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Original Research

An overview of Gurney method for estimating the initial velocities of fragments for high explosive munition

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Abstract
The literature survey, related to the initial velocity of fragments for HE ammunition is presented. The basic Gurney model for fragment initial velocity, that can be used for different munition configuration, is presented. The research we performed using the Gurney method for a different projectile types is given.

Keywords: fragment velocity; Gurney constant; warhead detonation;

1. Introduction

In the analysis of high explosive (HE) warheads with fragmentation, it is necessary to determine the initial velocity of the fragments, which is very important parameter of the terminal ballistics. Theoretical and experimental research has shown that the initial velocity of fragments formed by fragmentation of HE warheads depends on the ratio of explosive charge mass C and mass of warhead body M metal, as well as mechanical characteristics of warhead body material, type of explosive charge, and its detonation parameters.
Fig. 1 shows a schematic representation of the HE warhead detonation process (controlled fragmentation). The mechanism of fragmentation is complex. The process of projectile expansion begins with the initiation of the primary explosive charge and proceeds with the detonation of the main charge, whereby the energy of the explosive is transformed very quickly from a potential form into mechanical work. Explosions caused by rapid chemical reactions in the matter are characterized by the release of heat and the formation of large amounts of gaseous products expanding at high speed. The formation rate of gaseous products during detonation is so high that the chemical reactions inside the explosives are completed before the detonation products can significantly expand into the environment. The temperature of the detonation products is several thousand degrees Celsius, and the pressure of the detonation products at the time of completion of chemical reactions is very high (several hundred thousand bars). Due to such a state of gas, a process of the sudden expansion of the detonation products occurs, which causes the projectile body to expand and to fragment.

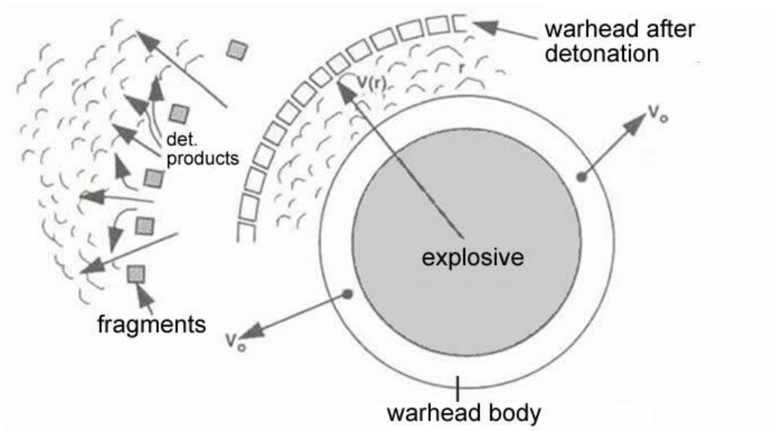


Figure 1. Schematic representation of the HE warhead detonation process [adopted from 12]

Data on the initial velocity of the fragments are needed to be able to estimate the elements of the trajectory of the fragments, and thus their kinetic energy at a given moment (during movement through the atmosphere).

The measure of the explosive power is mainly expressed in the literature using the strength of the shock wave generated by that explosive, or on the total chemical energy that the explosive contains. In this way, the velocity of the shock wave, the detonation pressure, and the heat generated by the detonation of explosives can be expressed. Although this way of understanding and assuming the properties of explosives is accurate, it does not provide information on the initial velocity that an explosive can communicate during detonation of munition to fragments [1].

During World War II, physicist Ronald W. Gurney published several scientific papers explaining how the initial velocity of fragments could be calculated with relatively high accuracy. His scientific works thus created a method that is still used today to calculate the initial velocity of fragments. This method was developed to suit different systems and configurations of metal-explosive systems. Although the shock wave plays a very large role in the transfer of energy from explosives during detonation to metal, Gurney in his method does not take into account the properties of the shock wave itself.

In his research, Gurney assumed [1] that during detonation, a final amount of energy is released by the explosives, which is converted into kinetic energy of fragments and kinetic energy of detonation gases. He also assumed that detonation gases have a uniform density and a linear one-dimensional velocity profile.

The Gurney method can be used for all one-dimensional metal-explosive systems.

The Gurney constant, which appears in his method, can be estimated experimentally (explosive cylinder expansion test), computer programs (in hydrocodes), and analytical models. Henry (1967), Jones (1980) and Kennedy (1970) reported Gurney’s constant values for certain explosives while Dobratz (1982) made the greatest contribution [2].

Some researchers (Kennedy, Randers-Pehrson, Lloyd, Odinstov) have proposed certain modifications of the Gurney model, and other authors (Hirsch, Chanteret, Chou-Flis, Kleinhanss, Hennequin) have applied the Gurney method to imploding configurations (configurations where the explosive is on the outside and the body on the inside; i.e. liner and explosive in HEAT warheads).

