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Criteria and evaluation of ballistic sensitivity of explosive reactive armor

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A theoretical analysis of the physics of the initial phase of interaction between explosive reactive armor and a shaped charge jet, i.e. of an armor piercing projectile, is accomplished. The final issue of this phase, which qualitatively determines the farther course of the interaction process, depends primordially on the explosive charge sensitivity in this armor. The main significant parameters of initiation process of explosive reactive armor are considered. The results of the experimental testing of the explosive reactive armor sensitivity, during interaction with a shaped charge jet and kinetic penetrator (armor piercing projectile) are given. The theoretical evaluation of the explosive sensitivity in this armor by modified Walker-Wesley criterion of the initiation is accomplished and some calculated interaction parameters, like the position of the initiation zone and time of initiation, are compared with relevant experimental results.

Key words: **explosive reactive armor, explosive sensitivity, shaped charge jet, armor piercing projectile, criterion of initiation**

Denotations and abbreviations

A_{ww} – coefficient of Walker-Wesley criterion
a_e – sound velocity in explosive charge,
a_m – sound velocity in penetrator material (jet, projectile)
B_{ww} – coefficient of Walker-Wesley criterion
C – impact parameter
C_{ww} – coefficient of Walker-Wesley criterion
D – detonation velocity in explosive charge
D_π – dimensionless Pi form
d_e – diameter of explosive charge
d_m – diameter of jet frontal part, diameter of projectile
E – initiation energy
k_h, k_t – experimental constants
P_π – impact parameter of the jet (projectile) and explosive
p, p_x – shock wave pressure
p_{CJ}, – detonation pressure
S_e – Hugoniot adiabate slope constant for explosive
S_m – Hugoniot adiabate slope constant for penetrator material (jet, projectile)
t – time
U – shock wave velocity
u – particle velocity (flow velocity behind a shock wave)
V_{fp} – frontal plate velocity
v_m – jet frontal part velocity, projectile velocity
v_r – recording speed
α_m – shaped charge attack angle
δ – thickness of ERA frontal plate
Δh_i – position of zone initiation
Δt_i – time of initiation
ρ_e – explosive charge density
ρ_m – penetrator material density (jet, projectile)
τ – impulse time-duration of a shock wave
AP – armor-piercing
API – armor-piercing-incendiary
APIT – armor-piercing-incendiary-tracing
APSFDS – armor-piercing-subcaliber-finastabilized-discarding-sabot
CCE – cast composite explosive
cr – critical value
DT – detonation wave
ERA – explosive reactive armor
HS – high-speed
MPE – modified plastic explosive
PETN – pentrite
SC – shaped charge
SW – shock wave
TNT – tri-nitro-toluole

Introduction

THE ballistic sensitivity of explosive charge in ERA presents its very important characteristic and from this point of view the theoretical analysis and experimental research of the initial phase of an ERA and penetrator interaction have a special interest, whichever penetrator is in question: shaped charge projectile, piercing projectile, firing ball, subcaliber armor-piercing projectile or debris produced during fragmentation of high explosive projectiles. Namely, depending on if it will start an initiation of explosive process in ERA or not, the functional characteristics of that kind of armor and further flow of the interactive process are extremely different. It is necessary to emphasize that sensitivity of explosive charge in ERA must be adapted so that the explosive is not activated in the case of hitting by firing or penetrative (pan-

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[1)] Military Technical Institute (VTI), Kataniceva 15, 11000 Belgrade zer) ammunition, and must be accurately activated in the case of hitting by the shaped charge projectile, i.e. in the case of interaction with a shaped charge jet.

The aim of the present work is an attempt to define a theoretical method and criterion for evaluation of the sensibility of explosive charge in ERA, that would be accepted in each of above mentioned particular cases. The modified Walker-Wesley criterion, which has been used primordially for estimation of explosive sensibility when it is exposed to action of the shaped charge jet, is adopted as a good initial base to define the conditions for initiation of explosive reaction of ERA.

In the paper especially are stressed: experimental verification of the explosive charge sensibility in ERA, determination of the location of the initiation zone and time initiation, and comparative analysis of the calculated values of the interaction parameters and experimental data. The ballistic sensitivity, i.e. explosive charge sensitivity, is determined numerically on the basis of the generalized and modified Walker-Wesley criterion, and the location of the initiation zone and time initiation on the basis of the equations derived by the procedure of the regressive analyses.

To perform experimental research a lot of methods are used, as follows:

- recording and registration of the interaction process using the IMACON 790 HS camera, in STREAK and FRAMING techniques,
- recording and registration of the process in impulse radiography technique using the Roentgen equipments SCANDIFLASH 600 kV, and
- range testing research of the ERA sensitivity in static and dynamic (by hitting) conditions.

In order to get a complete idea about the interaction and to analyze theoretically each phase of the process, including the primordial evaluation of the explosive sensibility, some experimental testing results of that complex interaction process considering more types of ERA and different types of penetrator are presented in the work, and they exceed the scopes of the work.

Review of the criteria for evaluationof the explosive shock sensitivity

The conditions of explosive charge initiation mostly depend on the shock wave intensity, i.e. on the initiation energy, that determines the velocity of the hammer (penetrator) and its physical characteristics. The shock sensitivity of the explosive most frequently has been tested in static conditions (Fall-apparatus and Gap-test) or under dynamic conditions by hitting (Bullet-test), and a lot of criteria for explosive shock sensitivity evaluation resulted from the mentioned tests.

- Criterion of the critical pressure

$$p = p_x \geq p_{cr} \qquad (1)$$

- Empirical criterion

$$C = v_m^{\,2} d_m \geq C_{cr} \qquad (2)$$

- Criterion of the critical energy

$$E = p_x u \tau \geq E_{cr} \qquad (3)$$

All the above mentioned criteria of initiation of the explosive charge consider that the surface of the front of the generated plane shock wave is larger than its critical value, which is *a priori* defined by testing conditions.

The real impact conditions of the shaped charge jet and ERA explosive charge (Fig.1) are very different from ideal conditions of initiation by the plane shock wave, due to the influence of real geometrical and physical parameters of the penetrator, and this fact must be considered when defining the criterion for evaluating ERA ballistic sensitivity.

