initiation criteria in non-encased explosive

Sensitivity of non-encased explosive to the shock wave is determined experimentally using a pressure pulse generated in the explosive sample after the impact of a metal flyer plate with different thickness and velocity. The method allows different pressure pulses, characterized by different duration times and amplitudes, to be generated. For each test, the Equations 4 and 5 can be used to determine the energy transferred to the explosive from the shock wave. The values can be used to determine the critical energy (E_c) for the detonation initiation of a specific explosive. If the energy transferred to the explosive after flyer plate impact is equal or higher than E_c , then detonation is initiated.

Literature includes data on the critical energy required to initiate a shock wave in military blast explosives manufactured by NATO member countries. E_c was determined experimentally by impacting a thin flyer plate propelled at high velocities using Equation 2. Table 1 shows the obtained data.

Table 1. Critical energies E_c for selected explosives

Explosive*	Composition [%]*	Density [kg/m ³]	E_c [MJ/m ²]	Ref.
PBX 9404	94/6 (HMX/plasticizer)	1842	0.64	[4]
		1840	0.45	[5]
Tetryl	100	1655	0.42	[4]
Composition B, cast	59.5/39.5/1 (TNT/RDX/wax) 64/36 (TNT/RDX)	1717	1.90	[4]
		1730	1.40	[6]
TNT, pressed	100	1550	0.63-0.67	[4]
TNT, liquid	100	1470	2.0	[8]
TNT, cast	100	1590	1.95	[7]**
Nitromethane	100	1120	2.5	[6]
LX-17	92.5/7.5 (TATB/Kel-F)	1900	1.50	[9]
PBX 9502	95/5 (TATB/Kel-F)	1880	1.50	[9]
RDX, plastic	86/14 (RDX/PB) 84/16 (RDX/PB)	1600	2.10	[6]
		1550	1.45	[9]

Note: * HMX – octogen, Kel-F – thermoplastic chloropolymer, PB – polybutadiene, RDX – hexogen, TATB – triaminotrinitrobenzene, TNT – trinitrotoluene; ** own estimates based on the results in [7]

A criterion for critical energy (Equation 2) for explosive initiation by impact, developed by Walker and Wasley [10], is widely used to estimate an explosive's response to the impact of a flyer plate propelled at high speed. If this criterion is used in the analysis of impact by a rod propelled at high speed, the experimentally determined E_c is significantly higher than the value obtained for the flyer plate impacting the same explosive. In [4, 11, 12], the critical energy criterion was modified, and can be used for both the flyer plate and the rod.

For a flat-ended rod, impact compression duration is controlled by the unloading wave propagated from the side rod surfaces, rather than its rear surface. The attempts to correlate E_c with the time required for the side waves to reach the axis of symmetry of the rod yields E_c values which are significantly higher than the equivalent values obtained from the experiments using flyer plates.

A more effective estimation is possible, if we consider that the loading time is not explicit in the original criterion. In the case of the propelled flyer plate, the duration of load τ is identical to time T , in which the maximum amount of energy (E_{\max}) is received by the explosive from the shock wave. This does not, however, apply to other projectile geometries. By combining E_c with time T , and not with the impact compression duration τ , it can be shown that E_c obtained in the experiments with rods, are similar to the values obtained in the experiments with flyer plates. More general form of Equation 2 was shown in [11], *i.e.* Equation 6:

$$E = U P T \quad (6)$$

The energy E for a specific impact is proportional to the volume of the explosive affected by the initial shock wave. Figure 1 shows the diagram of the structure of a shock wave penetrating the explosive after impact by a rod with a circular-cross section and a flat end.