Modifications of the Gurney base model mainly consisted of deriving formulas for geometric configurations of systems not covered by the original Gurney model, and for a larger range of M/C ratios.

Henry (1967), Jones (1980), and Kennedy (1970) also used Gurney’s method for different metal-explosive configurations.

Hirsch (1986) modified the basic Gurney formulas for exploding cylinders and spheres to extend their use to lower metal to explosive mass ratios *M/C* [2].

Another extension of the Gurney method was given by Chanteret (1983) who developed an analytical model for symmetric geometric configurations.

Fucke et all. (1986) and Bol and Honcia (1977) measured fragment velocities for large M/C ratios [2].

Karpp and Predeborn (1974, 1975) showed that the assumptions about the initial velocity of the fragments obtained by the Gurney method are adequate for cases when the flow is one-dimensional and for practical C/M relations that can be encountered in reality (0,1 <C / M <2) [2].

Aziz et al. performed an analysis for an open sandwich configuration, where the metal was considered a solid, and where the gases were approximated by the ideal gas equation [1].

Butz et al. (1982) analyzed Gurney’s model for symmetric sandwich configuration. They found that the Gurney model fully follows the results obtained experimentally, and even for very small M/C ratios. The smallest ratio they considered was 0,05, and even for such a small ratio, the Gurney model gave a result that agrees with the experimental result [1].

Cooper states that the Gurney constant can be estimated using the detonation velocity of explosives [3].

Different authors [4-11] investigated the influence of rarefaction waves from two ends in cylindrical warheads, since the length of casing is not infinite, and consequently, fragment velocities are lower than the Gurney velocity prediction. Gao [4] concluded that the fragment velocities in the central part of the warhead are not influenced by rarefaction waves when the *L/D* ratio (slenderness) was more than 2. Huang et al. [11] proposed modified formula for the fragment velocity from the cylindrical casing, initiated at one end. Charron [10] also analysed rarefaction waves influence on fragment velocity.

In recent times, numerical simulations in terminal ballistics are increasingly used. They are based on the formulas of continuum mechanics, using conservation equations, together with constitutive equations that define the behavior of the material, and specifying the initial and boundary conditions related to a given problem.

2. Gurney method

The Gurney equation describes the initial velocity of the fragments as a function of the ratio of the mass of the explosive charge to the mass of the metal body and the empirically determined constant (Gurney constant). In deriving the Gurney formula, a hollow cylinder of mass *M*, of inner radius *R*, filled with an explosive of mass *C* and density ρ is considered. The initial velocity of the fragments for the cylindrical configuration of the metal body and explosive can be written in the form:

$$v_M = \frac{\sqrt{2E}}{\sqrt{\left(\frac{M}{C} + \frac{1}{2}\right)}} \tag{1}$$

where the parameter $\sqrt{2E}$ represents the Gurney constant (the name characteristic Gurney velocity can also be found in the literature) and depends on the *M/C* ratio. The quantity E (so-called Gurney energy) has the dimension of energy per unit mass (J/kg), so the parameter $\sqrt{2E}$ has the dimension of velocity (because the unit for energy is J = kgm^2/s^2).
The generalized Gurney formula (for different body warhead shapes) can be written in the form:

$$v_0 = \sqrt{2E}\left(\frac{M}{C} + \frac{n_g}{n_g + 2}\right)^{-1} \tag{2}$$

where the constant n_g can have value of 1, 2 or 3, depending on whether the body is a flat, cylindrical or spherical configuration. A schematic representation of possible configurations is given in Fig. 2. A detailed derivation of these formulas can be found in references [2,14].

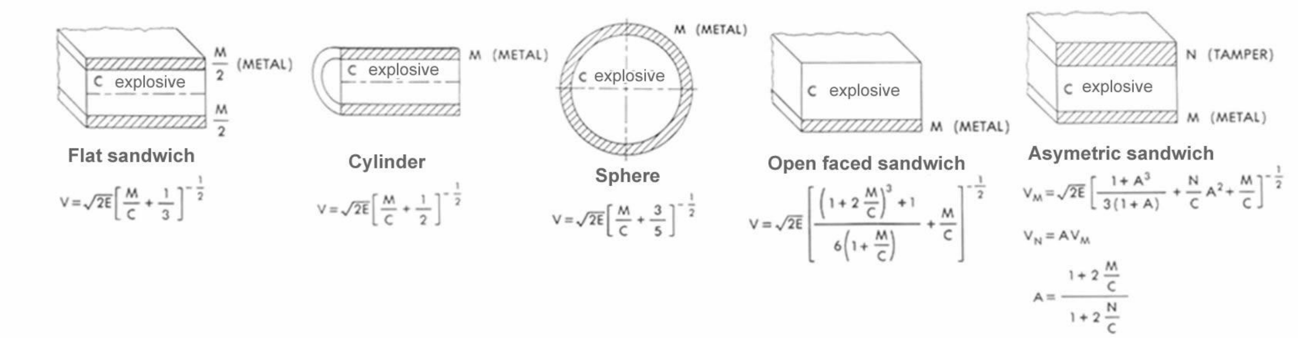


Fig. 2 Expressions for initial velocities of fragments in different geometric configurations [adopted from 2]