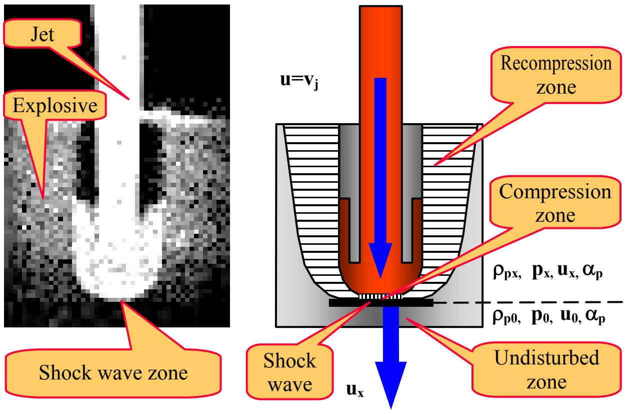


Figure 1. Physical (left) and mathematical (right) impact models of the shaped charge jet and explosive charge in ERA

Theoretical model of initiation of explosive reactive armor by the shaped charge jet

The physical model of ERA completely corresponds to the plane (two-dimensional) model of the closed explosive propulsion regarding contour conditions. The only difference appears in the method of initiation. In the case of ERA, the shaped charge jet provokes the initiation of the explosive charge (Fig.2), which is not the case with the plane model initiated from one of the ends, over the complete side surface (Fig.3): the initiation occurs then at the point on the top of the side.

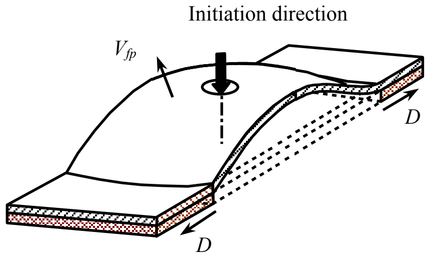


Figure 2. Plane explosive propulsion regarding contour conditions initiated at the top of the side

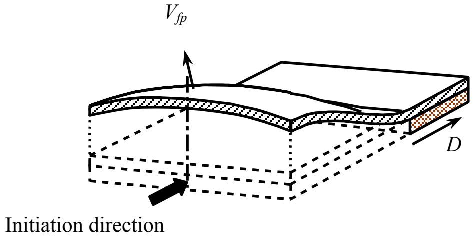
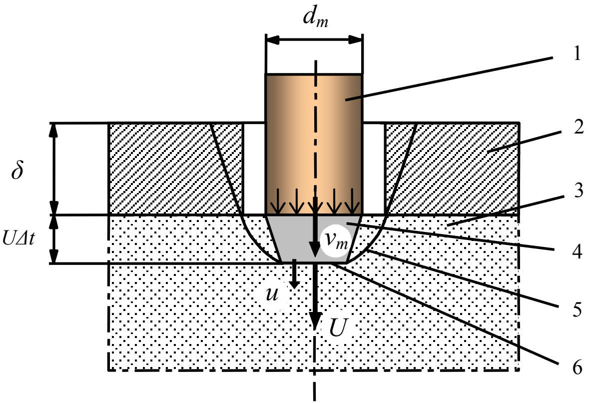


Figure 3. Plane explosive propulsion regarding contour conditions initiated from one of the ends

From this point of view, the initiation of explosive reactive armor by the shaped charge jet can be shown by an axy-symmetric three-dimensional physical model, the axial cross-section of which is presented in Fig.4 [1].



1.- Shaped charge jet, 4.- Zone of intensive compression
2.- Frontal plate, 5.- Front of the side shock wave
3.- Explosive charge, 6.- Front of the frontal shock wave

Figure 4. Axial cross-section of the axy-symmetric model of the interaction of explosive charge in ERA and the shaped charge jet

The process of interaction of ERA and the shaped charge jet starts by a physical contact of the frontal part of the jet with a velocity of v_{m0} and the ERA frontal plate (layer). The next phase of the interaction includes the jet penetration through the frontal plate of thickness δ, followed by appearance of the shock wave in the plate material, until the arrival of the jet to the explosive charge. At this moment the velocity of the frontal part of the shaped charge jet is $v_m(i)$ and it is less than v_{m0} value. The determination of the frontal part velocity of the shaped charge jet $v_m(i)$, during the penetration of the frontal plate of ERA is based on the hydrodynamic theory of the jet penetration [2].

The arrival of the shaped charge jet on the surface of the explosive charge causes a very intensive SW in explosive, the velocity of which is equal to U, and then the particle velocity (flow velocity behind the shock wave) is u (Fig.4). On the created SW two parts can be distinguished: front of the plane frontal SW and curved front of the side SW. The front of the plane frontal SW determines the limits of the zone of strong compression of explosive charge ($U\Delta t$) and initiation of the detonation process in the explosive charge directly depends on its diameter. The expansion wave, which spreads from the contact surface of the explosive charge and the layer, determines the form and intensity of the side SW. Its intensity decreases from the contact point with the frontal part of the plane SW to the contact point with the frontal plate of ERA.

If the intensity and diameter of the plane frontal SW are sufficient and if the SW impulse time lasts sufficiently, then the initiation of the explosive charge in ERA occurs. In other words, if the pressure in the front of the generated SW p_x is higher than the critical value p_{cr}, which determines the explosive sensitivity to the shock wave initiation under given conditions, and if the diameter of the plane frontal SW is greater than the critical diameter of explosive d_{cr}, the shaped charge jet will activate the explosive charge in ERA.

Modified Walker-Wesley criterion of initiation

Basically, the mechanism of the explosive initiation by the shock consists of the action of SW in the front of DW on the explosive charge that causes the appearance of the "hot spots" in the explosive and local activation of the explosive decomposition of the charge. If the relevant conditions are satisfied, the local explosive decomposition rapidly becomes a stable detonation process with a surface-front of the chemical reaction zone.

The critical energy of activation E_{cr} determines the condition for appearance of the explosive initiation under the action of SW. It presents the minimum critical energy that the SW must deliver to the unit surface of the explosive material to initiate the detonation process. The value E_{cr} depends on the type of explosive, granulation, initial explosive density and porosity, as well as on the characteristics of the explosive charge confinement.

In the case of the explosive initiation by the plane SW[1], the determination of the parameter E_{cr} value is based on the laws of mass balance (continuity equation), the momentum balance (equation of motion), and energy balance (equation of energy conservation), as well as on the equations of the shock adiabate of the donor (generator of the plane SW) and acceptor (tested sample - explosive charge) [2,4,5]

$$E_{cr} = p_x u t = \frac{p_x^2 t}{\rho_e U} = Const. \qquad (4)$$

where p_x is a value of the contact pressure, i.e. pressure in the generated SW.

The equation (4) is a well-known Walker-Wesley criterion of initiation and shows that the shock wave initiation of explosive does not depend only on the pressure in SW p_x, but on the duration of the impulse time of the shock wave t (duration time of the pressure p_x). For example, E_{cr} for pure cast TNT with 1620 kg/m^3 of density is 1340 kJ/m^2, and for pure pressed PETN with 1600 kg/m^3 of density, E_{cr} is 167 kJ/m^2. It is necessary to emphasize that the condition of shock wave explosive initiation is expressed frequently with the parameter $p_x^2 t$.

The research of the conditions of the explosive charge initiation by the impact of the cylindrical projectile [6,7], i.e. by the attack of the shaped charge jet [8,9,10,11], gave the possibility to modify and adopt the Walker-Wesley criterion of initiation for general conditions of ERA activation by the shaped charge.

