ANALYSIS OF TERMINAL EFFECTIVENESS FOR SEVERAL TYPES OF HE PROJECTILES AND IMPACT ANGLES USING COUPLED NUMERICAL - CAD TECHNIQUE

Alan Catovic, Berko Zecevic, Jasmin Terzic

University of Sarajevo, Mechanical Engineering Faculty, Defense Technologies Department, Vilsonovo setaliste 9, 71000 Sarajevo, Bosnia and Herzegovina

contact: catovic@mef.unsa.ba

Abstract:

Very important task of HE projectile terminal ballistics is determination of lethal area. Lethal area is a measure of fragment casualty-producing potential of an exploding projectile when employed against human targets, and can be expressed as a function of soldiers density and probability that the personnel will be incapacitated. Researchers worldwide use different criteria for human target densities. It means that expected number of casualties, after detonation of single projectile, will strongly depend on chosen criteria for soldiers density on terrain.

In our model, based primarily on U.S. Vulnerability 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/m^2. That means that the Isodensity curve [9], a curve which connects points with the same efficient fragment density, presents an envelope of HE warhead lethal zone. Soldiers standing inside of lethal zone will be incapacitated by an efficient fragment hit. It is important to note that data for fragment densities are obtained from experimental test in Arena facilities.

In order to perform analysis of terminal effectiveness for different types of HE projectiles and their impact angles, alternative approach with CAD technique was introduced. Using spline interpolation and 3D technique in CAD software, it is possible to predict 3D model of lethal zones for HE projectiles. Rotating and mirroring these 3D models in space helps us in determination of HE projectile attack angle influence on its lethal zone. Furthermore, using intersection CAD technique for obtained 3D models, 2D model of lethal zones can be obtained for different projectile impact angles. Areas of obtained 2D lethal zones can be determined in CAD software. This method can be great visual and intuitive engineering tool for analysis of terminal effectiveness.

Keywords: *natural fragmentation, lethal zones, HE projectiles*

1. INTRODUCTION

Important task of high explosive projectile terminal ballistics is determination of its lethal area. Acording to U.S. Vulnerability Model for Military Personnel, lethal area A_L is expressed as:

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

In equation (1) N_c is expected number of casualties, σ density of human targets in target area, and $P(x,y)$ is probability that the personnel in that element will be incapacitated [1].

Researchers worldwide use different criteria for human target densities. It means that expected number of casualties, after detonation of single projectile, will strongly depend on chosen criteria for soldiers density on terrain.

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

$$P(x,y) = 1 - [1 - P_B(x,y)] \cdot [1 - P_F(x,y)] \qquad \textbf{(2)}$$

where $P_B(x, y)$ is probability of incapacitation due to blast alone, and $P_F(x, y)$ probability of incapacitation due to fragments alone. Probability of incapacitation due to blast 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. This procedure is described in detail in previous paper [9]. Probability of incapacitation due to fragments $P_F(x,y)$ is predicted using expression [1]:

$$P_F(x,y) = 1 - e^{-d(x,y) \cdot A_t} \qquad \textbf{(3)}$$

Here A_t is presented area of the target, which for standing man is 0,5 m^2, for soldier in assault position 0,37 m^2 and for prone position of soldier 0,1 m^2, as depicted in fig 1.

Average density of efficient fragments *d(x,y)* is the key parameter in equation (3). Confidential data for average density of lethal fragments within a dynamic zone could not be find in available literature.

In US Arena test facilities, fragments are usually collected in one semicircular sector, and their respective velocities are measured in another. Hence, obtained experimental data contains information about velocity, mass, shape, and spatial distribution of fragments. Based on these data, lethal area of projectile can be determined.

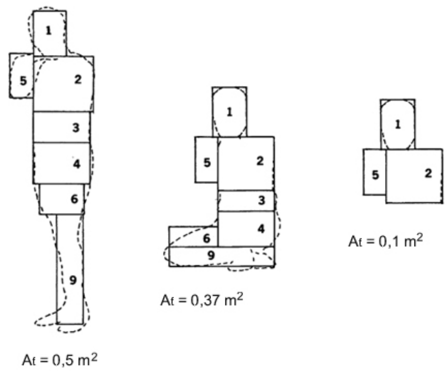

Fig 1. Different presented area of the target (soldier)

In our country another approach for Arena construction and spatial fragmentation test was used. To predict average density of efficient fragments we used the results from fragmentation test in fragmentation Arena [9], which consists of four semicircular sectors, with radiuses 10.5m, 14m, 17.5m, and 21m, respectively.