The expression for the initial velocity of fragments in flat symmetrical sandwich configurations (expression 2 at $n_g = 1$) can be used to calculate the parameters of explosive-reactive armor on tanks. Expression 2 at $n_g = 3$ is applied to hand grenades and some types of cluster projectiles, while expression 2 at $n_g = 2$ is reduced to expression (1) and is used to estimate the initial velocity of fragments in most HE warheads. Theoretically, the maximum initial velocity of the fragment is obtained when the mass of the body *M* approaches zero, and for cylindrical configurations it is $v_{0\max} = \sqrt{2}\sqrt{2E}$.
The Gurney constant can be estimated using tests, computer programs (using i.e. JWL equations of state for explosives), and analytical models (i.e. Kamlet and Finger use thermochemical parameters of explosive charge to estimate the Gurney constant; Kennedy gives the expression $E \approx 0{,}7E_D$, where E_D is the detonation heat of the explosive). Cooper states that the Gurney constant can be estimated via the detonation velocity of explosives *D* (which, depending on the density and composition of the explosives, can be determined in computer programs, i.e. EXPLO5), by the expression:

$$\sqrt{2E} = D/2{,}97 \tag{3}$$

The value of 2.97 from expression (3) was obtained by averaging the values of $\sqrt{2E}$ for known explosives (Table 1). This relationship is capable of accurately predicting $\sqrt{2E}$ of sensitive and moderately sensitive near ideal explosives; however, this equation is somewhat unsuitable for predicting $\sqrt{2E}$ of insensitive and nonideal explosives (ie. NTO, PBX-9502, AFX-902), because it overestimates $\sqrt{2E}$ of insensitive explosives [20].

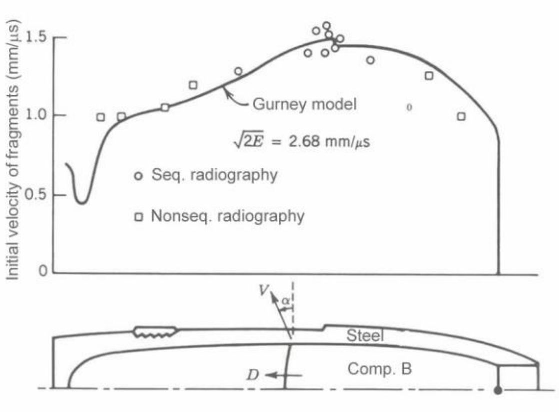
Table 1 shows the values of density, detonation velocity and Gurney constant for different types of explosive charges. Similar data for different types of explosives can be found in the NATO manual AASTP-1 [13].

Table 1. Experimental values of density, detonation velocity and characteristic Gurney velocities for different types of explosives [3]

Explosive	**Density (kg/m^3)**	**Det. velocity (m/s)**	**Gurney constant (m/s)**	$D/\sqrt{2E}$
Composition A-3	1590	8140	2630	3,09
Composition B	1710	7890	2700	2,92
Composition C-3	1600	7630	2680	2,85
Cyclotol (75/25)	1754	8250	2790	2,96
H-6	1760	7900	2580	3,06
Octogen	1835	8830	2800	3,15
LX-14	1890	9110	2970	3,07
Octol (75/25)	1810	8480	2800	3,03
PBX 9494	1840	8800	2900	3,03
PBX 9502	1885	7670	2377	3,23
PETN	1760	8260	2930	2,82
RDX	1770	8700	2830	2,97
Tetril	1620	7570	2500	3,03
TNT	1630	6860	2370	2,89
Tritonal (80/20)	1720	6700	2320	2,89

In real conditions, the initial velocity of the fragment represents the resultant of the initial velocity of the fragments (Gurney expression), the translational velocity of the projectile at the moment of impact on the target and the rotational velocity of the warhead (if the warhead rotates during the flight; gyroscopic stabilization). But since the translational and rotational velocity components are much smaller, only the initial velocity value, determined by the Gurney method, is usually used in the calculations. Using Gurney's methodology to estimate the initial velocity of the fragments ome does not make large errors in determining the total initial velocity of the fragments. By considering the values of the projectile's impact velocities (which are generally different for each angle of incidence), the calculation can be potentially closer to the real situation, with the spray of fragments moving in the direction of the projectile's movement.

In an axisymmetric system with variable diameter, the *C/M* parameter is calculated depending on the axial position. This means that the initial velocity of the fragments will also vary, depending on the position on the projectile body. The initial velocities of the fragments, calculated by Gurney's formula, agree well with the test data for HE projectiles, as shown in Fig. 3 (left). Fig. 3 (right) shows a comparison of the initial velocities, calculated by the Gurney method, with the experimental data for a steel cylinder with ratio L/D = 2 (ratio of length and diameter; warhead slenderness), filled with composition B and initiated from the left side. Fig. 3 illustrates how effects in the end part of the cylinder can affect the prediction of the initial velocities.