The modified Walker-Wesley criterion of explosive initiation by shaped charge jet considers the model of the impact of the cylindrical long rod (penetrator) and the cylindrical explosive charge. The criterion takes in to consideration a number of physical and chemical, as well as geometrical parameters of the explosive and shaped charge jet (projectile) such as:

- explosive charge density ρ_e,
- detonation velocity in the explosive charge D,
- detonation pressure p_{CJ},
- critical diameter of the explosive charge d_{cr},
- sound velocity in the explosive charge a_e,
- slope constant of the Hugoniot adiabate for the explosive S_e,
- penetrator material density (jet, projectile) ρ_m,
- jet frontal part velocity, projectile velocity v_m,
- diameter of the jet frontal part, diameter of the projectile d_m,

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[1] Experimental determination of E_{cr} in the cases of the plane shock wave initiation has been realized by the Gap-test [3], for which there are no uniform conventional testing conditions. Therefore, for one explosive, there are more different data for a value of E_{cr}, which define the explosive sensitivity, followed by previously determined experiment conditions.

- sound velocity in penetrator material (jet, projectile) a_m, and
- slope constant of the Hugoniot adiabate for penetrator material (jet, projectile) S_m.

The modified and generalized Walker-Wesley criterion of explosive initiation by cylindrical penetrator impact, in its final form reads

$$E_{cr} = \frac{p_x u \, d_m}{6 \, a_m} \tag{5}$$

The eq. (5) shows that the critical energy for the same explosive is not constant, as in the case of the plane shock wave initiation. In this case the critical energy depends on the physical and mechanical, as well as on the geometrical parameters of the shaped charge jet.

Regarding the fact that the mechanism of the initiation of the detonation process in the shaped charge in ERA happens in accordance with the scheme in Fig.4, the modified Walker-Wesley criterion of initiation of the explosive charge can be used in the case of the arrival of the shaped charge jet to the armor, as well as in the case of the impact of the firing ball, i.e. the armor piercing projectile with ERA.

The main parameters of the interaction of the explosive charge and the jet are critical energy E_{cr}, shock wave velocity U, pressure in the generated shock wave p_x, and particle velocity (flow velocity behind shock wave) u. The given parameters are determined by the system of equations

$$E_{cr} = \frac{\rho_e \, d_m \, u^2 \, (a_e + S_e u)}{6 \, a_m} \tag{6}$$

$$U = a_e + S_e u \tag{7}$$

$$p_x = \rho_e U \; u \tag{8}$$

The eq. (6) is derived from eq. (5) which contains eq. (7) and (8).

From the critical conditions of the initiation, given by eq. (6), and with known shock adiabates of the jet material (projectiles) and explosive, the flow velocity behind the shock wave u determines the equation

$$u = \frac{- B_{WW} + \sqrt{B^2_{WW} - 4 \, A_{WW} \, C_{WW}}}{2 \, A_{WW}} \tag{9}$$

where the constants A_{WW}, B_{WW}, and C_{WW} are

$$A_{WW} = \rho_e S_e - \rho_m S_m \tag{10}$$

$$B_{WW} = \rho_e a_e + \rho_m a_m + 2 \, S_m v_m \tag{11}$$

$$C_{WW} = - \left(\rho_m a_m v_m + \rho_m S_m v_m^2 \right) \tag{12}$$

After the determination of the parameters of the explosive charge initiation, the parameters of the modified Walker-Wesley criterion of initiation can be calculated, as well as the dimensionless Pi expression D_π [8] derived from Buckingham's Pi theorem[2] [12,13]

$$D_\pi = \frac{\rho_m \, p_{CJ}}{\rho_e^2 \, d_{cr} \, g} \; , \quad (g = 9.81 \text{m/s}^2) \tag{13}$$

and the parameter of the impact of the shaped charge jet (projectile) and the explosive P_π

$$P_\pi = v^2_m \; d_m \tag{14}$$

By marking the couples (D_π, P_π) in to the diagram of the depending $D_\pi = D_\pi(P_\pi)$, shown in Fig.5 and derived by the regressive analysis on the basis of the experimental results [8,14], the modified Walker-Wesley criterion of initiation of the explosive charge can be easily used.

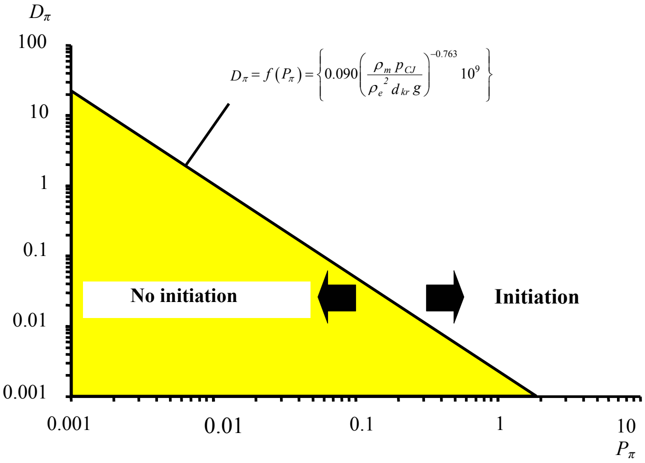

Figure 5. Regressive line of the modified Walker-Wesley criterion of initiation of the explosive charge

In the two-logarithmic diagram, the points (D_π, P_π) up the regressive line $D_\pi = D_\pi(P_\pi)$ correspond to the conditions of the initiation of the detonation process in the explosive charge of ERA, and vice versa, the points down the regressive line $D_\pi = D_\pi(P_\pi)$ correspond to the conditions of the absence of the explosive charge initiation.

Position of the zone initiation and the time initiation

The location of the zone initiation Δh_i and the delay time of initiation Δt_i, for the case of the interaction of the shaped charge jet and ERA explosive charge, shown in Fig.6, have been calculated on the basis of the empirical equations derived from procedure of regressive analysis [15].

The regressive expressions have the form of the potential functions

$$\Delta h_i = k_h \left[\frac{v_m(i)}{1000} \right]^{-4} \tag{15}$$

$$\Delta t_i = k_t \left[\frac{v_m(i)}{1000} \right]^{-6} \tag{16}$$

where k_h and k_t are the constants determined from experimental conditions [14,15,16,17,18], k_h=23.00 [m^5/s^4] and k_t=0.122 [m^6/s^5].

The Eqs. (15) and (16) consider the influence of the decreasing of the velocity of the jet frontal part on the location of the initiation zone and the delay time of initiation, because as a new actual condition of the explosive penetration.

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[3] The full name of Pi theorem frequently is labeled in the literature as the theorem of Washy-Buckingham-Riabouchinsky.