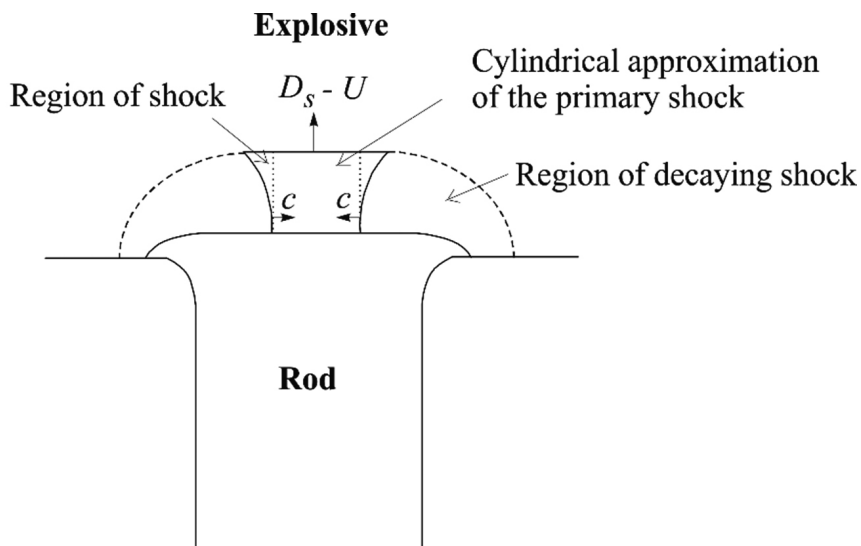


Figure 1. Diagram of explosive loading by the impacting rod: U and D_s – particle and wave velocity in the explosive, c – speed of sound in the explosive (reference system in relation to the contact surface) [11]

A good approximation of the shape of the primary shock wave is a cylinder with an increasing length in relation to the rod/explosive contact surface (length increase rate $D_s - U$) and decreasing radius due to the propagation of the side unloading waves moving at the speed of sound c . A study [11] shows that the time in which the cylinder reaches its maximum volume V_{\max} (and thus its maximum energy) is:

$$T = \frac{d_0}{6c} \quad (7)$$

where d_0 is the initial rod radius. The maximum energy for a flat-ended rod is:

$$E_{\max} = \frac{PUd_0}{6c} \quad (8)$$

where P and U are the parameters of a shock wave generated by the rod which can initiate detonation of the explosive. It can be shown that for a spherical-ended rod, the expression for the maximum energy is as follows [11]:

$$E_{\max} = \frac{PUd_0}{18c} \quad (9)$$

The general consensus is that when evaluating the sensitivity of an explosive to a shock wave, the ratio of rod length to its diameter (L/d_0), for which the transition from the flyer plate model to the rod model occurs, is approximately 1:4. The study [13] shows that the critical energy E_c is close to constant for the explosive and the cylindrical, flat-ended projectiles if

$$\frac{L}{d_0} = \frac{1}{12} \quad (10)$$

when $L/d_0 > 1/12$, the projectile is a rod, and time T is defined by Equation 7. In other cases, the projectile is a flyer plate and time $T = \tau$ is defined by Equation 2.

When selecting E_{\max} calculated for the maximum explosive volume compressed by the primary shock wave, it should be remembered that the higher value of E_{\max} can be achieved at a time from that moment until the unloading wave reaches the rod axis. This means that the impact which did not generate the required E_c for V_{\max} , may reach it a while later. A key constraint is V_{\max} , since the explosive initiation threshold will be reached if E_c occurs at the same time as V_{\max} . This point of view becomes more obvious when the relationships between the volume compressed by impact of the flyer plate and the rod is considered [11].

2.3. Detonation initiation criteria in encased explosive

The problem becomes more complex if the material is encased in an inert material (metal shell). A study [12] shows that in Equation 8, the diameter d_0 must be substituted by d_c calculated from the following equation:

$$d_c = d_0 - \frac{2d[c_i^2 - (D_i - u_i)^2]^{1/2}}{D_i} \quad (11)$$

where the subscript 'i' is related to an inert layer of thickness (d). The diameter d_c is lower than the rod diameter d_0 , since the shock wave propagated in the shell is weakened by the side unloading waves. The phenomena of shock wave weakening in the layer is similar to the shock wave weakening in the explosive – Figure 1. The study [12] shows that the Equation 11 can be used for layers with the thickness meeting the following inequality:

$$1 > \frac{d_c}{d_0} > 0.3 \quad (12)$$

For d_c smaller than $d_0/3$, the effect of side unloading waves in the shell is large enough for the pressure generated in the explosive to show distribution similar to the shock wave pressure generated after the impact of a spherical-ended rod. In this case, after determining the pressure and mass velocity at the front of the shock wave penetrating the explosive, the energy is calculated from the Equation 9.

If $d_c < 0$, the unloading waves reach the axis of symmetry and the shock wave is weakened at the entire area. The authors [12] suggest to determine the amplitude of the shock wave at the explosive interface using the following relationship:

$$\frac{P}{P_u} = \sqrt{d_0} \left[0.015 + 0.626 \exp \left(1 - \frac{1.443d}{d_0} \right) \right] \quad (13)$$

where P_u is the pressure of a shock wave at the rod-shell interface, d and d_0 are expressed in millimetres. The relationship (13) was obtained as a result of numerical simulation of the impact and penetration of the rods with diameter from 3 to 13 mm into metal objects.