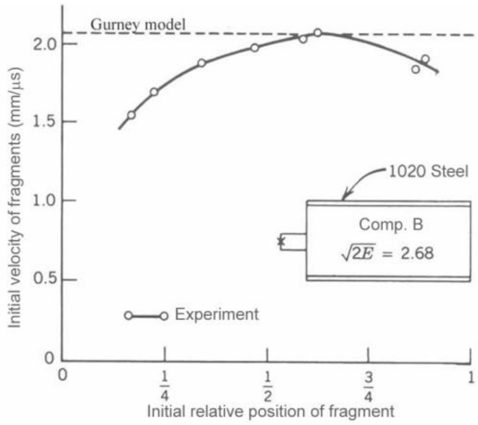


Figure 3. Comparison of the Gurney method with experimental data [adopted from 2]

The standard cylinder test, developed at Lawrence Livermore National Laboratory (LLNL), is used in the research of the phenomenology of the expansion of metal cylinders due to the action of explosive charges. Several types of explosives can be used, as well as several types of cylinder materials (i.e. copper and two types of steel with different percentages of carbon and alloying elements). Karpp and Predebon observed that in most of these experiments the maximum initial velocity of the fragments was achieved at the expansion ratio of the body $R/R_0 = 2$ (the diameter of the body in the process was expanded twice compared to the initial one). Even at the ratio $R/R_0 = 1{,}75$ - about 92% of the maximum initial velocity of the fragments has already been achieved. Nevertheless, it seemed necessary to consider the effects of gas leakage through the end parts of the cylinders, and to include the obtained models in non-stationary numerical simulations, to obtain more accurate values of initial velocities. In this sense, Karp and Predebon used the HEMP program, based on the finite element method, to model the process of natural fragmentation. The standard JWL equation of state for explosives was used, the cylinder was modeled as an elasto-plastic material, and the effects of gas leakage were taken into account. A comparison was made with the experimental data, for cylinders with different types of steel and with geometric ratios L/D = 2. The explosive charges were TNT, composition B and Octol. The agreement between the experiments and the calculation in the program was great [15].

When estimating fragment initial velocity for HE projectiles, the Gurney model and CAD techniques for modeling can be used (Fig. 4). I.e. 3D models of projectiles can be divided into quasi-cylindrical segments, with characteristic front, center and rear part. For each segment of the projectile body, the initial velocity of the fragments is determined separately, using expression (1), and thus the profile of the initial velocities of the fragments along the projectile body can be obtained. It is usually assumed there is no expansion of the projectile body before fragmentation and that the initial velocity vector of the fragments is normal to the projectile body on each segment. Crull and Swisdak [17] follow a similar procedure in their research.

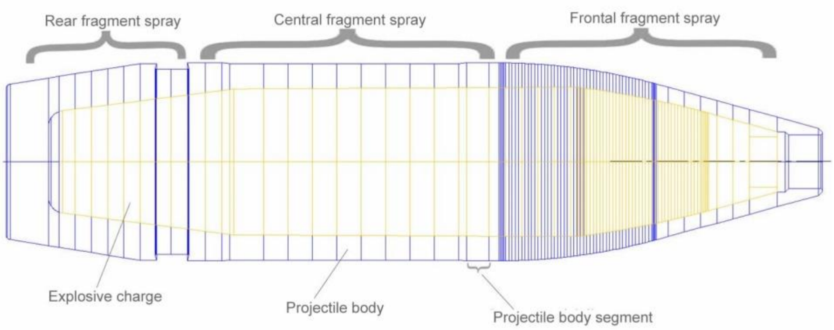


Figure 4. A 3D model of a HE projectile, divided into segments [16]

Numerical simulations are used often during the past 20 years, especially with the introduction of cheap and powerful processor clusters. These simulations are based on the conservation equations, with the use of equations of state, material strength, and fracture models. Figure 5 shows the results of a numerical simulation of the detonation of a 155mm HE M107 projectile, performed by Prytz et al. [18] in the AUTODYN, where the analysis of the initial velocities of the fragments was performed and compared with the values obtained in the Split-X program. The results show a relatively good agreement of the values of the initial velocities of the fragments, and potential for using the simulations for calculation of fragment initial velocities.