It is necessary to emphasize that Δh_i and Δt_i depend on the other impact parameters, as well (density of the jet material and explosive, sound speed in material of the jet and explosive, etc.), but the influence and variation of these parameters are relatively small in comparison with the jet velocity. Besides, since the dynamic pressure on the contact surface of the frontal side of the jet and cached explosive depends mostly on the jet velocity (quadratic function), the results of the dispersive analysis show that the velocity is the most significant factor which determines the values Δh_i and Δt_i.

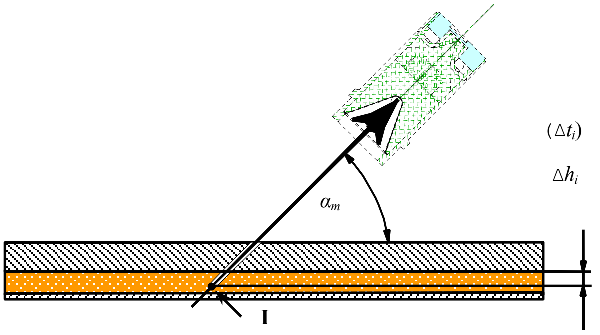


Figure 6. Position of the initiation zone in ERA explosive charge

Finally, it is necessary to emphasize a very important fact that exceeds the scopes of the this paper and that is the theoretical evaluation of the nature and the flow of the interaction process of the ERA and any kind of penetrator on the basis of the modified Walker-Wesley criterion of initiation is possible as well as the definition of the initiation parameters of the explosive charge under the impact of the shaped charge jet (E_{cr}, p_x, Δh_i, and Δt_i). Further more, the same fact is very important from the aspect of regular the ERA design as a powerful kind of additional protection of main armor of modern tanks and for optimum selection of parameters of construction of shaped charge in the tandem warhead.

Experimental research of the ballistic sensitivity of explosive reactive armor

Effects of small arms and piercing ammunition on explosive reactive armor

The estimation of requirements for the sensitivity of ERA explosive charge exposed to the impact of small arms and piercing ammunition is carried out on several models of ERA in dynamic conditions, i.e. by hitting ERA [19,20]. The block consisted of 9 elements of one ERA model that was tested experimentally, shown in Fig.7.

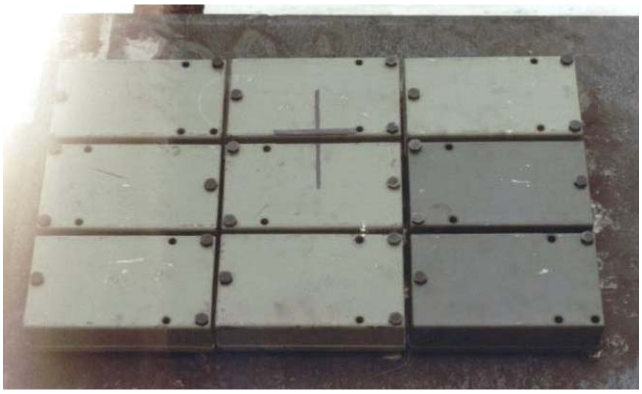


Figure 7. View of the block consisted of 9 ERA's elements prepared for sensitivity testing by hitting

The main physical, chemical, and geometrical parameters of the tested models of ERA and used types of ammunition are given in Tables 1, 2, and 3.

Table 1. Main characteristics and detonation parameters of explosive in ERA

No.	Explosive	Composition	ρ_e	D	p_{CJ}	d_{cr}	a_e	u_{CJ}	S_e
-	-	-	kg/m^3	m/s	MPa	m	m/s	m/s	-
1.	Cast composite (CCE)	RDX BaNO$_3$ Polyurethane	1832	6180	16.6	0.005	2400	1470	1.70
2.	Modified plastic (MPE)	PETN BaNO$_3$ Polyurethane	1830	6100	17.1	0.005	2400	1524	1.70

Table 2. Parameters of small arms and piercing ammunition

No.	Bullet	Material	ρ_m	v_m	d_m	P_m	a_m	S_m
-	ball	-	kg/m^3	m/s	m	m	m/s	-
1.	API ball 7.62 mm	Steel	7850	740	0.008	~0.010	3800	1.40
2.	APIT ball 20 mm	Steel	7850	853	0.020	~0.020	3800	1.40
3.	API ball 23 mm	Steel	7850	720	0.023	~0.020	3800	1.40

Table 3. Parameters of the armor piercing subcaliber ammunition

No.	Cartridge	Material	ρ_m	v_m	d_m	P_m	a_m	S_m
-	projectile	-	kg/m^3	m/s	m	m	m/s	-
1.	APSFDS projectile 100 mm	Tungsten	18600	1370	0.033	~0.300	3950	1.60
2.	APSFDS projectile 125 mm	Steel	7850	1815	0.040	~0.300	3800	1.40

The Figures 8 and 9 show the recordings of the armor piercing ball in moment of passing through the armor and the appearance of the output holes on the back side of the ERA configuration 3/15/1 (sandwich configuration consisting of 3 mm frontal steel plate, 1 mm back steel plate, and 5 mm explosive layer of thickness). After perforation, there was no activation of the explosive charge in ERA.

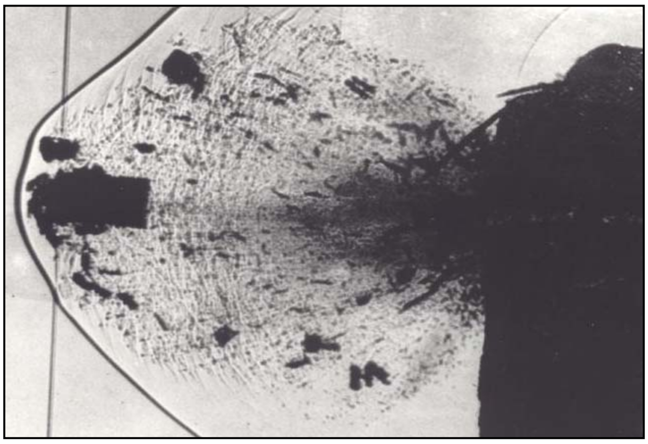


Figure 8. Schliren photography of the armor piercing ball passing through the armor

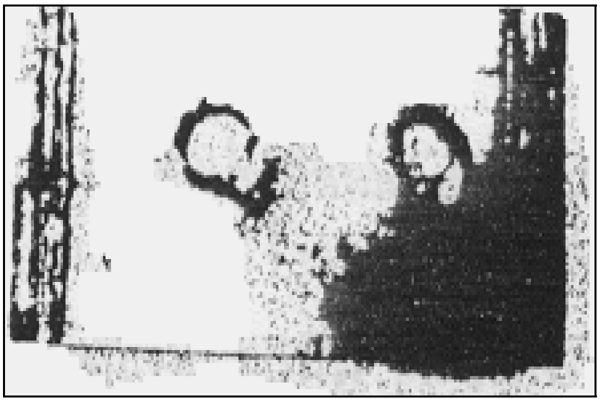


Figure 9. Perforations of the ERA element - output holes caused by 20 mm APIT ball

Impact of the shaped charge projectile on the explosive reactive armor

In order to understand better the phenomenon of interaction of ERA and the shaped charge projectile, i.e. shaped charge jet, as well as to verify experimentally the explosive sensitivity in ERA and some parameters that describe this process, the impulse radiography and high speed recording were also used. Three types of shaped charges: models of small caliber shaped charge (30 mm), models of medium caliber shaped charge (60 mm), and models of large caliber shaped charge (120 mm) were used in the experimental research.

