



Comparison of Lethal Zone Characteristics of Several Natural Fragmenting Warheads

Berko ZECEVIC, Alan CATOVIC and Jasmin TERZIC

*University of Sarajevo, Mechanical Engineering Faculty
Defense Technologies Department*

71000 Sarajevo, Bosnia and Herzegovina

*E-mail: zecevic@mef.unsa.ba, catovic@mef.unsa.ba,
terzic@mef.unsa.ba*

Abstract: Research of HE warheads lethal zone is very complex topic because of large number of controlled and independent, sometimes correlated, influencing factors. Capability for prediction of lethal zone is based on complexity of databases regarding natural fragmentation parameters, which should contain data about warhead body material characteristics, types of explosive charge, number, mass, initial velocity and spatial distribution of fragments, battlefield terrain, distribution of soldiers on battlefield, etc. Based on experimental research (fragmentation test in Arena facilities with two types of artillery projectiles and two types of rocket warheads), analytical and numerical methods used - projectiles lethal zones are predicted and analyzed. Influence of projectile design and explosive charges on warhead lethal zone is analyzed.

Keywords: HE warhead, lethal zone, Arena test, natural fragmentation

Introduction

Lethal zone is one of the most important parameter of HE warhead efficiency. By increasing its efficiency, expected number of warheads for target neutralization is decreased, which can be significant from tactical, operative, economic and logistic point of view when conducting military operations. There are many factors influencing HE warheads lethal zone (condition of launching, warhead geometry, mechanical characteristics of warhead components, detonator type,

explosive detonation parameters, detonation height, impact angle, impact velocity, fuse type, terrain configuration, characteristics of soldier spatial distribution over battlefield, density of soldiers). Because of complexity of these parameters, at the moment there is no universal model for defining lethal zone.

In our research of HE warhead lethal zones based model was an American U.S. Vulnerability Model for Military Personnel. This model defines Lethal area as a measure of the fragment casualty producing potential of an exploding projectile when employed against human targets [1]. According to U.S. Vulnerability Model for Military Personnel, lethal area A_L can be expressed as:

$$A_L = \frac{N}{\sigma} = \int_{-\infty-\infty}^{\infty} \int_{-\infty-\infty}^{\infty} P(x, y) \cdot dx \cdot dy \quad (1)$$

In equation (1) N is expected number of casualties, σ - density of human targets in target area, $P(x, y)$ - probability that the personnel in that element will be incapacitated (unable to perform their tactical function) [1].

Physical meaning of lethal area is that it is the expected number of casualties, after detonation of single warhead, using defined density of human targets. In mathematically determining this coefficient, it is assumed that personnel are uniformly distributed over the ground plane. Different researchers use different values of human target densities for different tactical situations, where σ is constant, but not uniform. Some use uniform (Eastern concept), homogenous and constant values of human target densities (i.e. 1 soldier per m^2 of terrain), other again use homogenous zig-zag formation of soldiers on $50 \times 10 \text{ m}^2$ terrain (USA concept).

Probability that the personnel will be incapacitated $P(x, y)$, using U.S. model Vulnerability Model, is computed by [1]:

$$P(x, y) = 1 - [1 - P_B(x, y)] \cdot [1 - P_F(x, y)] \quad (2)$$

where: $P_B(x, y)$ - probability of incapacitation due to blast alone, $P_F(x, y)$ - probability of incapacitation due to fragments alone.

Probability of incapacitation due to blast $P_B(x, y)$ is a function of ground range, rather than angle. Incapacitation from blast is determined from a function based on explosive type and weight in the subject projectile.

To predict probability of incapacitation due to blast alone $P_B(x, y)$ it is necessary to determine the radius R_B about the burst point for which the probability of incapacitation due to blast is 0. For smaller ranges $P_B(x, y)$ is 1 [1]. Radius R_B is determined as a function of scaled distance Z_s as:

$$R_B = Z_s \cdot \sqrt[3]{C_{\text{exp}}} \quad (3)$$

where C_{exp} is equivalent mass of explosive TNT. Scaled distance Z_s can be found using assumed incapacitating blast overpressure for humans [3].

Probability of incapacitation due to fragments $P_F(x,y)$ can be predicted using expression [1]:

$$P_F(x,y) = 1 - e^{-d(x,y) \cdot A_t} \quad (4)$$

In expression (4) A_t is presented area of the target, and $d(x,y)$ mean density of efficient fragments (determined from static fragmentation tests [8]). Presented area of the target A_t for standing man is 0,5 m², for soldier assault position - 0,37 m² and for prone position - 0,1 m² [3].