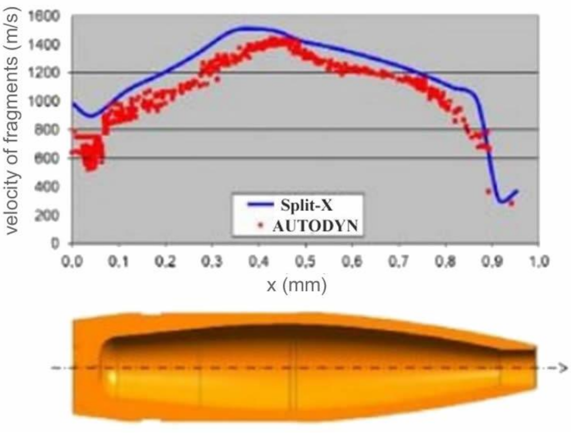


Figure 5. Initial velocities fragments for 155mm M107 (Split-X and AUTODYN) [18]

3. Application of Gurney method to HE projectiles

In our research (Zecevic et al. [19]), we analyzed the influence of explosive type and projectile design on the values of the initial velocities of fragments for different types of HE projectiles (artillery and mortar projectiles, as well as rocket projectiles warheads).
Figures 6 and 7 show the influence of explosives type (TNT and composition B) on the initial velocity of fragments for several types of HE projectiles (152 mm M84 artillery projectile, 128 mm M87 missile warhead and 120 mm mortar projectiles, models W1 and W2). The abscissa on the diagrams represents the relative distance of individual projectile segments from the top of the projectile.
The diagrams show that the use of explosives with better detonation characteristics (higher density, higher detonation velocity and higher detonation pressure of composition B compared to TNT charge) can significantly increase the initial velocity of the fragments.

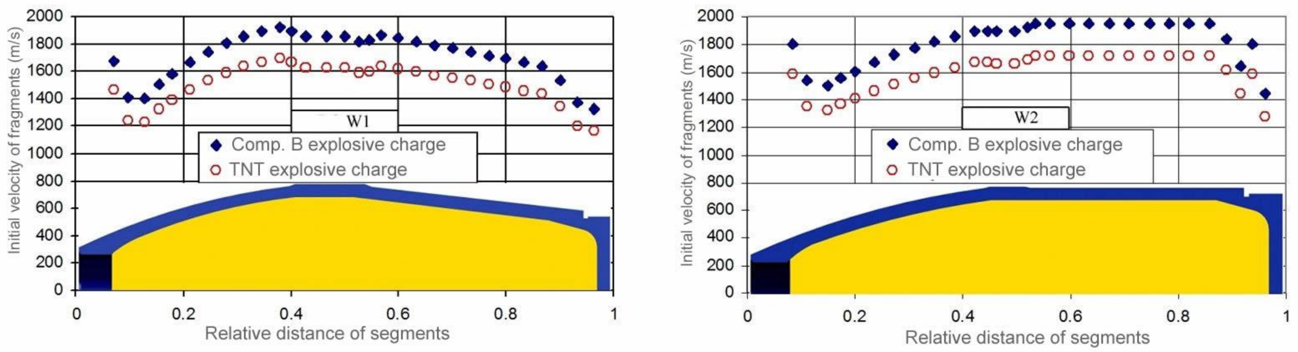


Figure 6. Variation of initial velocity of fragments, depending on the type of explosives (TNT and Composition B) for mortar HE projectiles 120mm (warheads W1 and W2) [19]

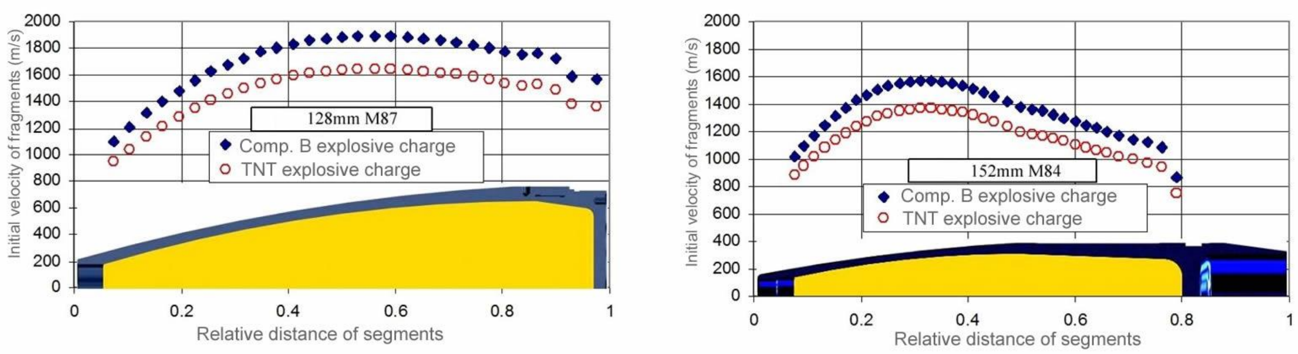


Figure 7. Variation of initial velocity of fragments, depending on the type of explosives (TNT and Composition B charge) for rocket projectile warhead - model 128mm HE M87 and artillery projectile - model 152mm HE M84 [19]