The testing detail of the explosive charge sensitivity in the ERA with configuration 8/8/1 activated by the small caliber SC model in the static conditions is shown in Fig.10.

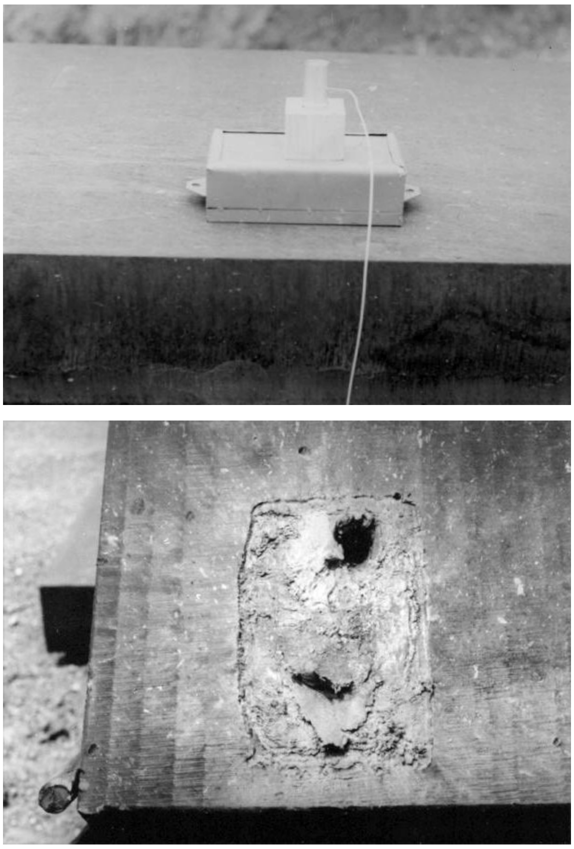


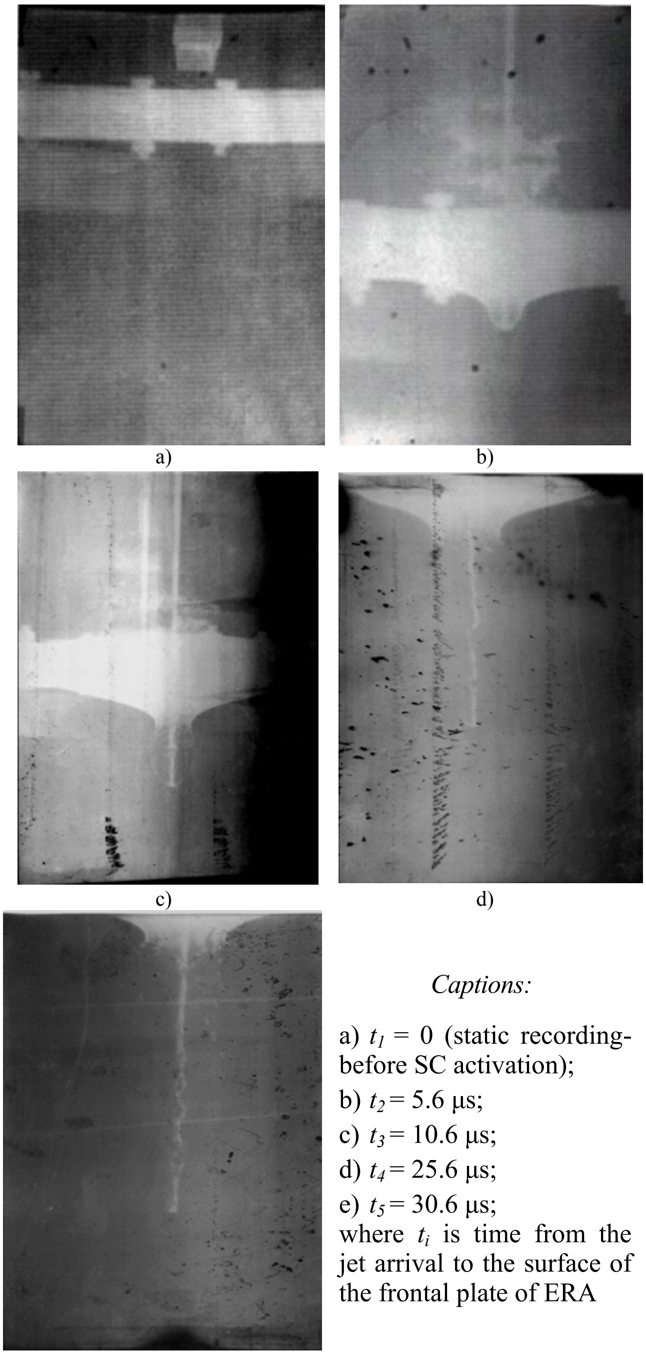
Figure 10. Static sensitivity test of the explosive charge in the ERA of configuration 8/8/1 under the jet attack of the 30 mm SC model (up - before activation, bottom - after activation)

The main physical characteristics and geometrical parameters of the shaped charge jet (in this case penetrator) for the used shaped charge models are given in Table 4.

Table 4. Main physical characteristics and parameters of the jet

No.	Shaped charge	Material	ρ_m	v_m	d_m	P_m	a_m	S_m
-	-	-	kg/m^3	m/s	m	m	m/s	-
1.	Small caliber SC model	Copper	8900	9000	0.0008	0.10	3960	1.50
2.	Medium caliber SC model	Copper	8900	8400	0.0015	0.30	3960	1.50
3.	Large caliber SC model	Copper	8900	8400	0.0020	0.72	3960	1.50

The shaped charge jet of 64 mm SC model, passing through the ERA configuration 3/15/1 with a modified plastic explosive at 90° attack angle, is shown in Fig.11 [14].



a) b)

c) d)

e)

Captions:

a) $t_1 = 0$ (static recording-before SC activation);

b) $t_2 = 5.6$ μs;

c) $t_3 = 10.6$ μs;

d) $t_4 = 25.6$ μs;

e) $t_5 = 30.6$ μs;

where t_i is time from the jet arrival to the surface of the frontal plate of ERA

Figure 11. Jet of the medium caliber SC model passing through the ERA configuration 3/15/1 ($\alpha_m = 90°$)

The radiograph recordings (Fig.11), show undisturbed passing of the jet frontal part (frames at moments: t_2 and t_3), initiation and intensity increase of the detonation process in the explosive charge in ERA and ERA layers spreading (frames at moments: t_2, t_3, and t_4), and finally, the dependence effects of the gaseous detonation products on stability and disintegration of the shaped charge jet - gasdynamic effect of the intensive whirling flow of detonation products (frames at moments: t_4 and t_5).