3. Estimating the shock wave parameters in the explosive

To determine the energy transmitted to the explosive resulting from projectile impact, the parameters of the primary shock wave in this material must be determined. Let's consider the impact of a flat-ended projectile on the explosive encased in a metal shell and assume that due to low shell thickness to diameter ratio, the impact can be described by a one-dimensional model of a plane medium motion. The image of the process of shock wave generation in a layered medium is shown in Figure 2 on an $x-t$ plane.

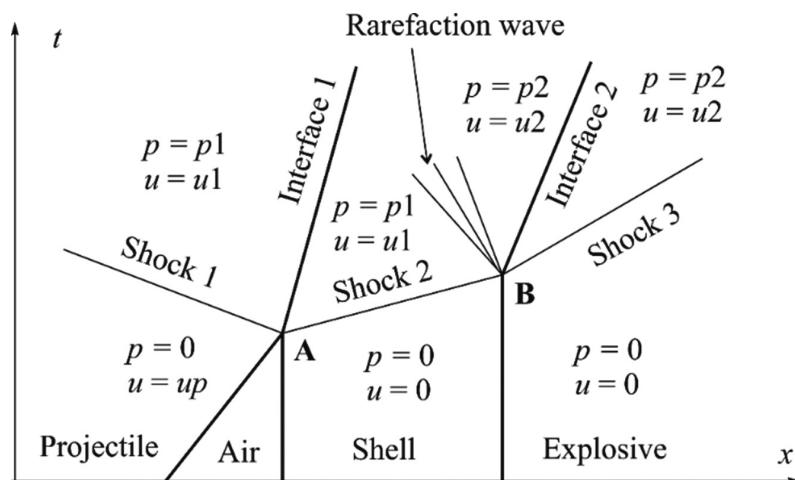


Figure 2. The wave image after the impact of a projectile on a shell layer encasing the explosive

At the moment of impact, a shock wave 1 is generated in the projectile material and a shock wave 2 is generated in the shell material. After refraction of the shock wave 2 at the explosive interface, an unloading wave is formed in the shell material, and shock wave 3 is propagated in the explosive. Assuming that the projectile velocity is sufficient for the compressive stresses in the material to exceed the yield point, a hydrodynamic flow pattern can be used. To determine the initial parameters of shock wave 2 and shock wave 3, a relationship between the continuity of mass and momentum at the front of the shock waves and the conditions of equality of pressure and mass velocity at the contact interfaces, are used.

For most homogenous materials, the experimental relationship between mass velocity u and shock wave velocity D_s can be approximated using the following linear relationship (Equation 14):

$$D_s = a + \lambda u \quad (14)$$

where constants a and λ are determined empirically. A study [14] shows that for high pressures in solids, the isentrope in the unloading wave can be defined with the shock adiabat equation resulting from Equation 14. Using the law of conservation of mass and momentum streams at the front of the shock wave and the relationship (14), the following shock adiabat equation can be obtained:

$$p = \rho_0 [\pm a + \lambda(u - u_0)](u - u_0) \quad (15)$$

Sign '+' refers to the wave propagating to the right (along the x -axis), sign '-' refers to the wave propagating to the left. u_0 is the mass velocity upstream of the shock wave front, ρ_0 – medium density. Equation 15 will be used to determine the parameters of shock wave 2 and shock wave 3, Figure 2.

The impact of a tungsten projectile on the steel layer and one of the two explosives: TNT or PBX-9404 will be analysed. Table 2 shows the material data for the projectile, shell and explosives.

Table 2. The coefficients in the empirical relationship (Equation 14) for the tested materials

Material	ρ_0 [kg/m ³]	a [m/s]	λ	Ref.
Mild steel	7840	3596	1.6863	[4]
Tungsten	18670	2860	2.08	[15]
TNT, cast	1614	2390	2.05	[6]
PBX-9404	1840	2430	2.57	[4]

A method of calculating the parameters of the shock waves will be presented using the impact of a tungsten subprojectile with a diameter of 5.85 mm, length of approx. 7 mm and velocity $up = 800$ m/s. The impact of the subprojectile on the steel shell generates a shock wave in the steel with the parameters determined by point A (Figure 3), corresponding to the intersection of the shock adiabat 1 for steel and the correspondingly shifted shock adiabat 2 for tungsten. The shock wave propagates in a 5 mm thick steel and is weakened by the side unloading waves. To calculate the diameter d_c of the shock wave reaching the interface with TNT, we must calculate the shock velocity in steel and the sound of speed behind the shock wave front. Since the pressure ($p = 18.15$ GPa) and mass velocity ($u = 518$ m/s) at the shock wave front are known, the propagation velocity can be determined from Equation 14. The sound of speed in steel, with the properties described by the adiabat (Equation 14), can be calculated from the following Equation 16:

$$c = a \left[\frac{(1-\eta)^2(1+\lambda\eta)}{(1-\lambda\eta)^3} \right]^{1/2} \quad (16)$$

where $\eta = u/(\alpha + \lambda u)$.