Immobilized projectiles, positioned 2m above the ground and parallel to the ground, were electrically detonated in the center of Arena [9]. Fragments were considered efficient if they penetrate wooden targets in Arena. Given data on fragment penetrations through wooden panels are used for determination of efficient fragment density for every sector of semicircular arena, and subsequently other terminal efectiveness parameters.

Efficient fragment density, in general case, can be presented as a function of polar zone angle θ and distance from the center of explosion *R*:

$$d_{sp} = f(\theta, R) \qquad \textbf{(4)}$$

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* = 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 [9].

Using experimental data on fragment penetrations, efficient fragment density for every panel is determined as:

$$d_{spi} = \frac{n_{spi}}{S_{spi}} \tag{5}$$

In expression (5) n_{spi} is number of efficient fragment for given panel, and S_{spi} is an area of every panel exposed to fragments [9].

Width of panel is constant for certain sector, and for semicircular arena used, interval of polar zone was 8,18º. That means that the 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 in Arena [9].

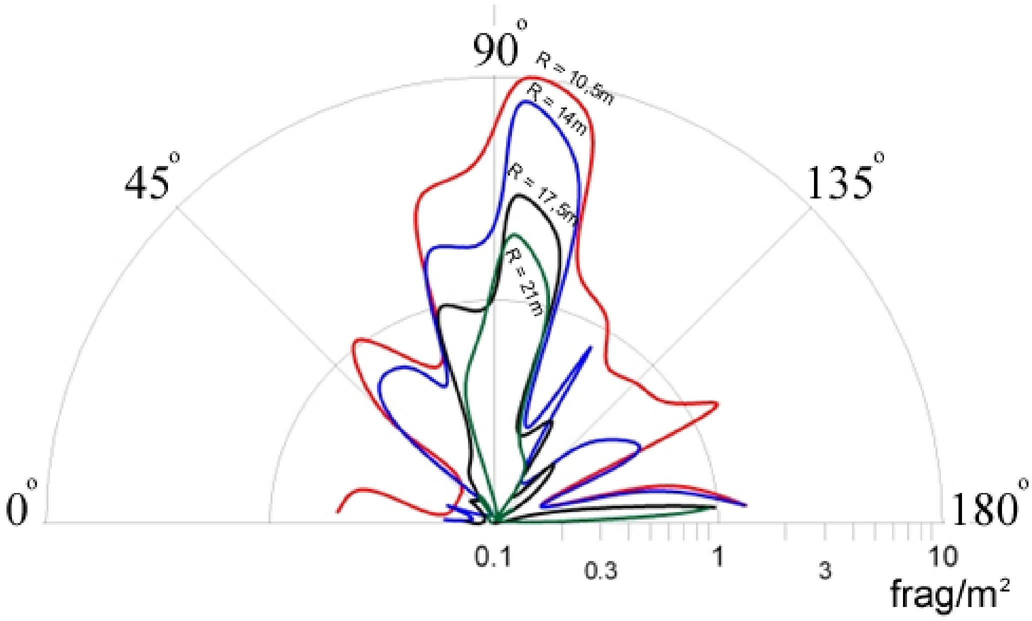

Fig 2. Efficient fragment density vs polar angle for different radiuses [9]

After determinaton of efficient fragment density, using expression (5) for every panel in arena, obtained results can be shown in polar diagrams, where axis of efficient fragment density is shown in logarithm scale (fig. 2). 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 [9].

Polar diagrams of efficient fragment density as a function of polar angle can be presented in a single graph, for all four Arena radiuses, as shown in fig. 2.

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 variables [9].

For every polar zone it is possible to define aproximation function 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:

$$d_{si} = k_1(\theta) \cdot R_i^{k_2(\theta)} \quad \textbf{(6)}$$

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

Using interpolation method of aproximative function, presented in expression (6), a group of points is obtained, with already defined density of efficient fragment - 1 frag/m^2. It is, however, possible also to define other values of efficient fragment density, i.e. - 2 frag/m^2 or 4 frag/m^2, depending on the experimental data we have, and research needs [9].

Obtained curves which connect points with the same efficient fragment density are named Isodensity curves [9], and example of this curve is shown on fig. 3.