Sensitivity evaluation of the explosive charge in ERA

A numerical simulation of the first, initial phase of the interaction process of the explosive charge in ERA with MPE and several types of the armor piercing and small arms ammunition, i.e. shaped charge jet of the SC of different calibers, has been realized on the basis of the system equations of the modified Walker-Wesley criterion of explosive initiation (Eqs. (4)-(14)).

Calculation results are given in Tables 5, 6, and 7.

Table 5: Interaction parameters of ERA explosive charge and small arms and armor piercing projectiles

No.	Bullet	ERA type	E_{cr}	p_x^2t	D_π	p_x	v^2d_m	Initia-tion
-	ball	-	MJ/m^2	MPa^{2}s	x10^9	MPa	m^{3}s^2	-
1.	API ball 7.62 mm	3/15/1	0.838	5.32	0.810	3.99	2044	no
2.		8/8/1	0.032	0.15	0.810	0.68	167	no
3.		8/5/1	0.032	0.15	0.810	0.68	167	no
4.	APIT ball 20 mm	3/15/1	7.560	58.1	0.810	8.14	10514	no
5.		8/8/1	2.117	13.4	0.810	3.9	5238	no
6.		8/5/1	2.117	13.4	0.810	3.9	5238	no
7.	API ball 23 mm	3/15/1	4.464	30.7	0.810	5.52	8615	no
8.		8/8/1	1.448	8.57	0.810	2.91	4292	no
9.		8/5/1	1.448	8.57	0.810	2.91	4292	no

The experimental results of the sensitivity testing of explosive in ERA exposed to the action of small arms and armor piercing ammunition [19,20], as well as the results of the numerical simulation (Table 5), show that there is no activation of the explosive charge in ERA of any configuration. In the worst case the ignition of ERA explosive charge is possible only when hit by 20 and 30 mm armor piercing and incendiary ammunition. However, even then there is no initiation of the explosive decomposition of the charge.

Table 6: Interaction parameters of ERA explosive charge and subcaliber armor piercing projectile

No	Cartridge	ERA type	E_{cr}	p_x^2t	D_π	p_x	v^2d_m x10^3	Initia-tion
-	projectile	-	MJ/m^2	MPa^{2}s	x10^9	MPa	m^{3}s^2	-
1.	APSFDS projectile 100 mm	3/15/1	21.9	189	1.936	11.65	60.7	yes
2.		8/8/1	21.1	179	1.936	11.36	58.6	yes
3.		8/5/1	21.1	179	1.936	11.36	58.6	yes
4.	APSFDS projectile 125 mm	3/15/1	59.3	598	0.817	18.47	129	yes
5.		8/8/1	56.6	565	0.817	17.95	125	yes
6.		8/5/1	56.6	565	0.817	17.95	125	yes

Table 7: Interaction parameters of ERA explosive charge and the shaped charge jet

No	Shaped charge	ERA type	E_{cr}	p_x^2t	D_π	u	p_x	v^2d_m x10^3	Initia tion
-	-	-	MJ/m^2	MPa^2 s	x10^9	m/s	MPa	m^{3}s^2	-
1.	Small caliber SC model	3/15/1	9.87	170	0.922	4125	71.1	60.9	yes
2.		8/8/1	8.47	140	0.922	3901	64.5	54.8	yes
3.		8/5/1	8.47	140	0.922	3901	64.5	54.8	yes
4.	Medium caliber SC model	3/15/1	16.9	284	0.922	3992	67.1	103.7	yes
5.		8/8/1	16.7	267	0.922	3921	65.1	100.3	yes
6.		8/5/1	16.7	267	0.922	3921	65.1	100.3	yes
7.	Large caliber SC model	3/15/1	22.9	388	0.922	4017	67.8	139.9	yes
8.		8/8/1	22.4	378	0.922	3987	66.9	138.0	yes
9.		8/5/1	22.4	378	0.922	3987	66.9	138.0	yes

Theoretical results, shown in Tables 6 and 7, are absolutely compatible with results of the experimental testing of the sensitivity of ERA explosive exposed to impact of 100 and 125 mm subcaliber APSFDS projectiles, as well as to attack of the shaped charge jet [14].

Determination of the position of the initiation zone and the time of initiation

In the case of interaction of the shaped charge jet and explosive charge in ERA, the position of the initiation zone Δh_i and the time of initiation Δt_i, illustrated in Fig.12, has been calculated on the basis of empirical equations (15) and (16). The calculated values of the above mentioned parameters of the interaction of ERA and the jet are given in Table 8.

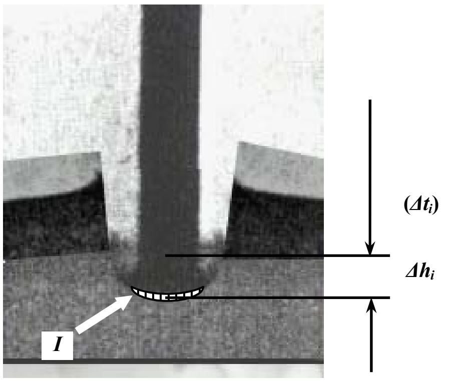
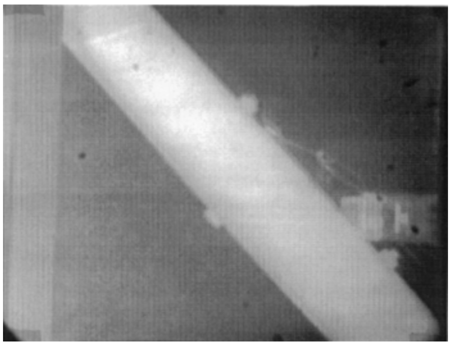


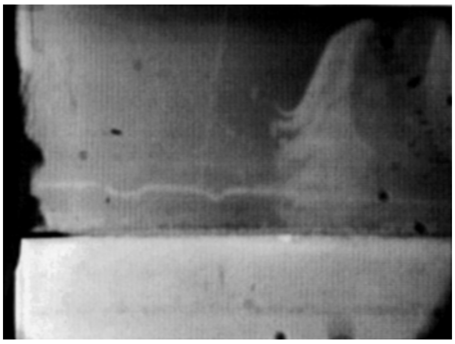
Figure 12. Position of the initiation zone in ERA explosive charge (illustration)

In addition, the research of these interaction parameters [21] was accomplished by recording the process using the techniques of impulse radiography (Fig.13) and high speed photography in FRAMING and STREAK modes (Fig.14 and 15, respectively). In order to determine the position of the initiation zone and the initiation time delay, the STREAK recordings (Fig.15) of the emerging detonation wave on the lateral side of ERA explosive charge initiated by a jet of the medium caliber SC model, are used.