The diameter d_c calculated from Equation 11 is larger than 0. Thus, a shock wave with the parameters defined by point A, reaches the explosive interface. The parameters at the steel-explosive (TNT) interface are determined by point B at the intersection of shock adiabat 4, representing the changes in pressure and mass velocity in the unloading wave in steel, and the shock adiabat 3 of the TNT. Since, in this case, d_c is lower than $d_0/3$ to calculate the energy of the shock wave in TNT, Equation 9 and the shock wave parameters corresponding to point B, were used. The speed of sound in the TNT compressed by the shock wave was calculated using the Equation 16.

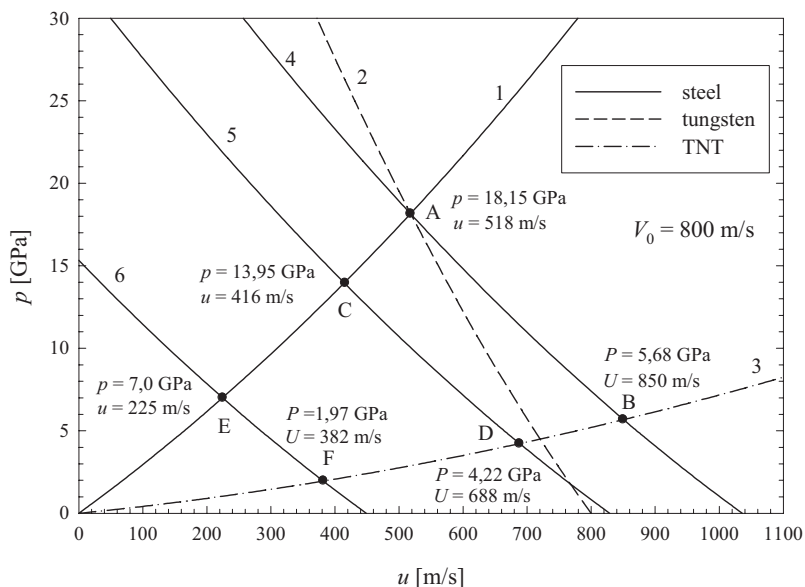


Figure 3. A graphic method to estimate the shock wave parameters in TNT

For a steel shell thickness of 7 mm, the calculated d_c is negative. This means that the side unloading waves have weakened the shock wave during propagation to the TNT interface across its entire cross-section. The pressure of the shock wave reaching the interface with the explosive can be estimated using Equation 13. The characteristic curves of the wave are determined by point C at the adiabat 1, and for TNT, at the interface with the steel, point D at the intersection of unloading adiabat 5 and the shock adiabat 3 for the TNT.

The parameters corresponding to this point can be used to estimate the impact energy in TNT, in accordance with Equation 9. A similar method was used to determine the parameters of the shock waves for a steel thickness of $d = 10$ mm (points E and F in Figure 3).

Using the described method, the following relationship between the energy of the primary shock wave in TNT and PBX-9404, after the impact of the tungsten subprojectile and the thickness of the steel shell, was determined (Figures 4 and 5). The results presented can be used to evaluate the response of the materials to the subprojectile impact.

