UDC: 531.58(047)=20 COSATI: 19-04, 14-02

Determination of main parameters of jet penetration into the homogenous steel obstacle

Marinko Ugrčić, PhD (Eng)¹⁾ Miroljub Vukašinović, PhD (Eng)²⁾

The theoretical and experimental determinations of kinematic and dynamic parameters of the shaped charge jet necessary to analyze the process of jet penetration have been realized. The procedure of the experimental determination of jet penetration velocities is given as well as the critical jet velocity during the penetration into the homogenous obstacle. The procedure is based on the use of the logic analyzer and special captures to record the discrete data of the curve - the penetration length depending on time. A polynomial form of that mathematically fitted functional curve gives the possibility to determine the critical jet penetration velocity. Also, the results of the experimental determination of the penetration velocities of the copper shaped charge jet during the penetration into the homogenous steel obstacle are shown. The use of these results, obtained by the given procedure, in the program code for a numerical simulation of the shaped charge function and jet penetration, enables a more accurate calculation of jet kinematic and dynamic parameters (velocities, contact pressures, etc.) and penetrability in to obstacles of different mechanical properties.

Key words: physics of explosion, shaped charge, jet penetration, critical velocity, contact pressure.

Denotations and abbreviations

- A coefficient in the equation of Tait
- a_0 coefficient of polynomial equation
- a_1 coefficient of polynomial equation
- a_3 coefficient of polynomial equation
- a_4 coefficient of polynomial equation
- Cu copper
- l length of jet penetration
- *n* exponent in the equation of Tait
- p_x pressure on the contact surface
- p_{cr} critical (stagnation) pressure
- p_{cr} critical (stagnation) pressul r – coefficient of correlation
- r_m tensile strength of material
- t time
- *t_{cr}* critical (total) penetration time
- $u = v_i$ jet velocity
- *u_x* penetration velocity without the influence of obstacle mechanical properties
- u_{x0} penetration velocity with the influence of obstacle mechanical properties
- v₀ specific volume of material
- v_x specific volume of material under high pressures
- *v_{jcr}* critical (stagnant) jet velocity
- α compressibility coefficient of material
- α_m compressibility coefficient of the jet
- α_n compressibility coefficient of the obstacle
- ρ_0 initial density of material
- ρ_x density of material under high pressures
- ρ_{mx} density of jet material under high pressures
- ρ_{m0} initial jet density

- ρ_{px} density of the obstacle material under high
- pressures
- ρ_{p0} initial obstacle density
- HB brinell Hardness
- HRC rockwell Hardness
- HP-4 denotation of the obstacle steel plates quality
- GAO generator for electrical activation

Introduction

THE shaped charge is a special explosive device that has been used in the military and civil industry for different purposes, for example: penetrating, cutting, forming, welding, etc. The process of the shaped charge jet formation and penetration into the homogenous obstacle, generally, like other phenomena of the penetration, belongs to the class of nonlinear mechanics problems, and it can be described very successfully by equations of the fluid mechanics in the field of the shock wave theory. This is possible due to the enormously high values of the velocities, pressures and temperatures that follow this process when the penetrator and obstacle materials behavior is similar to the fluid behavior.

Theory

During the impact, i.e. during the jet penetration into the obstacle, the shock wave is generated in the obstacle material and jet material. For the determination of the penetration velocity and pressure onto the contact surface (collision surface) of the jet and the obstacle during the penetration process, a well-known equation of the shock wave the ory for an ideal case [1-3] is used

¹⁾ Military Technical Institute (VTI) of the Yugoslav Army, Katanićeva 15, 11000 Beograd

²⁾ Technical Testing Center, Vojvode Stepe 445, 11000 Beograd

$$u_x = u - \sqrt{p_x} \left(\frac{1}{\rho_{m0}} - \frac{1}{\rho_{mx}} \right) = \sqrt{p_x} \left(\frac{1}{\rho_{p0}} - \frac{1}{\rho_{px}} \right)$$
(1)