The most extreme point on the DW profile determines the position Δh_i of the initiation zone, i.e. the initiation point I in the explosive charge (B point in Fig.15). The technique of continual photo-recording, i.e. STREAK technique [14], was carried out with v_r=5000 m/s streak recording speed, so that the time basis for reading characteristic time-sequences from recordings was defined simultaneously.

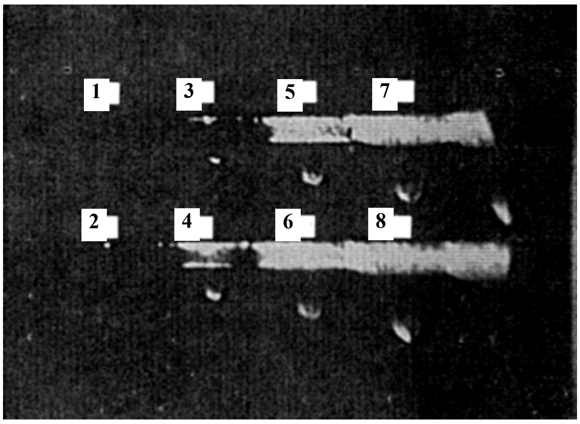


a) t_0 = 0 μs (static recording)

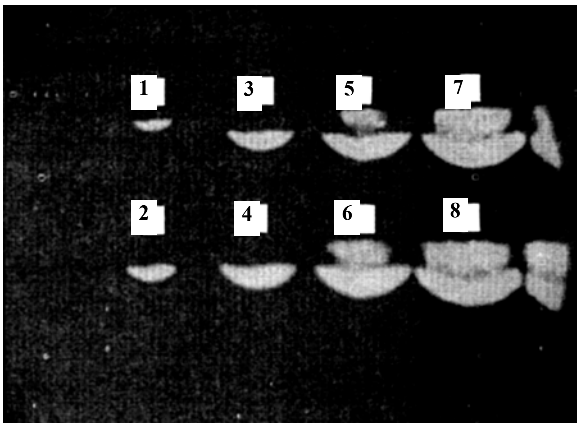


b) t_i = 35.6 μs

Figure 13. Jet of the medium caliber SC model passing through the ERA configuration 3/15/1 at attack angle α_m = 45° (radiographs)

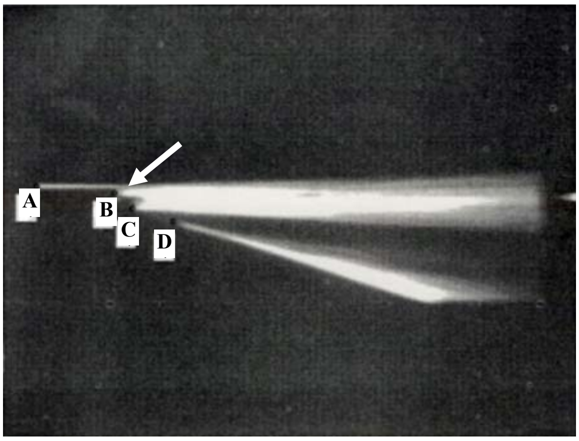


a) Interframe time 1.0 μs

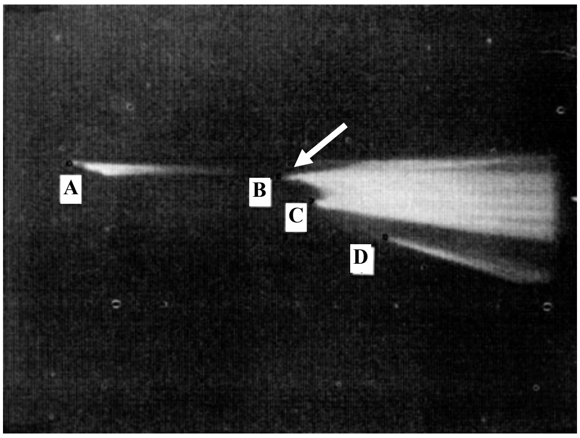


b) Interframe time 0.5 μs

Figure 14. Jet of the medium caliber SC model passing through the ERA configuration: a) 3/15/1 and b) 3/15/0, at 90° attack angle (FRAMING recordings)



a) Streak recording speed 5000 m/s



b) Streak recording speed 5000 m/s

Figure 15. Jet of thee medium caliber SC model passing through the ERA configuration 3/15/1 at a) 90° and b) 45° attack angle (STREAK recordings)

Since the explosive charge initiation is of the "at point" type (zone *I,* in Fig.12), the evolution of DW goes from the initiation point in the form of concentric circles (viewed in the axial cross-section) and after some distance DW emerges on the uncovered surface of explosive. The high-speed camera records the first appearance of DW on the uncovered surface of explosive like a light trace in the film, i.e. as B point in the photo-recordings (Fig.15). Knowing streak recording speed, detonation velocity of explosive charge, and ratio coefficient (proportional reducing of the real dimensions of the model in streak recording) and using the values of the space and time coordinates from each streak recordings registered in each particular experiment, as well as the time-calibrated recordings, we can determine the position of the initiation zone and the initiation time of ERA activated by the shaped charge jet.

The typical streak recordings of an emerging DW on the uncovered surface of explosive charge in the case of the interaction of ERA and the shaped charge jet inclined at 90° and 45° attack angles are shown in Fig.15.

The position of the initiation zone and the initiation time of ERA are determined on the basis of experimentally obtained data read from the streak recordings given for shaped charge jet attack angles α_m=90° and 45°, and shown in Table 8, side by side with relevant theoretically predicted values.

Table 8: Position of the initiation zone and the initiation time of ERA charge

No.	Attack angle	Theoretical value		Experimental value	
		Δh_i	Δt_i	Δh_i	Δt_i
-	-	m	µs	m	µs
1.	α_m=90°	0.0048	1.33	0.0030	0.82
2.	α_m=45°	0.0049	1.38	0.0041	1.58

The analysis of the results given in Table 8, show that the decrease of the jet attack angle causes an increase of the position of the initiation zone and the initiation delay time. This is compatible with the results of the theoretical prediction, since the increasing of the thickness of the frontal metallic plate of ERA produces a decrease in the velocity of the jet frontal part $v_m(i)$ which engages in the interaction with explosive and causes its activation. The increase of the thickness of the ERA frontal metallic plate in experimental testings was achieved by decreasing the jet attack angle.

Comparative analysis of data with recent results of research of ERA initiation caused by shaped charge jet attack

Peugeot’s results whit include comprehensive and exhaustive research works performed in the field of the initiation of explosive charge in ERA exposed to shaped charge jet attack, are discussed in [14]. Peugeot’s criterion of the limit explosive sensitivity depending on the diameter of the charge and jet velocity is based on the equation of impulse (transmitted to the explosive) that is given in the form of the potential function of pressure

$$p^n \tau = I \tag{17}$$

Derived on the basis of the assumed dependence of the impulse the critical energy of explosive activation takes the final form

$$E_{cr} = \frac{K}{\rho_e U} p^{2-n} \tag{18}$$

The main results of the experimental research presented in the diagram (Fig.16), confirmed the validity of eq. (18).