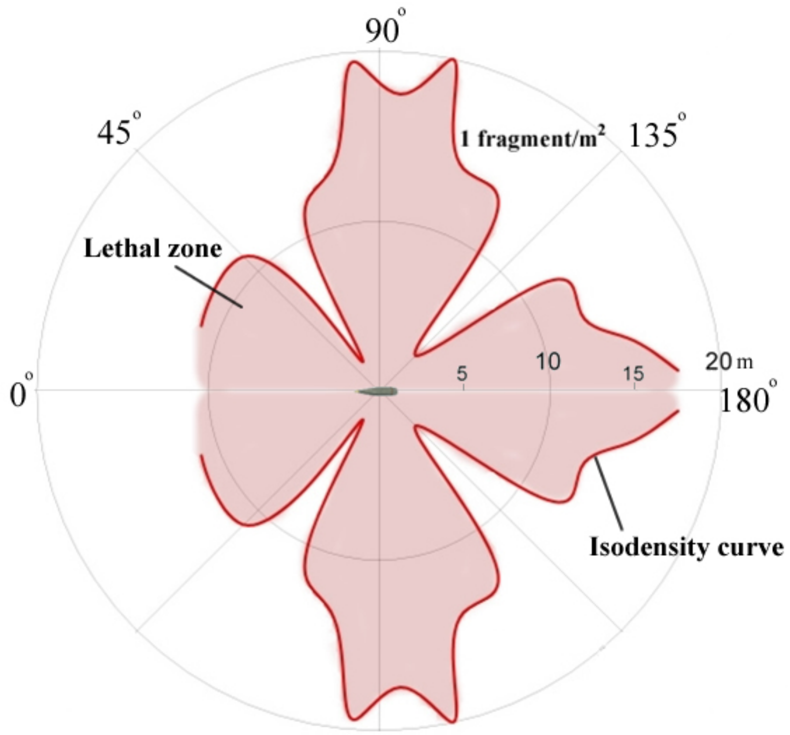

Fig 3. Isodensity curve and lethal zone for 0° projectile impact angle [9]

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/m^2, as shown in figure 3. That means that the Isodensity curve represents an envelope of HE warhead lethal zone [9]. 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 leve in Arena.

Based on equations (1) and (2) from U.S. Vulnerability Model for Military Personnel, and using our model for determination of efficient fragments average density *d(x,y)* from semicircular Arena, it is possible to predict expected number of casualties of HE projectiles, for different types of projectiles, and different types of presented areas of the soldiers on virtual battlefield. For this task we introduced numerical integration tehnique and made program script in software package MatLab©.

In our reasearch we tried to make the most of our experimental data, incorporating the basics of US Vulnerability Model in order to determine projectile lethal area. However, this modified model is limited to use only for 0° impact angle of projectile, since experimental data from Arena are obtained from horizontally (and static) detonated projectile, placed parallel to the ground.

In order to perform analysis of terminal effectiveness for different types of HE projectiles and different impact angles, alternative approach with CAD (**C**omputer **A**ided **D**esign) technique is introduced.

2. INTERFACE FOR CAD MODELLING OF LETHAL ZONES

Input data for CAD modelling of lethal zone are distances from the center of detonation to the points with efficient fragment density equal to 1 frag/m^2, as well as the coordinates of panel centers for semicircular Arena (fig. 4), respectivelly.

After succesful modelling of points with efficient fragment density of 1 frag/m^2, using spline interpolation technique in CAD software, Isodensity curve, mentioned earlier, is obtained (fig. 5).

Note that this curve can also be found using other graphical software, such as Grapher©, but their use is limited to 2D models and diagrams. In this procedure, however, isodensity curve represent the initial and key curve for 2D model of lethal zone, based on which 3D model of lethal zone will be obtained.

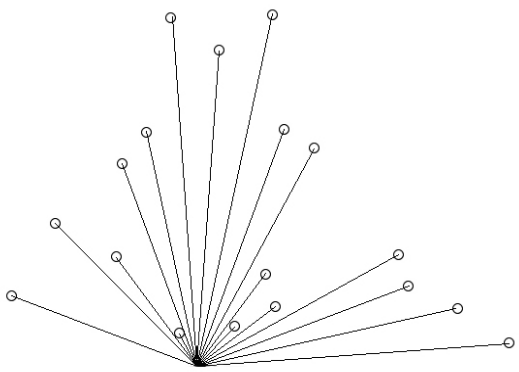

Fig 4. Points in CAD software with efficient fragment density equal to 1 frag/m^2

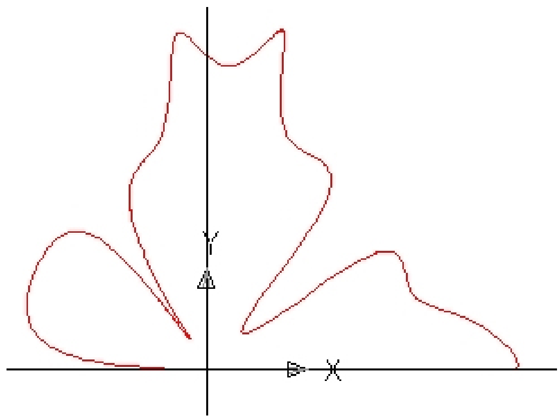

Fig 5. Interpolation spline curve obtained in CAD software (Isodensity curve)

Isodensity curve, presented in fig. 5, envelops only the half of lethal zone for given projectile. But since all projectiles are axisymmetric bodies, total lethal zone is easily obtained by multiplying with two, or graphically mirroring isodensity curve.