Figure 8 shows the influence of projectile design on the values of the initial velocity of fragments for several types of HE projectiles (artillery projectiles 105mm, 122mm, 152mm and 155mm, rocket projectile warheads 128mm and mortar projectiles 120mm).
The diagrams in Fig. 8 show that by changing only the design of the projectile (i.e. increasing the ratio of the mass of the explosive to the mass of the projectile body *C/M*, reducing the thickness of a body) can also significantly increase the initial velocity of the fragments on individual segments of the projectile. The maximum initial velocities of the fragments are achieved in the central parts of the HE projectile, where the largest mass ratios *C/M* are present.
Fig. 8 also shows the simultaneous influence of both the type of explosive and the design of the projectile on the initial velocity of the fragments for 122mm caliber artillery projectile. Thus, the 122mm HE M76 projectile, which has a higher *C/M* ratio and explosive (composition B) with better detonation characteristics than in the case of 122mm OF-462 (TNT) projectile, has a higher initial velocity of fragments on all projectile segments.
The higher initial velocity generally corresponds to the higher kinetic energies of the fragments leading to a larger lethal zone of the projectile.

If we look closely at initial velocities values of fragments for projectile 122mm HE OF-462 (maximum value of around 1200 m/s) in Fig. 8, the front part of the 122mm OF-462 projectile has somewhat higher initial velocities. On the other hand, the rear spray of fragments has a lower initial velocity, because of the smaller *C/M* ratio.

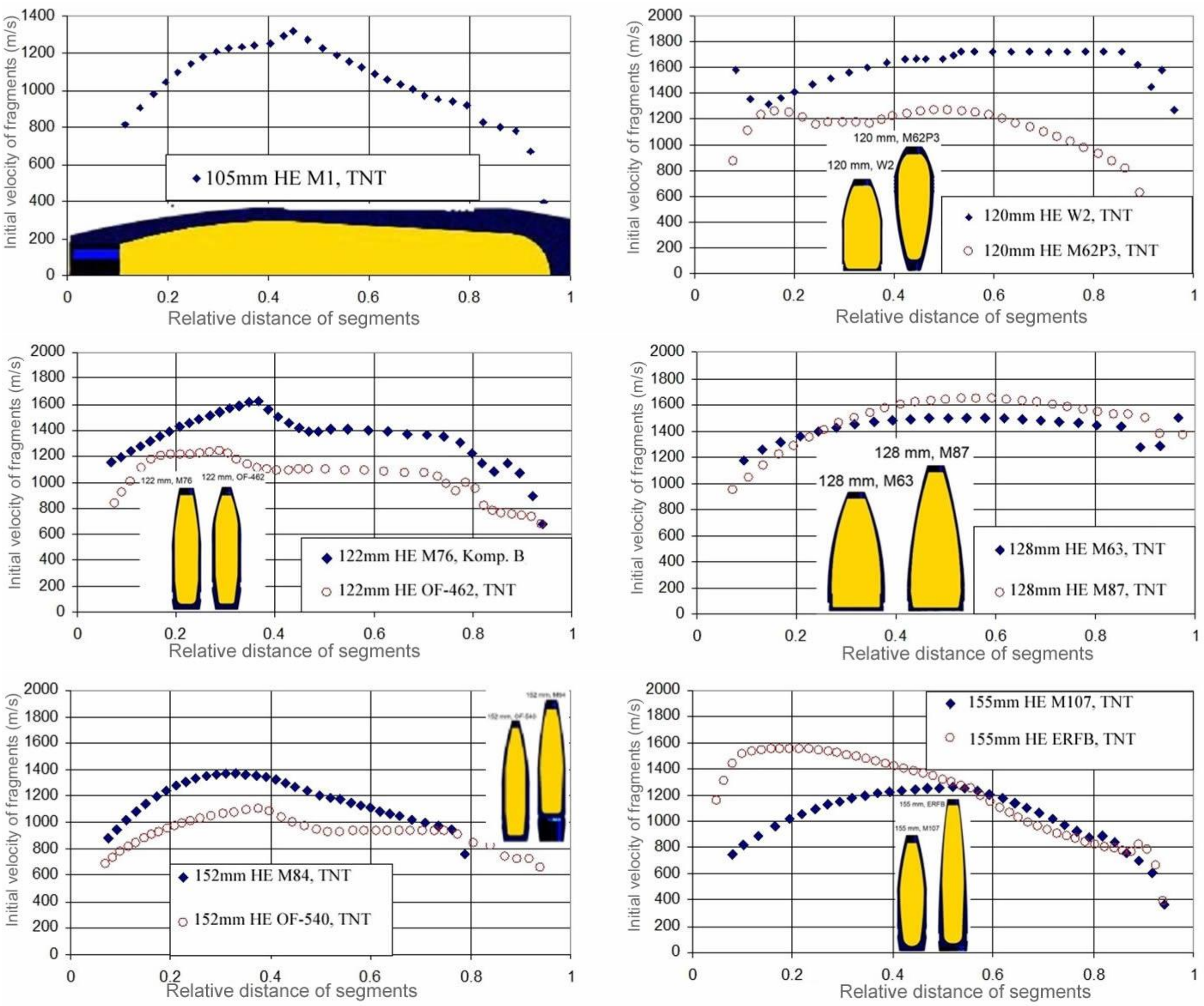


Figure 8. Influence of projectile design on the values of the initial velocity of fragments for several types of HE projectiles [19]

Catovic [20] provided a different way of displaying the initial velocities of fragments (comparing i.e. to Fig. 8), presented via a polar diagram (Grapher software can be used) in which one axis represents the initial velocities of the fragment (units m/s) and the angular axis of the diagram represents the angles measured from the projectile axis to the centers of the individual projectile segments. The point of origin (lower part of Fig. 9) is represented by the projectile center of mass.