In order to satisfy the calculation accuracy it is shown that the material compressibility for the pressure values over 10^9 Pa may not be ignored. Supposing $v_x = v_0(1-\alpha)$ and in consideration of the compressibility of the jet material and the obstacle material, after some transformation of equation (1), the equations for the determination of the penetration velocity and the contact pressure are given in the form

$$u_x = \frac{u}{1 + \sqrt{\frac{\alpha_m}{\alpha_n} \frac{\rho_{p0}}{\rho_{m0}}}}$$
(2)

$$p_{x} = \frac{\rho_{m0}u^{2}}{\left(\sqrt{\alpha_{m}} + \sqrt{\alpha_{p}\frac{\rho_{m0}}{\rho_{p0}}}\right)^{2}}$$
(3)

The equation of state for material that with sufficient accuracy defines the relation between the pressure and the material density is known as equation of Tait (law of Tait)

$$p_x = A \left[\left(\frac{\rho_x}{\rho_0} \right)^n - 1 \right]$$
(4)

The coefficient of compressibility α defined by the ratio $\alpha = 1 - \rho_x / \rho_0$ and equation (4) lead to the expression

$$\alpha = 1 - \frac{1}{\left(1 + \frac{p_x}{A}\right)^{\frac{1}{n}}}$$
(5)

The final equations for the determination of the penetration velocity and the contact pressure that consider the material compressibility [1] are given by the substitution of expression (5) in eqs. (2) and (3).

Under real conditions during the obstacle penetration, the real penetration velocity is lower due to the mechanical resistance of the obstacle material r_{mp} , so-called *internal pressure in the obstacle material* in the impact theory and denoted as a p_{cr} . Finally, the equation for the determination of the real penetration velocity u_{x0} is

$$u_{x0} = u \sqrt{\frac{1}{\left(1 + \sqrt{\frac{\alpha_m \rho_{p0}}{\alpha_p \rho_{m0}}}\right)^2} - \frac{p_{cr}}{\rho_{p0}} \frac{\alpha_p}{u^2}}{(1 + \sqrt{\frac{\alpha_m \rho_{p0}}{\alpha_p \rho_{m0}}})^2}$$
(6)

The end of the jet penetration, i.e. the zero penetration velocity ($u_{x0} = 0$) appears at the instant when the contact pressure decreases to the value of the internal pressure in material ($p_x = p_{cr}$). It occurs at the critical, i.e. stagnation value of the jet velocity $u = u_{cr} = v_{icr}$.

The real jet velocity near the value of which the obstacle penetration rapidly begins to stop, i.e. the critical or stagnation jet velocity $u=u_{cr}=v_{jcr}$, is obtained on the basis of eq. (2) for $u_x = u_{exp}$

$$u_{cr} = v_{jcr} = u_{exp} \left(1 + \sqrt{\frac{\alpha_m}{\alpha_p} \frac{\rho_{p0}}{\rho_{m0}}} \right)$$
(7)

The value of the penetration velocity $u_x = u_{exp}$ is determined experimentally at the stagnation point nearly prior to the instantaneous stopping of the penetration. It is necessary to emphasize that the rapid transition process of the penetration stagnation, when $u_x = u_{exp}$ decreases at a range value $u_x = 0$, corresponds at the same time to a very small (negligible) relative change of the jet velocity.

On the basis of the known values of the stagnation jet velocity u_{cr} for the given materials of the jet and the obstacle, the critical value of the contact pressure p_x ($p_x = p_{cr}$) equal to the mechanical resistance of the material under dynamic conditions, is calculated by the following equation



All other calculations are based on the equations of the upgraded hydrodynamic theory of the shaped charge function and the jet penetration for the general non-stationary case [1-6].

Calculation of the kinematics parameters of the shaped charge jet

A sample of the experimental 60 mm shaped charge model is treated numerically and experimentally in the paper. The axial cross-section of the shaped charge is illustrated in Fig.1.

In order to realize the calculation of the claimed parameters, the discretisation of the metallic liner has been executed on 30 radial segments. Also, the kinematic and dynamic parameters of the metallic liner were determined for the collapsing conditions at the medium point of each liner segment.

The main parameters of the shaped charge jet including the jet and the slag elements velocity, length and mass, have been calculated by the self-developed HYDRO program routine, realized on the basis of the above mentioned hydrodynamic theory [5,6]. The calculation results are given in Table 1.