To determine mean density of efficient fragments $d(x,y)$ we used the results from fragmentation test in semicircular Arena.

Immobilized projectiles, parallel to the ground, were electrically detonated in the center of Arena. Projectiles were positioned 2m above the ground. Arena consisted of radiuses $R_1 = 10.5$ m, $R_2 = 14$ m, $R_3 = 17.5$ m, and $R_4 = 21$ m. Thickness of wooden (fir) panels in Arena was 1 in. (25,4 mm). All panels were positioned in the same ground level. Every sector consisted of N panels, marked with 1 to N marks, starting with the one closer to projectile's front part. After the detonation of projectiles, panels were subjected to fragments flying towards them.

Fragments were considered efficient if they penetrate wooden targets. Fragment penetrations are numbered and obtained data represented input in further calculations [3]. Given data on fragment penetrations through wooden panels can be used for determination of efficient fragment density for every sector of semicircular arena.

Efficient fragment density, in general case, is a function of polar zone angle θ and distance from the center of explosion R :

$$d_{sp} = f(\theta, R) \quad (5)$$

Prediction of efficient fragment density as a function of polar zone for constant values of distance from the center of explosion is based on assumption that $R = \text{const}$. In this way, based on experimental results, efficient fragment density function as a function of polar zone for every radius of Arena can be determined. Using experimental data on fragment penetrations, efficient fragment density for every panel is determined as:

$$d_{spi} = \frac{n_{spi}}{S_{spi}} \quad (6)$$

In expression (6) n_{spi} is number of efficient fragment for given panel (penetrating fragments), and S_{spi} is area of panels exposed to fragments.

Width of panel is constant for certain sector, and for semicircular arena used, interval of polar zone was 8.18° (total angle interval of one sector - 180° divided with total number of panels in given sector - 22). That means that width of panels is changing depending on distance from the center of explosion. This way interval of polar angle remains the same for all sector radiuses.

After determinaton of efficient fragment density, using (6) for every panel in arena, obtained results can be shown in polar diagrams, where axis of efficient fragment density is usually shown in logarithm scale. In these diagrams value of distance from the center of explosion is constant ($R = \text{const}$), while efficient fragment density, depending on polar angle θ , is variable.

Points with determined values of efficient fragment density, depending on polar zone, can be interpolated with spline function, in order to get smooth curve which represents the overall trend of efficient fragment density function for certain distance from the explosion. Polar diagrams of efficient fragment density as a function of polar angle can be presented in a single graph, for all four Arena radiuses.

Experimental data on number of penetrations through panels can also be used for determination of efficient fragment density as a function of polar zone as well as distance from the explosion. In that case, polar angle θ and distance from the explosion R are variable. With expression (6) efficient fragment density for every panel in arena can be found. As a next step, for every polar zone it is possible to define approximation function of efficient fragment density for different distances from explosion (Figure 1).

Polar diagram is shown in upper part of Figure 1, with efficient fragment density points defined for all Arena radiuses (R_1 to R_4), as a function of polar angle θ . From one angular section (i.e. 81.82° to 90° , shown in Figure 1) efficient fragment density points can be taken (four points). Based on these points functional relation between fragment density and distance is derived.

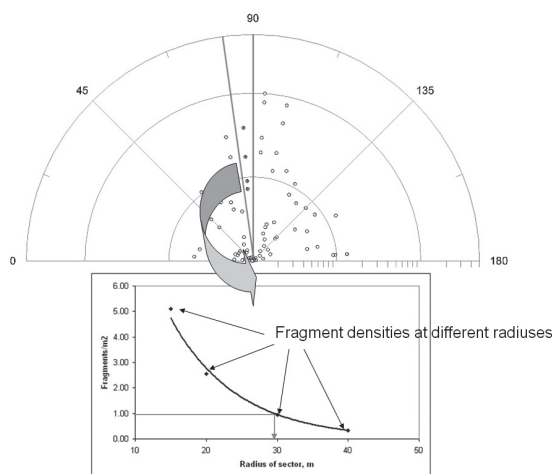


Figure 1. Determination of efficient fragment density for different distances from explosion.