The directions in the lower part of Fig. 9 (on the projectile) should not be confused with the initial velocity vectors; they serve here only to estimate the angles measured from the projectile axes to the centers of the individual projectile segments (in order to construct the diagram in Fig. 10). Such diagrams can be useful in visualization of the parameters for HE projectile terminal ballistics. We used polar diagrams also in our model for determination of HE projectile lethal zones [21].

In our research [20] we used the Gurney model also as an integral part of a new method for determination of lethal radius for high-explosive artillery projectiles (Fig. 10). In this model, the values of the initial velocity of fragments are required in order to accurately calculate fragment trajectory through the atmosphere on its way to the target. This method showed promising results confirming the applicability of the Gurney model.

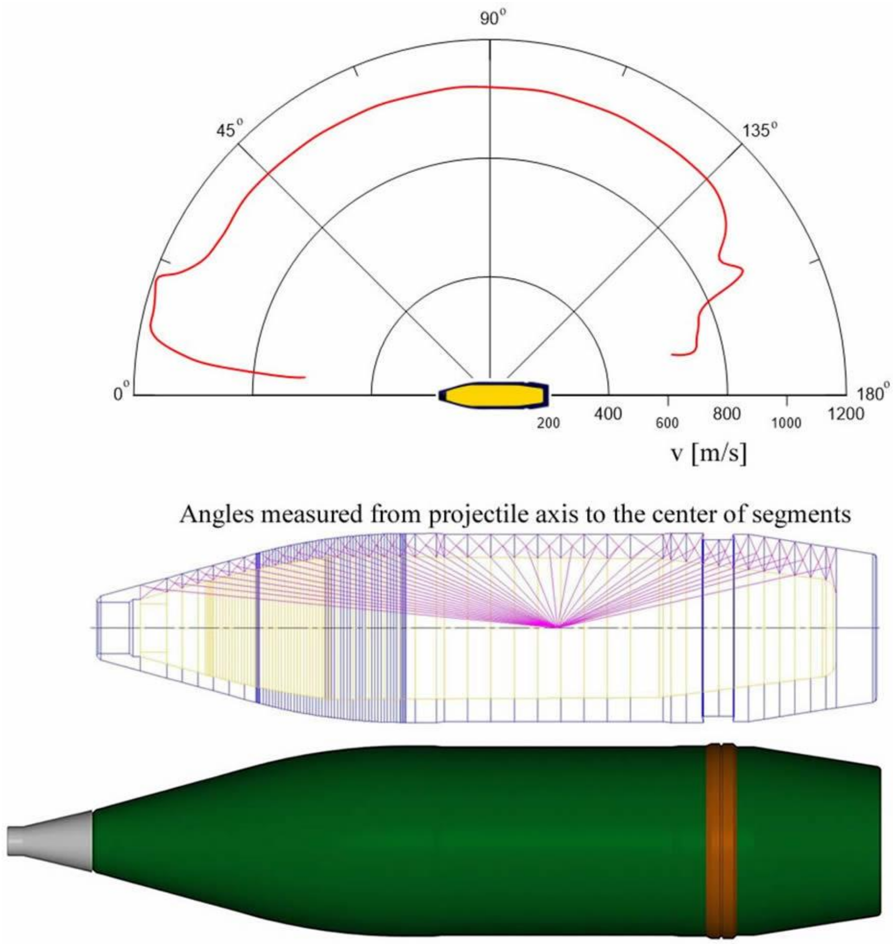


Figure 9. Variation of initial fragment velocity for 122mm HE OF-462 projectile as a function of segment position, presented using the polar diagram [adapted from 20]