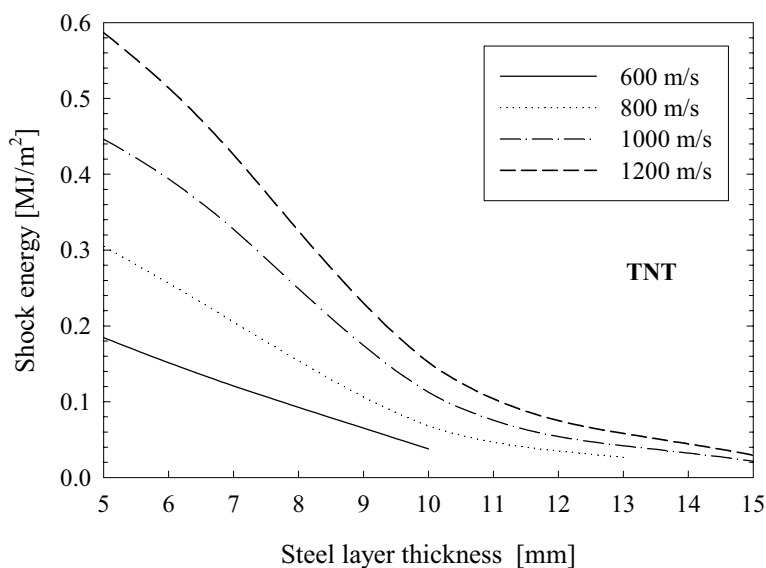


Figure 4. The relationship between the energy of the shock wave in TNT and the thickness of the steel shell after the tungsten subprojectile impact at different velocities

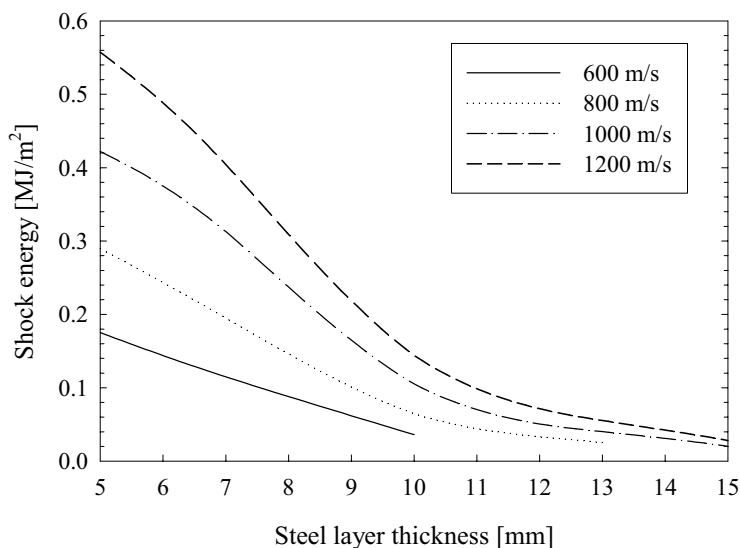


Figure 5. The relationship between the energy of the shock wave in PBX-9404 and the thickness of the steel shell after the tungsten subprojectile impact at different velocities

An analysis of the relationship in Figures 4 and 5, shows that despite the large difference between the density of TNT (1,614 kg/m³) and PBX 9404 (1,840 kg/m³), the differences in the estimated shock wave energies are less than 5%. The curves determined for TNT and PBX-9404 can be used to determine the shock wave energy in other explosives characterized by different densities. A comparison of the critical energies in Table 1 with those in Figures 4 and 5 shows that among the explosives listed in the table, only PBX-9404, nitramine and pressed TNT can be initiated by the tungsten projectile propelled at 1000-1200 m/s, if those explosives are encased by a steel shell with a thickness of less than 5 mm. A steel shell with a thickness of 10 mm should protect the explosives against initiation. The other materials will not be initiated if they are encased by a steel shell with a thickness of at least 5 mm.

4. Evaluation of the response of explosives encased in steel shell to the impact of tungsten subprojectile

98 and 120 mm mortar projectiles and 122 and 150 mm artillery projectiles were analysed as targets. Ammunition design data from publicly available materials – technical drawings and projectile models – were used. Table 3 shows the data used to evaluate the response of the explosive encased in the projectile shell to the impact of an AHEAD ammunition subprojectile. As in section 3, the tungsten projectile weight was 3.3 g and its diameter was 5.85 mm.

Table 3. Parameters of the tested mortar and artillery projectiles

Mortar and artillery projectiles	Parameters
98 mm mortar shell with a fragmentation projectile	Explosive: compacted TNT, reloaded by pressing Shell: special cast iron or C-60 steel Wall thickness: 16 to 24 mm
120 mm mortar projectiles:	
a) OF-843-A fragmentation missile	Explosive: compacted TNT Shell: special cast steel Wall thickness – 15.5 to 19 mm
b) OF-843 fragmentation missile	Explosive: compacted TNT Shell: C-60 steel Wall thickness: 15.5 to 18 mm
OF-462 122 mm artillery fragmentation projectile	Explosive: compacted TNT (average density 1.5 g/cm ³) or cast TNT Shell: C-60 steel Wall thickness: 10 to 16.5 mm
OF-540 152 mm artillery fragmentation projectile	Explosive: compacted TNT Shell: C-60 steel Wall thickness: 15 to 23 mm

As stated previously, the main factor causing the initiation of the explosive is the energy of the primary shock wave in the explosive. The shock wave propagating in the medium, compresses it by impact resulting in a sudden increase in temperature. A critical energy criterion determines the energy of the primary shock wave and the maximum volume, at which the shock wave is generated.