In order to determine the distance on which efficient fragment density is equal to one, based on given points, regression analysis and interpolation of following function is needed:

$$d_{si} = k_1(\theta) \cdot R_i^{k_2(\theta)} \quad (7)$$

where $k_1(\theta)$ and $k_2(\theta)$ are constants obtained from regression analysis procedure.

After defining approximation function of efficient fragment density for each polar zone (22 approximation curves), points with equal efficient fragment density on terrain can be found. Using interpolation method for approximation function, presented in expression (7), a group of points is obtained, with already defined density of efficient fragment – 1 frag/m². Obtained curves which connect points with the same efficient fragment density we called - *Isodensity* curves.

In our model *Lethal zone* of HE warheads is defined as a zone on the battlefield in which an efficient fragment density is greater or equal to 1 frag/m². That means that the Isodensity curve presents an envelope of HE warhead lethal zone.

There is high probability that a soldier standing inside of lethal zone will be incapacitated for further military service by an efficient fragment hit.

Conditions for determination of lethal zones using this procedure are zero attack angle of projectile and ground detonation, since calculations are based on detonation of projectile standing horizontally and in ground level.

Test Methods for He Projectiles Natural Fragmentation Assessment

Two types of artillery projectiles (122 mm OF-462 and 122 mm M76) and two types of rocket projectile warheads (128 mm M63 and 128 mm M87) were subjected to Arena tests (Figure 2).

Influence of new projectile design, more energetic explosive charge and both variations together are compared.

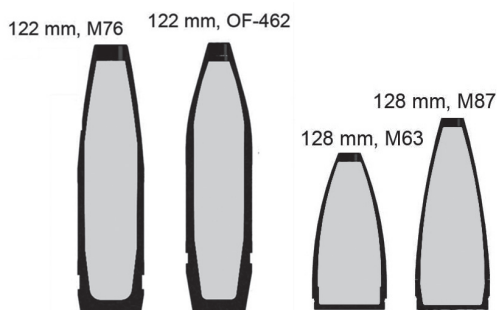


Figure 2. Projectiles subjected to Arena testing [4-7].

Data for experimentally tested projectiles is shown in Table 1, where C_{exp}/M represents the ratio of explosive charge mass to projectile body mass and value t_{av}/d ratio of equivalent projectile body thickness to equivalent diameter of explosive charge [4-7].

Table 1. Data for experimentally tested projectiles [4-7].

Projectile	Explosive	Expl. mass (kg)	Det. velocity (m/s)	Projectiles tested	C_{exp}/M	t_{av}/d
122 mm OF462	TNT	3.55	6620	10	0.230	0.185
122 mm M76	Comp. B	4.43	7437	10	0.305	0.149
128 mm M63	TNT	2.42	6620	3	0.405	0.093
128 mm M87	TNT	2.89	6620	5	0.474	0.083
128 mm M87	Comp. B	3.15	7437	8	0.516	0.083

In Table 2 parameters of projectile body material were shown. where σ_v (MPa) represent material yield strength. σ_m (MPa) is tensile strength. and ϵ (%) material relative elongation.

Table 2. Projectile body material parameters [6]

Projectile	Explosive	Body material (ex Yu standard)	σ_v (MPa)	σ_m (MPa)	ε (%)
128 mm M63	TNT	Č.1737VP	441-549	731-837	20-22.5
128 mm M87	TNT	Č.1737VP	441-549	731-837	20-22.5
128 mm M87	Comp. B	Č.1737VP	441-549	731-837	20-22.5
122 mm OF462	TNT	Č.1737VP	441-549	731-837	20-22.5
122 mm M76	Comp. B	Č.9180VP	523	760	19-22

Analysis and Interpretation of Results

Density of efficient fragments

Polar diagrams of efficient fragment density for 4 radiuses (4 Arena sectors) are presented in Figure 3 for all tested projectiles. Polar coordinate system is shown in logarithmic scale.

All polar diagrams (Figure 3) show that efficient fragment density function has decreasing character with increasing the distance from the center of explosion. with specially emphasized lateral zone.

From first diagram of efficient fragment density for artillery projectile 122 mm OF-462 (Figure 3) it can be concluded that efficient fragment density function keeps its characteristic shape for all radiuses of Arena. Especially dominant is main (lateral) spray of efficient fragments. This spray gives maximal density of efficient fragment (10 frag/m² on first radius of Arena).