The zero values of the jet element velocity, length and mass (rows 1,2,3, and 4 in Table 1) at the top of the metallic liner (apex zone) are caused by the critical conditions of collapse, under which the regular formation of the coherent shaped charge jet is missing [5-9]. It should be also mentioned that the effects of the jet micro-instability in the frontal part, largely described in [7] and shown in Fig.2, are a reason due to which there is no formation nor penetration of the first six jet elements. The radiographs have been recorded at the moments $\tau_1 = 5.6\mu s$ and $\tau_2 = 10.6\mu s$ from the detonator activation. They clearly illustrate the negative effects of the micro-instability in the jet frontal part: incoherency, particularly intensive whirling and top confluence (small radial growth at the jet top due to the inverse velocity gradient of the frontal jet elements).



Geometrical and physical characteristics of the shaped charge

Caliber: 60 mm

- Explosive charge: flegmatized octogen (average density 1.75 g/cm³)
- Booster: flegmatized hexogen (average density 1.71 g/cm³)
- Detonator: pentryte (average density 1.61 g/cm³)
- Metallic liner: electrolytic copper (density 8.93 g/cm³)
- Angle of metallic liner cone: inner 50°, outer 51°
- Metallic liner apex radius 8.5 mm
- Thickness of metallic liner: progressive, min. 1.0 mm
- Metallic body: duralumin (density 2.75 g/cm³)
- Thickness of metallic body: 1.5 mm
- Waveshaper: inert plastic mass
- Stand-off: 3 calibers
- Initiation: at point by electrical igniter

Figure 1. Axial cross-section of the experimental 60 mm shaped charge model

Table 1. Calculated parameters of the jet and slag of the 60 mm shaped charge

Segment	Jet element	Jet el ement	Jet el ement	Slag element	Slag element	Slag element
(step)	velocity	length	mass	velocity	length	mass
i	v_j	Δl_j	Δm_j	v_n	Δl_n	Δm_n
(-)	(m/s)	(m)	(kg)	(m/s)	(m)	(kg)
1	0.000	0.00000	0.00000	1789.256	0.00120	0.00005
2	0.000	0.00000	0.00000	1477.162	0.00120	0.00014
3	0.000	0.00000	0.00000	1004.741	0.00120	0.00032
4	0.000	0.00000	0.00000	945.711	0.00120	0.00049
5	8004.923	0.00227	0.00007	881.160	0.00373	0.00058
6	8846.862	0.00219	0.00009	818.622	0.00327	0.00069
7	8893.276	0.00212	0.00011	761.497	0.00300	0.00081
8	8646.862	0.00211	0.00012	738.391	0.00281	0.00093
9	8404.923	0.00211	0.00013	714.433	0.00267	0.00102
10	8167.074	0.00211	0.00016	689.932	0.00256	0.00113
11	7932.201	0.00212	0.00016	665.031	0.00247	0.00128
12	7698.924	0.00213	0.00018	639.792	0.00240	0.00140
13	7465.785	0.00215	0.00020	614.236	0.00234	0.00151
14	7231.299	0.00217	0.00021	588.359	0.00229	0.00162
15	6993.972	0.00220	0.00022	562.141	0.00225	0.00169
16	6752.308	0.00223	0.00023	535.557	0.00221	0.00193
17	6504.748	0.00228	0.00024	508.572	0.00217	0.00200
18	6249.726	0.00233	0.00024	481.150	0.00214	0.00212

Also, it is very interesting to compare the total mass of the jet and the slag given in Table 1, the ratio of which is practically 1:10.

The change of the jet elements velocities, primordial for the analysis and the determination of the jet penetration velocities, is illustrated in Fig.3. The lower curve in the same diagram shows the change of the slag elements velocities. Also, in the apex zone of the cone, there are evident differences between the jet elements velocity of the copper liner with the conical apex (supposed theoretical case) and the jet elements velocity of the homothetic copper liner with the rounded apex (real construction of the shaped charge).



 $T_1 = 5.6 \mu s$ $T_2 = 10.6 \mu s$

Figure 2. The effects of the micro-instability in the jet frontal part (incoherency, whirling and top confluence) - 60 mm shaped charge jet radiographs



Figure. 3. The jet and the slag elements velocity depending on the position (from the top to the end of the cone)

Series 1 – Jet elements velocity with the conical apex of the copper liner Series 2 – Jet elements velocity with the rounded apex of the copper liner Series 3 – Slag elements velocity with the rounded apex of the copper liner

Experiment

The experimental determination of the jet penetration velocity and the contact pressure during the penetration and its critical values at the end of the penetration process is very complicated because of the nature of the phenomenon accompanied by abnormally high pressure values (million bars of range) and velocities (10 thousands m/s of range).