It is assumed that spatial distribution of fragments around detonating HE projectile is axisymmetric. It means that, by rotating isodensity curve around symmetry axis, 3D model of lethal zone is obtained. These 3D models are very important engineering tool since they can be used in analysis of influence of projectile impact angle on lethal zone. Also, one is able to calculate exact volume of 3D lethal zone in virtual space using this technique.

When researchers want to examine the influence of projectile impact angle on its lethal zone, 3D model of lethal zone can be rotated around axis perpendicular on projectile symmetry axis. This procedure is shown in fig. 6, for 0°, 30°, 60° and 90° projectile impact angle. Step for impact angle in analysis can be also considerable smaller (i.e. 5°), depending on research.

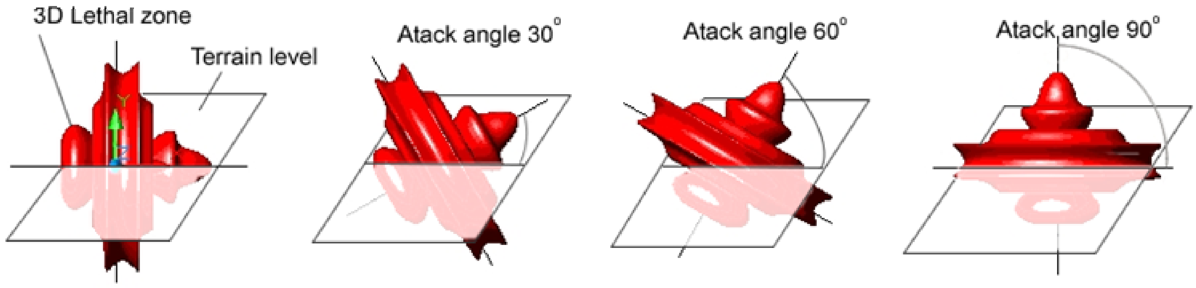

Fig 6. 3D model of warhead lethal zone for different projectile angle of atack [2]

By using intersection technique in CAD software, one can find HE projectiles lethal zones for different impact angles of projectile.

In fig. 7 lethal zones for different projectile impact angles (30° step) are shown. It is clear that increase in impact angle leads to signifficant increase of lethal zone for projectile, and that greatest lethal zone will have HE projectile with impact angle as close to 90° as possible.

Procedure of determination of lethal zone real area is conducted in CAD software using appropriate software tools. Method described here is very accurate and fast, so analysis including CAD technique doesn't consume much computer resources.

Intuitive interfaces and tools for CAD modelling of lethal zones, described in this paper, enable visualisation of 2D and 3D lethal zones, calculation of 3D lethal zone volume as well as 2D lethal zone real area for different impact angles of projectile.

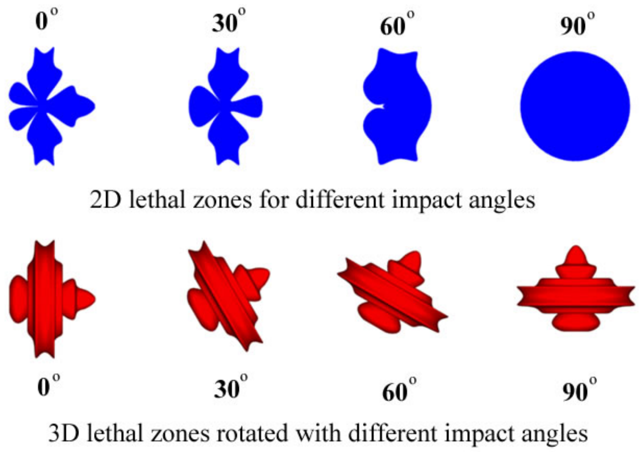

Fig 7. 2D and 3D Lethal zones for different projectile impact angle [2]

3. EXPERIMENTAL PLAN

Experimental test in semicircular fragmentation Arena [9] were conducted with two types of artillery projectiles, 122mm OF-462 and 122mm M76, as well with two types of rocket projectile warheads, 128mm M63 and 128mm M87, all shown in fig. 8.

Projectiles 122mm OF-462, 128mm M63 and 128mm M87 were charged with TNT, while projectiles 122mm M76 and 128mm M87 were charged with composition B. This way influence of projectile design, explosive type, and both design and explosive type can be seen in analysis of terminal effectiveness.

Data for tested projectiles are presented in table 1. Ratio C_{exp}/M is the ratio of explosive charge mass to projectile body mass and t_{av}/d_{av} is the ratio of equivalent projectile body thicknes to equivalent diameter of explosive charge [9].