Artillery projectile 122 mm M76 (Figure 3). filled with Comp. B explosive charge. has very wide lateral spray of fragments. and significant rear spray of fragments. while front spray of efficient fragments is very reduced. Characteristic shape of efficient fragment density function is similar for all 4 radiuses. with an exception of significant decrease of efficient fragment density for distances greater than 14m.

Maximal efficient fragment density for presented radiuses is around 20 frag/m². shown in Figure 3 for first two radiuses. in lateral spray of fragments.

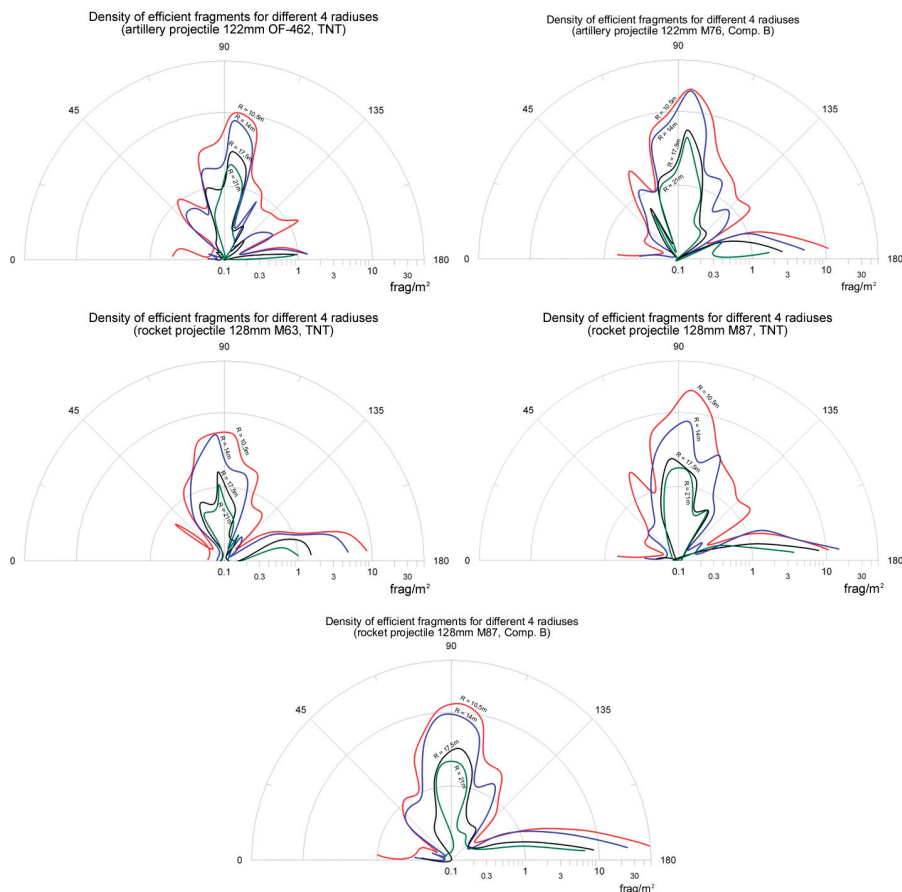


Figure 3. Polar diagrams of efficient fragment density.

When comparing these two artillery projectiles of the same caliber, projectile 122 mm M76 is designed with optimal external and internal projectile path (higher ratio C_{eks}/M , and smaller t_{av}/d), and also more energetic explosive is used as main charge - Composition B). These changes were very influential, since 122 mm M76 projectile has noticeably larger efficient fragment density and much more wider sprays of fragments.

Polar diagrams of efficient fragment density for rocket projectiles warhead 128mm are shown also in Figure 3. Warhead 128 mm M63, filled with TNT (Figure 3), has wide lateral and rear spray of fragments, but significantly smaller overall efficient fragment density comparing to other tested projectiles. Maximal efficient fragment density for warhead 128 mm M63 is around 9 frag/m², in rear

spray of fragments, which is interesting. It seems that rocket projectiles warheads all have large rear spray of efficient fragments.

Rocket projectile warhead 128 mm M87 has also, for both explosive charge, very large rear spray of fragments, besides dominant lateral spray. This leads to conclusion that soldiers located behind detonating warhead 128 mm M87 may be hit by incapacitating fragment, and remain incapable for further activity. For warhead 128 mm M87 (TNT) (fig. 3) maximal efficient fragment density is around 20 frag/m², in lateral spray of fragments. This spray fast loses its shape, but remains reasonably wide, even after 21 m distance from explosion.