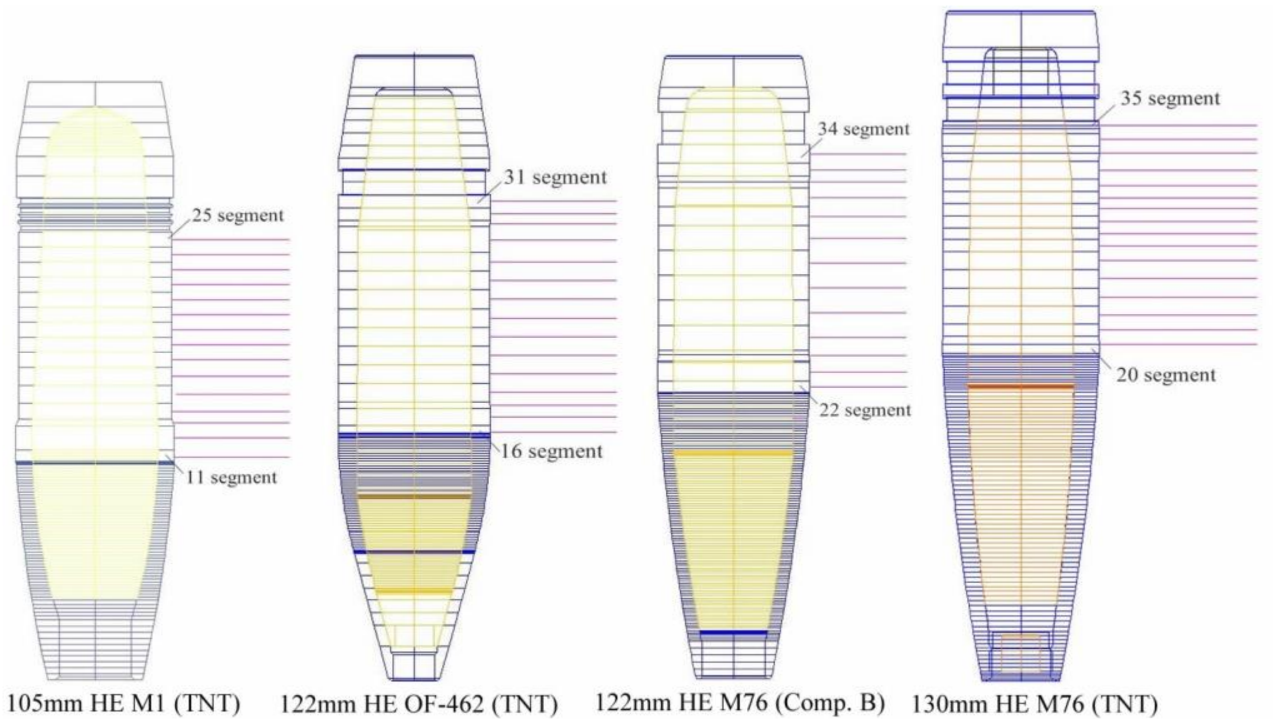


Figure 10. Body segments of artillery projectiles, for which Gurney method is applied, used in our model for determination of the lethal radius [20]

4. Limitations of Gurney model

The scope of application of Gurney equations is limited due to certain assumptions taken when deriving them. Henry (1967), Jones (1980) et al. and Kennedy (1970) made a list of these limitations, and they are cited by Walters and Zukas [2]:

- ***Range of M/C ratio***. Henry (1967) claims that Gurney's equations give good results for the range 0,1 < M/C < 5, while Kennedy (1970) claims that the range of application of Gurney's equations is 0,2 < M/C < 10.
- ***Acceleration phase.*** The Gurney method in its basic form is not able to analyze motion during acceleration. Therefore, Henry (1967) and Jones (1980) et al. took advantage of the assumption of a linear velocity profile in uniformly dense gas and combined it with the gas state equation to obtain acceleration when moving a metal plate, and came to two conclusions. The first conclusion is that detonation gases must be fully allowed to expand to atmospheric pressure, and the second is that the fragment will reach the calculated velocity only if no external force acts on it in the acceleration phase.
- ***Assumption of the gas velocity profile.*** Assumptions of the linear velocity profile and constant density of the expanding gas are essential assumptions. Gurney's method in its basic form neglects the effect of maximum pressure. On the other hand, although these assumptions give certain errors, they greatly facilitate and shorten the derivation of Gurney formulas.
- ***Resistance to deformation.*** The forces in the metal that oppose the deformations are not taken into account, except for inertia. These forces reduce the assumed initial velocity of the fragment.
- ***Metal fragmentation.*** Metal disintegration is possible when the *M/C* ratio is < 2 for high-density explosives. The explosion can in some cases be prevented if a cavity of a few millimeters is made between the explosive and the metal.
- ***Early cracks on the projectile body***. Leakage of detonation gases through cracks in the body can significantly reduce the assumed initial velocity of the fragment, depending on the geometry of the crack and the amount of gas released.

5. Conclusions

The literature related to the initial velocity of fragments for HE ammunition is presented. The basic formulas for fragment initial velocity, that can be used for different configurations of munition, are presented. In the last part, the research we performed using the Gurney method for different types of projectiles is given.
The Gurney model for fragment initial velocity, which can be used for various ammunition setups, is described. The research we conducted using the Gurney method for various types of projectiles is given.
The results show that the use of explosives with better detonation characteristics and geometry with higher *C/M* ratio one can increase the initial velocity of the fragments. Limitations of Gurney model are also presented.

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