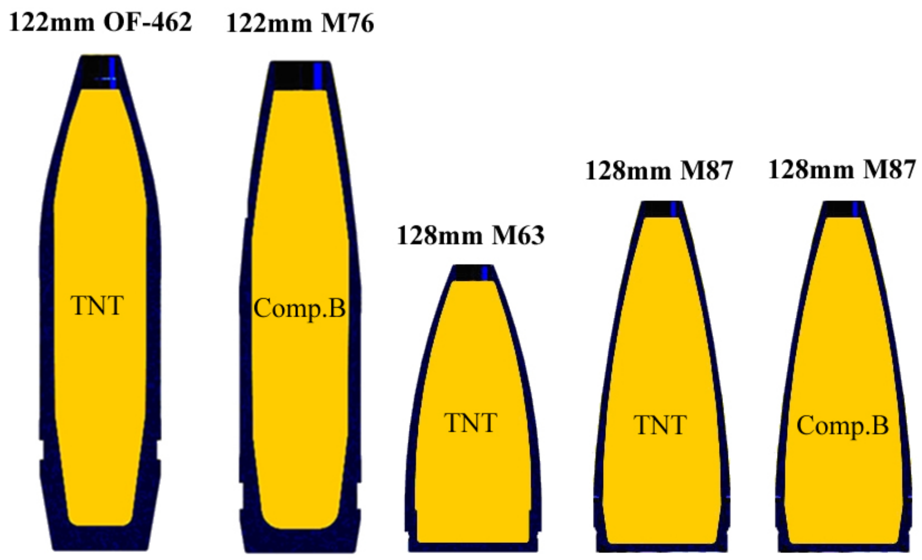

Fig 8. Projectiles tested in Arena[9]

Table 1. *Data for experimentally tested projectiles* [9].

Projectile type	Explosive type	Expl. charge mass (kg)	Expl. density (kg/m^3)	Detonation velocity (m/s)	Tests	C_{exp}/M	t_{av}/d_{av}
122mm OF-462	TNT	3,55	1515	6620	**10**	0,230	0,185
122mm M76	Comp. B	4,43	1580	7437	**10**	0,305	0,149
128mm M63	TNT	2,42	1515	6620	**3**	0,405	0,093
128mm M87	TNT	2,89	1515	6620	**5**	0,474	0,083
128mm M87	Comp. B	3,15	1580	7437	**8**	0,516	0,083

4. ANALYSIS AND DISCUSSION OF RESULTS

4.1 Expected number of casualties

Lethal area A_L is a measure of the fragment casualty-producing potential of an exploding projectile when emplyed against human targets. It is defined such that the expected number of casualties N_c is equal to A_L times density of human targets σ [1].

In order to determine expected number of casualties N_c (equation 7) double integral was solved (numerically integrated) for a positive function of two variables, which represents the volume of the region between the surface defined by the function (on the three dimensional Cartesian plane) and the plane which contains its domain.

Expected number of casualties N_c can be presented in following form:

$$N_c = \sigma \cdot \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P(x,y) \cdot dx \cdot dy \qquad \textbf{(7)}$$

Researchers use different criteria for human target densities, and in equation (7) density σ is constant, and depends on chosen criteria. Since probability of incapacitation *P(x,y)* is nondimensional, expected number of inacapacitated soldiers has unit of soldiers/m^2.

Programmable script in software package MatLab© was written and used for determination of expected number of casualties N_c. Script also enables visualisation of 3D function of incapacitation probability.

Input data for script are coordinates that corresponds to the center of each panel in semicircular Arena, and appropriate values of total incapacitation probability, which depends on probability of incapacitation due to blast, and probability of incapacitation due to fragments, determined from equation (2).

Based on known values of radiuses (distances from the center of detonation) on which probability of incapacitation due to blast alone is uqual to 1, average efficient fragment density values determined from Arena test, and adopted presented area of the target (standing man - 0,5 m^2, soldier in assault position - 0,37 m^2, prone position of soldier - 0,1 m^2), total probability of incapacitation is determined, hence expected number of casualties is predicted, assuming defined value of soldier density on the battlefield.