Warhead 128 mm M87 (Comp. B) has the greatest efficient fragment density – over 50 frag/m². It is interesting to note that this density is present in rear spray of efficient fragments. When comparing warheads 128 mm M63 and 128 mm M87, conclusion arises that highly optimized design (and use of Comp. B explosive charge) for warhead 128mm M87 leads to improved performances compared to older warhead type 128mm M63. For warheads 128 mm M87 with different explosive charges, significant differences are presented only in rear spray of efficient fragments, where warhead M87 with Comp. B shows better performances.

Prediction of lethal zones

Prediction of lethal zones, based on representation of isodensity curves, is made using software package Grapher[®]. Points with the same efficient fragment density are interpolated using spline function, and results for projectile 122 mm OF-462 are presented in diagram in Figure 4. In this polar diagram, radius vector for efficient fragment density is presented as a function of polar angle. Polar coordinate system axis is in logarithmic scale. In Figure 5 angular width of fragment sprays are also shown for projectile 122mm OF-462.

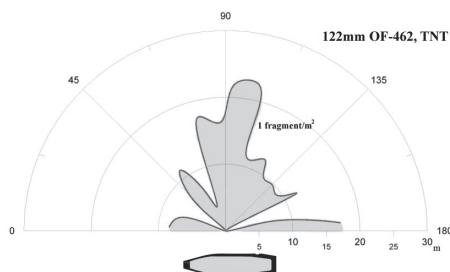


Figure 4. Lethal zone for 122mm OF-462.

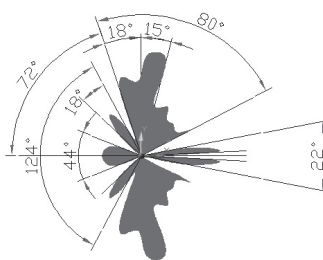


Figure 5. Width of lethal zone sprays (122 mm OF462).

Lethal zones are predicted for zero attack angle of projectile and ground detonation and they generally consist of three dominant sprays. front. lateral and rear spray (Figure 4). For every lethal zone. lateral side is the most dominant side of the zone. This practically means that soldier standing in area around the warheads that doesn't belong to its lethal zone can remain unharmed after the detonation. while there is high probability that he will be incapacitated if he is positioned inside lethal zone.

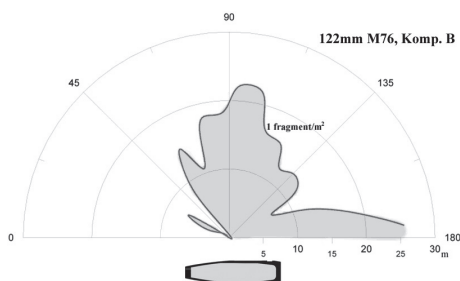


Figure 6. Lethal zone for projectile 122 mm M76.

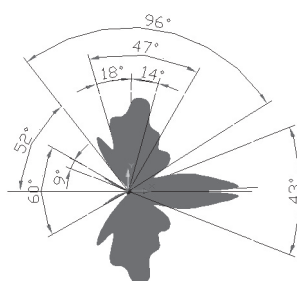


Figure 7. Width of lethal zone sprays for 122 mm M76.

Artillery projectile 122 mm OF-462 has highly stochastic shape of lethal zone (Figures 4 and 5). which consists of three main parts. Front part of lethal zone has three smaller sprays (Figure 5) with angle width of 18° and 44° . Lateral spray of lethal zone is 80° wide and has exposed center part with angle width of 15° . Last part of lethal zone is very small. with angular width of 22° .

Artillery projectile 122 mm M76. with explosive charge Comp. B. has very interesting lethal zone (Figures 6 and 7). It has very small front part of the zone. but dominant lateral spray has angular width of 96° . Inside of this dominant spray are two smaller characteristic sprays which are 47° and 14° wide. Rear part of the zone is 43° wide. From Figures 6 and 7 it can be concluded that efficiency of projectile 122 mm M76 is highest in lateral and rear space around the projectile. What is unusual here is that target. located in front of the projectile (up to angle 52°). is relatively safe. This confirms some of the soldier statements in which they claim that they were positioned only a couple of meters in front of the projectile. and remained unharmed during the battle.