In the tested mortar and artillery projectiles, only cast or compacted TNT was used. The average density of the compacted TNT is approx. 1.5 g/cm³. The density of cast TNT is between 1.58 to 1.6 g/cm³. The critical energy for cast TNT is $E_c = 1.95 \text{ MJ/m}^2$. The available literature does not include any information on the critical energy for TNT compacted by extrusion. A study [16] includes the results of a gap test, in which the sensitivity of the explosives to a shock wave generated by an explosion of a standard initiating charge, is tested. For TNT, the following critical pressures were obtained:

- cast TNT: 63 kbar,

- compacted TNT: 29 kbar,
- pressed TNT: 20 kbar.

The authors of a study [7] showed a correlation between the sensitivity of the explosive to the impact of a steel cylinder and its sensitivity to a shock wave in the gap test. The ratio of critical pressure for pressed and cast TNT is $20/63 = 0.32$, whereas the ratio of critical energy for those explosives in the test with a projectile impact is $0.63-0.67/1.95 = 0.32-0.34$ (Table 1). Using the correlation discussed in study [7], the critical energy of compacted TNT was determined as follows:

$$E_c = 1.95 \cdot 29/63 = 0.90 \text{ MJ/m}^2.$$

A comparison of the critical energy of the shock wave for cast and compacted TNT with the values in Figure 4, shows that the impact of a tungsten subprojectile on the tested mortar and artillery projectiles at right angles, will not initiate an explosive detonation, even if the tungsten cylinder impacts the projectile at 1000-1200 m/s. For those velocities, an estimated energy of the shock wave in TNT for a 10 mm thick steel shell is less than 0.2 MJ/m^2 , whereas, the critical energy for cast and compacted TNT is 1.95 and 0.90 MJ/m^2 , respectively. An impact at an angle smaller than a right angle will generate a shock wave with lower energy, for example, impact of a tungsten cylinder at 45° or 60° on a 10 mm thick steel shell will generate a shock wave in TNT with an amplitude 4 and 8 times lower respectively, than at normal impact, [17]. Even if the tungsten subprojectile hits the object moving at a certain velocity at a sharp angle, and the resultant impact velocity is higher than the subprojectile velocity, the amplitude of the shock wave generated in the TNT will be lower than the amplitude of the shock wave resulting from a perpendicular impact. An AHEAD subprojectile with a mass of 3.3 g will not initiate detonation of cast and compacted TNT encased in the shells of the tested mortar and artillery projectiles.

Based on the comparison of the impact energy in Figure 4 and the data in Table 1, for mortar and artillery projectiles with shell thicknesses over 10 mm, loaded with explosives characterized with a sensitivity corresponding to PBX-9404, nitramine or pressed TNT, the conclusion remains unchanged, *i.e.* the explosives will not be initiated.

If the tested mortar and artillery projectiles (with shell thickness as per Table 3) are hit with more than one tungsten cylinder, but the distance between the cylinders is larger than their diameter, the explosives in the shells will not be initiated. The impact of the first subprojectile will not affect the energy of the shock wave generated by the second subprojectile, thus, the risk assessment must allow for the energy criterion for a single projectile only. This results from the analysis of the detonation initiation process after the impact of the projectile described in section 2.2.

5. Summary

A method of estimating pressure and total energy of a shock wave in an explosive following impact by a projectile on a non-encased charge and a charge encased in a metal envelope, is proposed. Detonation initiation criteria were presented for those systems. A method of evaluating the response of an encased explosive to projectile impact, is proposed.

It was shown that the estimated energy of a shock wave generated in a TNT charge encased in at least 10 mm thick shell following impact by a tungsten subprojectile at 1000-1200 m/s, is less than 0.2 MJ/m^2 and is an order of magnitude smaller than the critical energy required to initiate detonation in cast TNT (1.95 MJ/m^2) and 5 times smaller than the critical energy for compacted TNT (0.90 MJ/m^2). This means that artillery projectiles loaded with different types of TNT will not detonate on impact of a tungsten subprojectile.

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