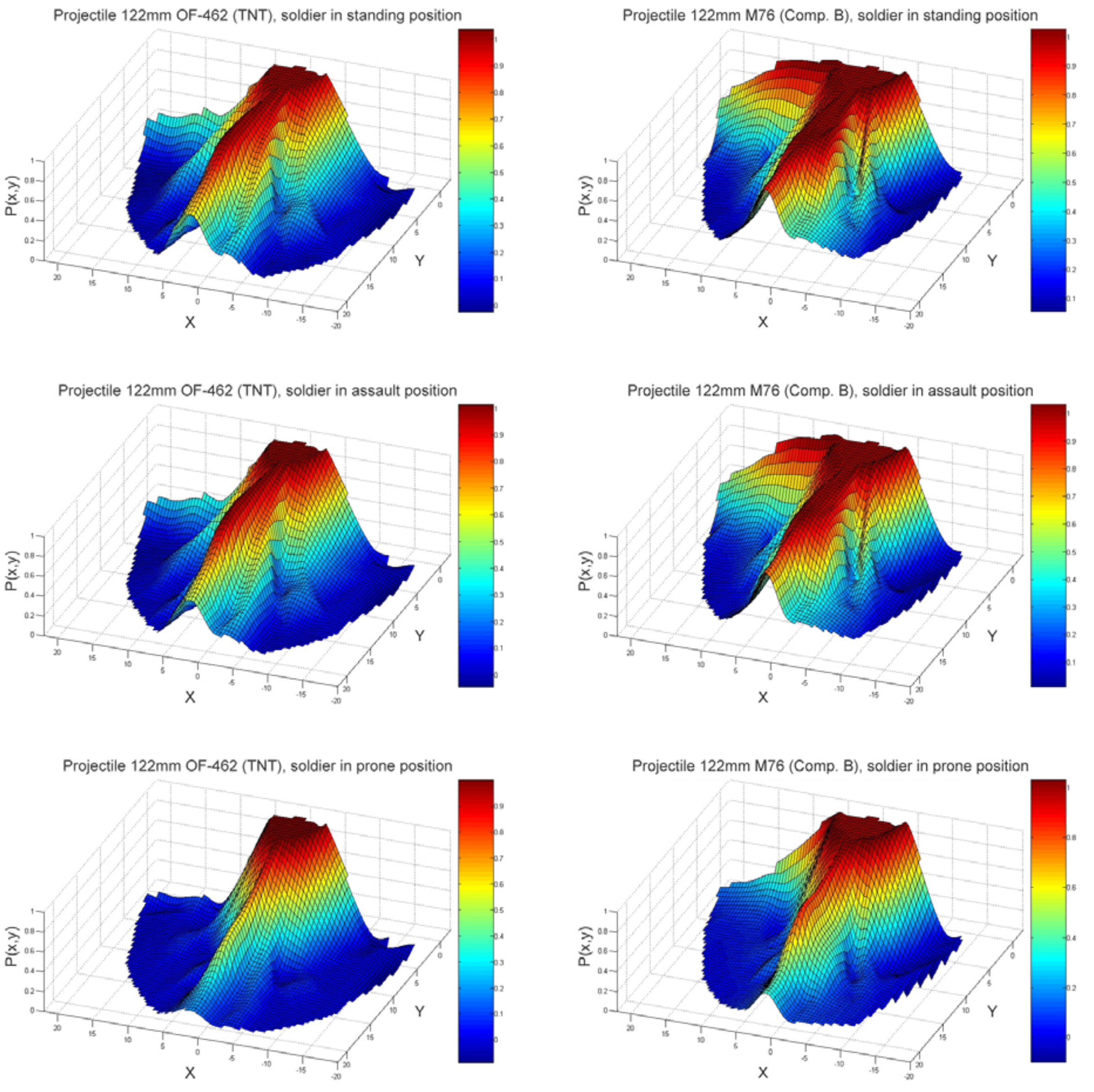

Fig 9. Incapacitation probability as a function of three different presented area of the soldier, for projectiles 122mm OF-462 and 122mm M76

Determined total probability of incapacitation (three dimensional diagrams) for two types of artillery projectiles and rocket projectile warheads are shown in fig. 9 and 10, for three different presented area of the target. This analysis is based on following conditions: ground detonation and 0 ° impact angle od projectile.

Hypothetic projectile in diagrams is located in point with coordinates (0,0) and its top is facing negative side of X axis. All diagrams have equal scaling ratio, X and Y axis limit the plane of terrain and have dimension of meters, while Z axis represent total probability of incapacitation *P(x,y)* of a soldier. Values of incapacitation probability are between 0 and 1.