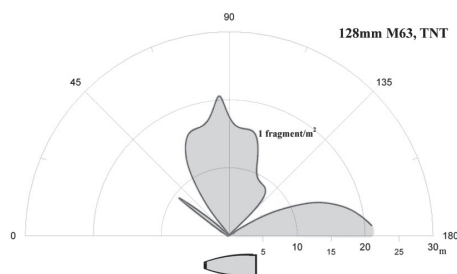


Figure 8. Lethal zone for 128 mm M63.

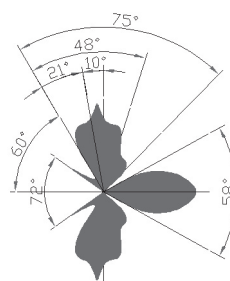


Figure 9. Angular width of sprays for 128 mm M63.

Projectile 122 mm OF-462 is developed after world war II. and its predecessor – projectile 122 mm M76 is introduced in the armament some twenty years ago. That is the reason why projectile 122 mm OF-462 has poorer performances (smaller lethal zone) comparing to 122 mm M76. It is the consequence of smaller quantity of explosive TNT (also lower energetic characteristics than comp. B used in 122 mm M76). bigger ratio t_{av}/d (thicker shell). smaller ratio C_{eks}/M . and smaller slimness of front part of projectile 122 mm OF-462.

In Figures 8 and 9. lethal zones and angular width of its sprays are presented for warhead 128 mm M63. filled with TNT. This warhead has very wide rear part of lethal zone. with angular width of 58° (almost as the lateral spray). Front part of lethal zone for 128 mm M63 is quite small and doesn't effect warheads efficiency significantly. Lateral spray of lethal zone for warhead 128 mm M63 encompass an angle of 75° . with particularly exposed central segment. 48° wide. Large surface of lethal zone rear spray greatly influences its efficiency. because of high angular width.

In Figures 10-13 lethal zones (polar diagrams and diagrams of angular width of zone parts) are presented for warhead 128 mm M87 (TNT and Comp. B). modified and improved version of warhead 128 mm M63.

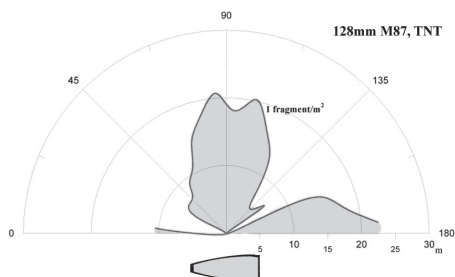


Figure 10. Lethal zone for warhead 128 mm M87 (TNT).

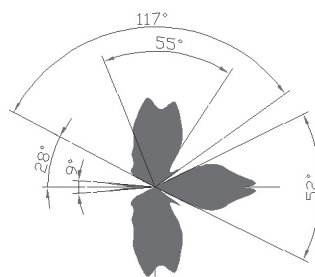


Figure 11. Width of lethal zone sprays for 128mm M87 (TNT).

Using Comp. B in warhead 128mm M87 (Figures 12 and 13) general shape of lethal zone has not changed much comparing to lethal zones for 128mm M87 with TNT. Lateral and rear part of lethal zones are also dominant. Lateral part has angular width of 96° . and rear part 56° . Inside of dominant lateral spray there are two characteristic sprays. 12° and 52° wide.

Warhead 128 mm M87 is improved version of warhead 128 mm M63. with higher ratio C_{eks}/M . smaller ratio t_{av}/d . and higher slimness. Advantage gained with this new design and more energetic explosive is apparent in increase of lethal zone and width of its lateral spray.

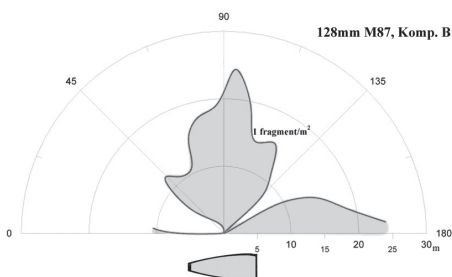


Figure 12. Lethal zone for warhead 128 mm M87 (Comp.B).

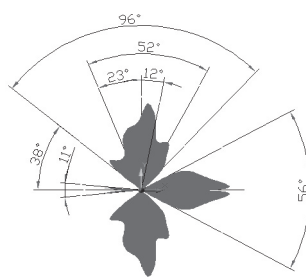


Figure 13. Width of zone sprays for 128 mm M87(Comp.B).