The jet penetration velocities, like the stagnation velocity of the jet penetration, have been determined most frequently by the method of the continual impulse radiography or the electro-magnetic method (in special cases only) and by the method of sequential analysis [2,6,10]. On the basis of the values of the jet velocity penetration obtained experimentally and eqs. (7) and (8) it is possible to calculate the value of the jet velocity and the contact pressure at the stagnation moment of the penetration.

The experimental determination of the jet penetration velocity (Fig.4) is based on the measuring of the time (sequences) needed by the shaped charge jet to pass on a priori defined distance (depth of the layers of the steel obstacle) [2,10,11,12].



Figure 4. The experimental determination of the jet penetration velocity [11]

For measuring (recording) the characteristic temporary intervals of the jet penetration into the obstacle, the method of sequential analysis of the timing phases of process by the logic multi-channel analyzer is used. The scheme of the experimental measuring installations, necessary for the method of sequential analysis, is shown in Fig.5.



Figure 5. The method of the sequential analysis of the process (set-up scheme) $% \left({{{\rm{S}}_{{\rm{s}}}}} \right)$

For experimental measuring, the 40-channel logic analyzer HP-16500A type and the digital oscilloscope NICOLET-4094B type are used as control instruments. Besides these mentioned complex and very precise electronic measuring instruments, the special electronic equipment is used. The equipment developed by the VTI and intended for the same research consists of: device for an activation by the safety key (GAO-2), high-voltage transformer with possibilities for the instantaneous electric discharge (GAO-2A) and applied for the shaped charge activation, interface with a filter for the noise suppression in electrical signals, etc. Naturally, there is an auxiliary measuring equipment: power supply (battery +12V), multi-coaxial cables, foliar captures of electrical signals, etc.

The use of the mentioned method in the experimental measuring of the jet penetration of the 60 mm shaped charge into the armor steel obstacle of HP-4 quality (r_m =min. 9300 10⁵ Pa, HB=min. 280) made it possible to record a series of experimental data – the penetration length

depending on time (Fig.6). Each point in the integral diagram of the total penetration time has been calculated on the basis of the average value of the jet penetration time during the layers penetration of 20 mm thickness, determined on the specimen of 6 single experiments. The stagnation of the jet penetration was registered after t_{cr} =112.5 μ s of the total penetration time. Simultaneously, the length *l*=260 mm of the total penetration was realized.

A polynomial form of the functional relation of the penetration length depending on time (Fig.7), made by the mathematical fitting of the experimental data and shown in Fig.6, is

$$l(t) = a_3 t^3 + a_2 t^2 + a_1 t + a_0$$
(9)

In eq.(9) the values of the coefficients are a_0 =+2.1517, a_1 =+3.7242, a_2 = -0.020, a_3 =+4.8·10⁻⁵, and the coefficient of correlation is r^2 =0.9999.

The first derivation of eq.(9) gives the function of the jet penetration velocity depending on time in the form of the quadratic polynomial equation, graphically shown in Fig.6 as well

$$u_{x0} = \frac{dl(t)}{dt} = 3a_3t^2 + 2a_2t + a_1$$
(10)

The value of the critical, i.e. the stagnation jet penetration velocity u_{x0} =1046.7 m/s has been calculated by the substitution $t = t_{cr}$ =112.5 μ s of the total (critical) time of the penetration in eq.(10).

This value of the critical jet penetration velocity with eqs. (7) and (8), respectively, makes it possible to determine the critical, i.e. the stagnation jet velocity v_{jcr} =2225 m/s and the critical value of the contact pressure p_{cr} =527483·10⁵ Pa. Nonlinear eq.(8) has been resolved by the numerical iterative method.

The relevant experimental data and some literature data realized practically in the similar experimental conditions are given in Table 2. On the basis of these data the quality of the given results can be accurately estimated as well as the validity of the proposed method for the determination of the critical jet velocity.

The comparative analysis of the results from Table 2 shows that the critical values, i.e. the stagnation values of the jet velocities depend on the type and the mechanical properties of the jet material and the obstacle material. Also, it shows that the suggested method has a possibility to record with sufficient accuracy all variations of the stagnation velocity range, for example, in the case of varying only mechanical properties of the steel obstacle (variation of mechanical resistance and hardness) while all other experimental conditions stay un1.38 5(ance)t the4658.2BT9.9i On the basis of the hydro-code with the implemented system eqs.(1)-(8) the jet penetration velocity functional depending on the penetration length has been calculated. The given theoretical and the relevant experimental curve are shown in Fig.8. In the same diagram, the curve of the jet velocity profile is also given to compare the range values of the jet velocities and the corresponding penetration velocities during the penetration.