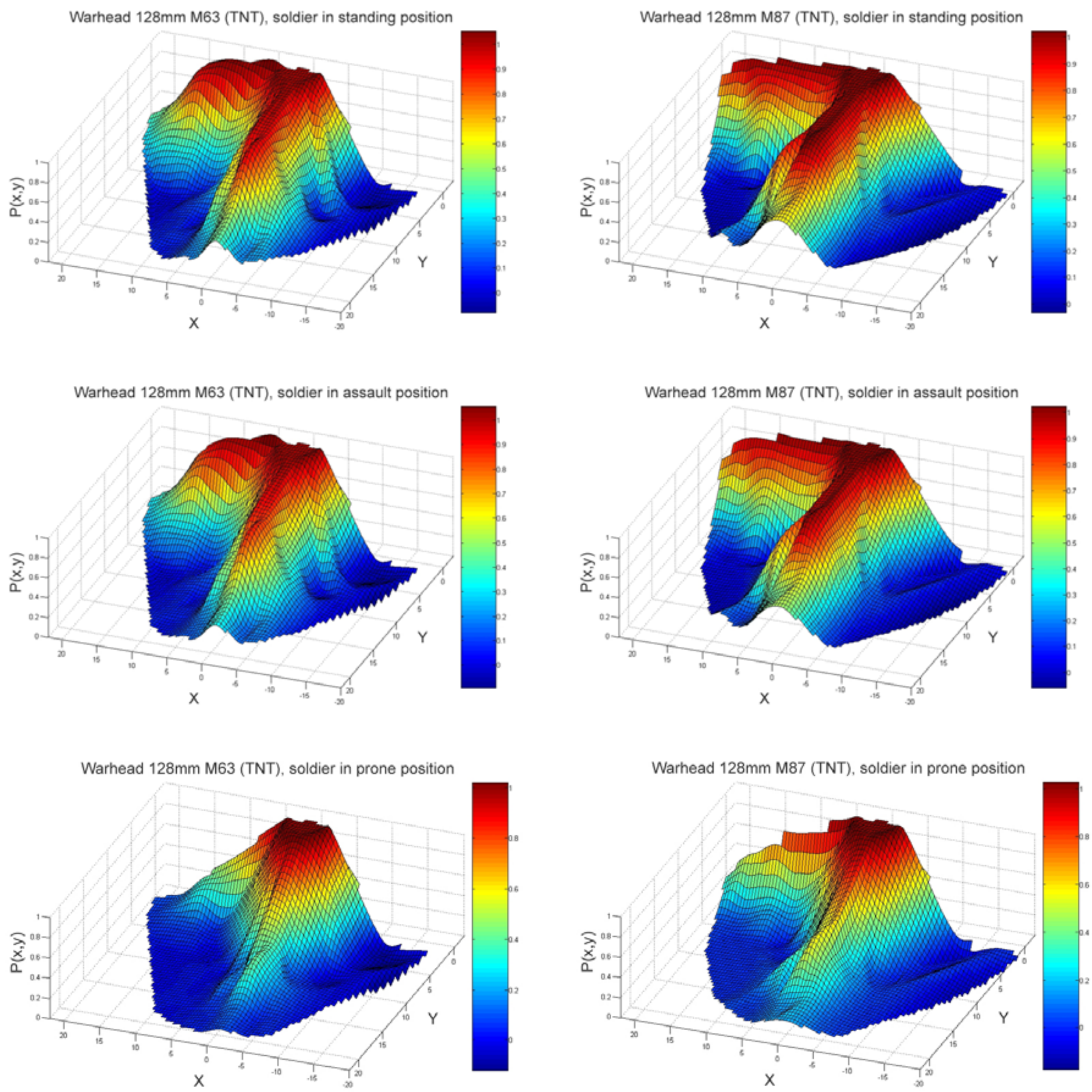

Fig 10. Incapacitation probability as a function of three different presented area of the soldier, for rocket projectile warheads 128mm M63 and 128mm M87

Overall trend in diagrams (figures 9, 10) is such that total incapacitation probability rapidly decreases with decrease of presented area of target, for the same conditions of impact point (0° impact angle) and detonation height (ground detonation level).

Diagrams also show that for smaller presented areas of target, incapacitation probability function has more uniform shape, which means that incapacitation probability for soldier in prone position is almost equal in all directions. While in diagrams where presented area of target is larger (assault and standing position of soldier), incapacitation probability is dominant in lateral zone. It is a consequence of higher efficient fragment density in laterall fragment spray.

Diagrams in figure 10 show that total incapacitation probability for rocket projectile warheads 128mm M63, filled with TNT, and 128mm M87, charged with composition B, is signifficantly larger in the zone behind detonating warhead, comparing with artillery projectiles 122mm OF-462 and 122mm M76.

After the total probability of personnel incapacitation *P(x,y)* is determined and density of human targets σ defined, expected number of casualties N_c can be predicted for tested warheads and projectiles.

Density of human targets σ is determined for two cases. First one (used in ex Yugoslavia) uses criteria which suggests larger number of soldiers on the battlefield (ful frontal formation - 1 soldier/m^2). Second approach uses criteria that eight man infantry squad on line (infantry deployed in 10 x 50 meter area) defines density of soldiers as 0,016 soldiers/m^2 [5].