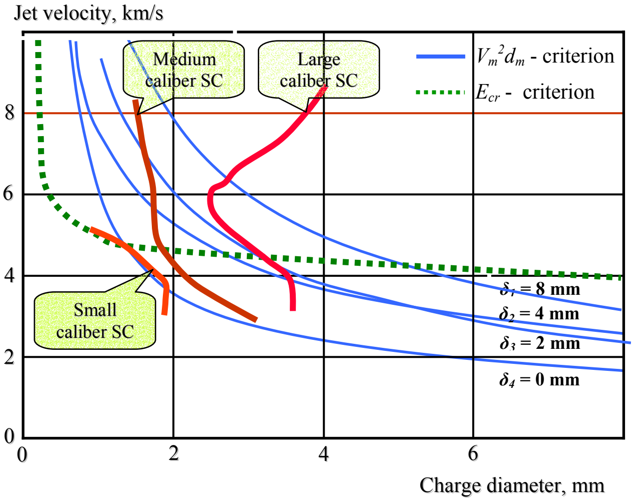


Figure 16. Illustration of Peugeot′s criterion for the limit sensitivity of ERA depending on the diameter of explosive charge and jet velocity

The family of the curves shown by a full line indicates that the increase of the jet diameter causes the decrease of the required values of the parameter $V_m^2 d_m$, as well as that the increase of the thickness of the frontal steel plate of ERA (δ) causes the increase of the required $V_m^2 d_m$. In relation to the criterion of the critical energy, the region of reliable activation of ERA is found over the broken line that represents the critical energy of activation E_{cr} caused by the attack of the shaped charge jet, and vice versa. It can be noticed that conditions as well as the very impulse of initiation of the explosive reaction in the charge depends on the shaped charge caliber (marked by thicker full lines in Fig.16)

One interesting thing from the point of view of the obtained data is their general compatibility with the results given in [14] showing agreement in theoretical and experimental research of initiation (introduction of general criterion to evaluate explosive sensitivity, choice of the range of variation of thickness and materials of ERA frontal plate, choice of the range of variation of shaped charge calibers, etc.), as well as impressive compatibility of all research results.

Conclusion

The theoretical analysis of the conditions of ERA explosive charge initiation during the attack of the shaped charge jet as well as the kinetic armor piercing projectiles has shown that a generalization of the criterion for evaluation of explosive sensitivity can be realized. It is possible due to asimilar mechanism of the initiation of explosive reaction provoked by perturbations in the charge, caused by the induced shock wave (effect of the impact of the penetrator and ERA) in the explosive.

The generalization of the criterion for sensitivity evaluation of the explosive charge is accomplished on the basis of the modified Walker-Wesley criterion of initiation. The theoretical generalization of the criterion has been possible because of considering all significant impact parameters (geometry of the penetrator and ERA, real penetration velocity of the penetrator through explosive, etc.) and physical and chemical characteristics of the material of the penetrator (shaped charge jet or armor piercing projectile) and the explosive charge in ERA.

The experimental research of the initiation of the explosive charge in ERA exposed to attack of the shaped charge jet and the armor piercing projectile, carried out using the techniques of the impulse radiography and high speed photography, facilitated considerably understanding of the physics of this interactive process, especially its initial phase (explosive charge initiation), which defines a character and a further course of the interaction process.

The experimental testing, which included the variations of the impact conditions as well as the characteristics of ERA and the penetrator, gave the possibilities to determine the values of the parameters of initiation (E_{cr}, p_x, Δh_i, and Δt_i) for each particular case.

The comparative analysis and good accordance of the calculated and experimental data, confirmed the validity and generality of the modified Walker-Wesley criterion of initiation. In other words, the criterion can be accepted in the theoretical evaluation of the initiation of the detonation process of ERA explosive charge exposed to the attack of any kind of penetrator. In that way, the problem of limited application of the well known criterion of initiation by plane shock wave ($V_m^2 d_m$) is overcome, especially in the cases treated in the paper, when the penetrator (donor) is extremely small in diameter.

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Kriterijumi i ocena balističke osetljivosti eksplozivnog reaktivnog oklopa

Izvršena je teorijska analiza fizikalnosti početne faze procesa interakcije eksplozivnog reaktivnog oklopa i kumulativnog mlaza, odnosno probojnog projektila. Konačni ishod ove faze, koja kvalitativno određuje dalji tok procesa interakcije, zavisi prvenstveno od osetljivosti eksplozivnog punjenja u ovom oklopu. Razmatrani su osnovni uticajni parametri koji utiču na pobuđivanje eksplozivnog procesa u eksplozivnom reaktivnom oklopu. Dati su rezultati eksperimentalnog ispitivanja osetljivosti eksplozivnog reaktivnog oklopa pri interakciji sa kumulativnim lazom i kinetičkim penetratorom (pancirni i podkalibarni projektili). Izvršeni su teorijska ocena osetljivosti eksploziva u ovom oklopu primenom modifikovanog Voker-Veslijevog kriterijuma inicijacije i poređenje određenih proračunskih parametara interakcije, kao što su položaj zone inicijacije i vreme inicijacije, sa eksperimentalnim rezultatima.

Ključne reči: **eksplozivni reaktivni oklop, osetljivost eksploziva, kumulativni mlaz, probojni projektil, kriterijum inicijacije, teorijska analiza, eksperimentalno istraživanje.**

Критерии и оценка баллистической чувствительности взрывчатой реактивной брони

Здесь произведен теоретический анализ физической начальной фази процесса взаимодействия взрывчатой реактивной брони и фасонной зарядной струи, т.е. пробивного снаряда. Окончательное завершение этой фазы, которая качественно определяет дальнейшее направление процесса взаимодействия, прежде всего зависит от чувствительности взрывчатой зарядки в этой брони. Здесь рассматриваны главные влиятельные параметры, которые оказывают влияние на возбуждение процесса взрыва в взрывчатой реактивной брони. Здесь приведены результаты опытного исследования чувствительности взрывчатой реактивной брони при взаимодействии с фассоной зарядной струей и кинетического проникающего элемента (пробивные снаряды). Здесь проведены - теоретическая оценка чувствительности взрывчатого вещества в этой брони применением модифицированного критерия начала Вокер-Весли и сравнение определенных расчетных параметров взаимодействия, каковы положение зоны начала и время начала с опытными результатами.

Ключевые слова: взывчатая реактивная броня; чувствительность взрывчатого вещества, фасонная зарядная струя, пробивной снаряд, критерий инициирования, теоретический анализ, опытное исследование.