Values of Lethal zone area A_{LZ} are determined for projectiles. and summary results are shown in Table 3.

Table 3 shows that. generally speaking. best efficiency from the standing point of lethal zone. gives artillery projectile 122 mm M76. with comp. B. whose lethal zone area A_{LZ} is 585.1 m^2 . Following is rocket projectile warhead 128 mm M87 (Comp. B) with lethal zone area A_{LZ} of 583.7 m^2 . Even though conclusion might arise that projectile 122 mm M76 gives best performances. it should be

pointed out that shell of warhead 128 mm M87 has 2.76 times (176%) smaller mass than projectile 122 mm M76 shell. and that projectile 122 mm M76 has 1.4 times (40%) higher mass of explosive than warhead 128 mm M87. Since lethal zone area is similar for both projectiles (0.23% smaller for 128 mm M87) one can conclude that rocket projectile warhead 128 mm M87. filled with composition B. gives best overall performances. considering all the paramateres and scaling all projectiles to their relative sizes.

Table 3. Lethal zone area A_{LZ} for tested projectiles

Projectile	Lethal zone area A_{LZ} [m ²]
122 mm M76 (Comp. B)	585.1
122 mm OF-462 (TNT)	397.9
128 mm M63 (TNT)	432.2
128 mm M87 (TNT)	524.9
128 mm M87 (Comp. B)	583.7

When considering influence of explosive charge on lethal zone parameters for the same warhead design and warhead shell material (steel Č.1737) for rocket projectile warhead 128 mm M87. using composition B as explosive charge instead of TNT. increase in lethal zone is 10%.

Influence of new design on lethal zone parameters for the same caliber (128mm). the same shell material (steel Č.1737) and the same explosive type (TNT) can be seen from the Table 3. Lethal zone area of warhead 128mm M63 is smaller for 17.6% compared to warhead 128mm M87. Thus. optimization of warhead design leads to significant improvement in its lethal zone.

When design is improved and also more energetic explosive type used. as in case of projectile 122mm M76 compared to 122mm OF-462. increase of 32% for lethal zone area is obtained. This means that smaller ratio t_{av}/d . and higher ratio C_{eks}/M gives better performances for projectile.

Similar result is obtained for other case of warhead design improvement and use of composition B instead of TNT. Comparing the lethal zone area of warheads 128 mm M87 (Comp. B) and 128mm M63 (TNT). Table 3 shows that there is increase of lethal zone for 26% in case of projectile 128 mm M87.

General conclusion arises that using new. more optimal design of warhead and more energetic explosive materials leads to biggest improvement in lethal zone areas for all tested projectiles.

Conclusion

Method for prediction of efficient fragment density, isodensity curves, and lethal zones for HE warheads with natural fragmentation is described. Basics of the model represents U.S. Vulnerability Model for Military Personnel.

Based on fragmentation Arena tests for two types of artillery projectiles and two types of rocket projectile warheads, analytical and numerical methods were described. During our research prediction of efficient fragment density function is made for 4 sectors of Arena presented with different radiuses. Lethal zones are predicted and analyzed, with special interest in angular width of lethal zones sprays, as well as comparison of lethal zone areas A_{LZ} for different projectile types.

Analysis of projectile design and explosive charge type influence on warhead efficiency performance (lethal zone in this case) is made. Varying explosive charge type (for the same design and shell material) lethal zone can be increased to 10%, and changing the design – applying new optimized projectile path (for the same shell material and explosive type), lethal zone is also increased, this time by 17.6%.

It is shown that best results can be achieved with optimization of external and internal path of projectile (new optimized design), in conjunction with use of more energetic explosive material as main charge. Results show increase of lethal zone up to 32% with modern projectiles and warheads 122 mm M76 (Comp. B) and 128 mm M87 (Comp. B), comparing to their older versions 122 mm OF-462 (TNT) and 128 mm M63 (TNT).

Reccomendation for further work in prediction of lethal zones and HE warheads terminal ballistics are as follows:

- Prediction of 3D model of lethal zones and analysis of lethal volume.
- Research of influence of projectile attack angle and detonation above ground on warhead lethal zone.
- Defining the function which describes dependence of attack angle and lethal zone.
- Constant increase of database regarding HE warheads terminal ballistics (materials used, types of explosive charge, experimental tests).
- Unification of models in universal software for prediction of lethal zone for HE warheads with natural fragmentation.

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