Figure 8. Jet velocity and jet penetration velocity depending on the penetration length

The overlapping of the theoretical and the experimental curve of the jet penetration velocity is very impressive. The comparative analysis shows that the first significant discrepancies appear after 180 mm of the penetration length, which corresponds to the jet velocities under 4000 m/s, i.e. to the conditions of subsonic jet penetration when the jet elements velocities are below the value of sound speed in the steel obstacle $v_j(i) < 4000 \text{ m/s} = c_{Steel}$. The calculated theoretical values of the jet penetration velocities are greater than the real values determined experimentally due to the successive equilibration of the jet dynamic pressures and the dynamic resistance of obstacle material at the contact surface and progressive and more significant influence of the mechanical properties of obstacle in the final zone of the jet penetration.

Finally, it is necessary to emphasize that the error of the experiment measurement of the jet penetration velocities is under 0.1%, and at the same time the numerical accuracy of the calculation of the stagnation jet velocity and the contact pressure, as well as the jet elements penetration velocities, is realized with an error under 1.0E⁻⁴. From the point of view of modern engineering practical work in the filed of construction of shaped charge projectiles and evaluation of terminal ballistics effects it is absolutely acceptable.

Conclusion

The theoretical determination of some kinematic and dynamic parameters of the shaped charge jet necessary to analyze the process of the jet penetration has been realized. The final equations for the determination of the jet penetration velocity and the contact pressure are given. In order to satisfy the calculation accuracy the equations consider the material compressibility and the mechanical resistance of the obstacle material under dynamic conditions. All other calculations are based on the equations of the upgraded hydrodynamic theory of the shaped charge function and the jet penetration for the general non-stationary case. A sample of the experimental 60 mm shaped charge model is treated numerically and experimentally in the paper. The main parameters of the shaped charge jet including the jet and the slag elements velocity, length and mass have been calculated by the HYDRO program routine, realized on the basis of the above-mentioned hydrodynamic theory.

It is shown that the displayed procedure of the theoretical and experimental determination of the critical jet velocity as well as the jet penetration velocities during the penetration into the homogenous obstacle based on the use of the logic analyzer and special captures makes it possible to evaluate these parameters accurately. The comparative analysis of reference data has confirmed the validity of this method in the experimental determination of the critical velocity of the copper shaped charge jet during the penetration into the homogenous steel obstacle. Also, the use of these results in the HYDRO program code for one numerical simulation of the shaped charge function and jet penetration, enables a more accurate calculation of jet penetration velocities, contact pressures and jet penetrability in obstacles with different mechanical properties.

The comparative analysis has shown that the calculated theoretical values are in good accordance with the experimentally determined results of the jet penetration velocities and the critical jet velocity.

References

- BAUM,F.A., STANJUKOVIĆ,K.P., SCHEHTER,B.I. Fizika vzriva, Second and adapted edition, Moscow, 1975.
- [2] UGRČIĆ,M. Contribution to the theory of interaction of the explosive armor and shaped charge projectile. Doctoral dissertation, Faculty of mechanical engineering of University in Belgrade, Belgrade, 1995.
- [3] DÉFURNEAUX, M. Théorie hydrodynamique des charges creuses et de la pénétration des jets. ENSTA, Paris, 1983.
- [4] STAMATOVIĆ, A. Physics of explosion, Ivexy, Belgrade, 1995.
- [5] UGRČIĆ,M. Numerical simulation and optimization of the shaped charge function. *Naučnotehnički pregled*, 1998, vol.XLVIII, no.4, pp.30-41.
- [6] UGRČIĆ,M. Modeling and Simulation of Interaction Process of Shaped Charge Jet and Explosive Reactive Armour. International Conference EXPLOMET'95, El Paso - USA, 1995.
- [7] UGRČIĆ,M. Active waveshapers as correctors of the detonation wave in the modern shaped charge constructions. Master's thesis, Faculty of mechanical engineering of University in Belgrade, Belgrade, 1991.
- [8] UGRČIĆ,M., BLAGOJEVIĆ,M. Theoretical and experimental method for determination of detonation wave parameters in the charge with hemispherical wave shaper. *Scientific Technical Review*, 2002, vol.LII, no.3.
- [9] UGRČIĆ,M. The Contribution to the Optimization of Detonation Wave Profile in the Shaped Charge Construction. 19th International Symposium on Ballistics, Interlaken, Switzerland, 2001.
- [10] MURGAŠKI,S., PRODANOVIĆ,LJ. Some experiences in measurement of the ultra-high phenomena of shaped charge function. Int. doc., VTI-02-02, 1980.
- [11] VUKAŠINOVIĆ,M. et all. *Multi-layer armor with composite plates*. Int. doc., VTI-02-01-0154, 1990.
- [12] UGRČIĆ,M., MILIČIĆ,G., JANEV,J., DŽINGALAŠEVIĆ,V. Technical report of the researches of the interaction effect of the shaped charge jet and explosive armor. Int. doc., VTI-02-01-0329, 1991.
- [13] HELD,M. Penetration Cutoff Velocities of Shaped Charge Jets. Propellants, Pyrotechnics, and Explosives, 1988, no.13, pp.111-119.
- [14] WALTERS,W.P., ZUKAS, and J.A. Fundamentals of shaped charges, A Wiley-Interscience Publication. John Wiley and Sons, New York, 1989.
- [15] DÉFURNEAUX, M. Organisation d'un programme analytique pour le calcul des charges creuses. *Sciences et techniques de l'armament*, 1977, no.51, 4^e fasc., pp.647-676.

Određivanje osnovnih parametara prodiranja mlaza kroz homogenu čeličnu prepreku

Rad obrađuje rezultate teorijsko-eksperimentalnog određivanja kinematičkih i dinamičkih parametara kumulativnog punjenja neophodnih za analizu procesa prodiranja mlaza. Izložena je metoda eksperimentalnog određivanja brzina prodiranja kao i postupak određivanja kritične brzine prodiranja kroz homogenu prepreku. Metoda je zasnovana na primeni logičkog analizatora i specijalnih davača koji se koriste za registrovanje diskretnih podataka krive - dužina probijanja u zavisnosti od vremena. Ovako dobijena matematički fitovana kriva polinomijalnog oblika omogućava određivanje kritične brzine mlaza. Takođe su prikazani rezultati eksperimentalnog određivanja kritične brzine mlaza formiranog dejstvom kumulativnog punjenja s bakarnom oblogom pri prodiranju kroz homogenu čeličnu prepreku. Korišćenje ovih rezultata u programu HYDRO za numeričku simulaciju funkcije kumulativnog punjenja i penetracije mlaza omogućava tačnije određivanje kontaktnog pritiska i probojnosti kumulativnog mlaza na preprekama različitih mehaničkih karakteristika.

Ključne reči: fizika eksplozije, kumulativno punjenje, prodiranje mlaza, kritična brzina, kontaktni pritisak.

Détermination des principaux paramètres de la pénétration du jet dans l'obstacle d'acier homogène

Les paramètres dynamiques et cinématiques du jet de la charge creuse, nécessaires pour l'analyse du processus de pénétration du jet, sont déterminés par la voie théorique et expérimentale. Le procédé de la détermination expérimentale des vitesses de pénétration est donné aussi bien que la vitesse criticale du jet pendant la pénétration dans l'obstacle homogène. Le procédé est basé sur l'application d'un analyseur logique et les capteurs spéciaux pour l'enrégistrement des données discrètes de la courbe – la longueur de la pénétration en fonction du temps. La forme polynômiale de cette courbe facilite la détermination de la vitesse criticale de pénétration du jet. Les résultats de la détermination expérimentale des vitesses de pénétration du jet d'une charge creuse en cuivre pendant la pénétration dans l'obstacle d'acier homogène sont également donnés. Ces résultats sont utilisés pour créer un programme pour la simulation du fonctionnement de la charge creuse et de la pénétration du jet facilitant ainsi le calcul des paramètres dynamiques et cinématiques du jet (vitesses, pressions de contact, etc.) et la pénétrabilité dans des obstacles aux propriétés mécaniques différentes.

Mots-clés: physique de l'explosion, charge creuse, pénétration du jet, vitesse criticale, pression de contact.