Results for both approaches of defining target densities and diferent presented areas of target are shown in table 2. Note that designations N_{C1} and N_{C2} define expected number of soldier casualties, using first and second concept of defining soldier density σ, with detonation of single projectile (warhead) on ground level and zero impact angle of projectile.

Table 2. *Comparation of expected number of casualties for tested projectiles*

Projectile	**N_{C1} (A_t=0,5m^2)**	**N_{C2} (A_t=0,5m^2)**	**N_{C1} (A_t=0,37m^2)**	**N_{C2} (A_t=0,37m^2)**	**N_{C1} (A_t=0,1m^2)**	**N_{C2} (A_t=0,1m^2)**
122mm OF-462, TNT	444	7	391	6	237	4
122mm M76, Comp.B	589	9	528	8	326	5
128mm M63, TNT	440	7	388	6	229	4
128mm M87, TNT	529	8	469	7	272	4
128mm M87, Comp.B	612	9	545	8	324	5

Data from table 2 clearly indicate that expected numbers of soldier casualties N_c are much more higher using first approach where number of soldiers on the battlefield represent ful frontal formation (1 soldier/m^2).

On the other hand, table 2 also shows that highest expected number of casualties for standing and assault soldier position gives warhead 128mm M87, filled with composition B, followed by artillery projectile 122mm M76, also filled with comp. B. This is obvious, since both warheads present highly optimized design of their predecessors (128mm M63 and 122mm OF-462, respectivelly), and have more powerful explosive charge – composition B. However, in prone position best results gives projectile 122mm M76, followed by 128mm M87 (comp. B).

Expected number of casualties can be presented using best fitting approximative funtion depending on soldier presented area. Obviously, expected number of casualties N_c is increasing with increase of the presented area of the target A_t. Proposed regression function that best fits the data can be expressed in general form:

$$N_c = n \cdot A_t^{\,m} \qquad \textbf{(8)}$$

where *n* and *m* are constant, determined using regression analysis.

Equation (8) can be used for this kind of analysis since correlation coefficients of regression functions are all larger than 0.99 for tested projectile.

4.2 Analysis of influence of projectile impact angle on lethal zone using CAD technique

Prediction of 3D lethal zone was done using AutoCAD©, software package for CAD modelling and analysis. Input data for analysis were points in space with equal efficient fragment density (1 frag/m^2).

In order to get 3D lethal zone model, based on 2D lethal zone obtained by spline interpolation through points with the same efficient fragment density – thus obtaining isodensity curve, tools Polyline© and Revolve© are used. By combining these tools, one is able to conduct software model transformation by rotation of basic 2D lethal zone around projectile symmetry axis.

Figure 11 shows 3D lethal zones for tested artillery projectiles 122mm M76 and 122mm OF-462, and rocket projectile warheads 128mm M63 and 128mm M87. As can be seen projectile 122mm M76 was packed with explosive comp. B, as well as one model of 128mm M87 warhead. Note that projectile positioned in the centre of 3D zone in diagrams is not scaled properly, it is signifficantly smaller than shown in fig. 11, but it serves rather as an indicator of firing direction. Stohastic shape of 3D model is obvious. These 3D lethal zones (figure 11) are obtained from 2D lethal zone models which were determined using experimental data in Arena.

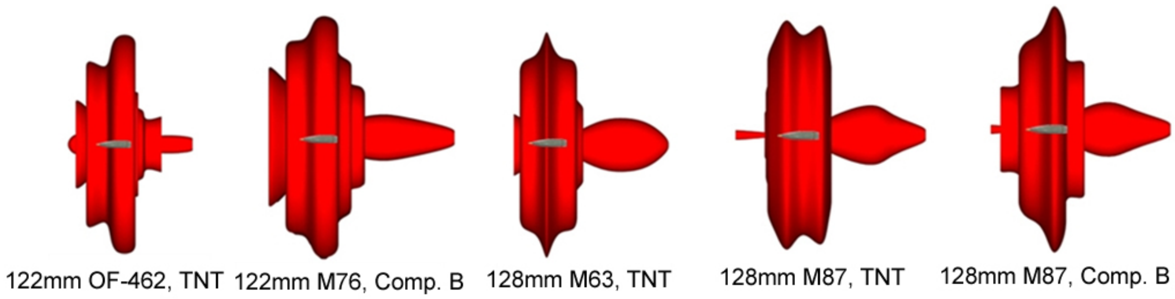

Fig 11. 3D lethal zones for tested projectiles

However, advantage of 3D models is that they can be further used in analysis od 2D lethal zones for different impact angles, and later in possible analysis of influence of terrain level on projectile lethal zone.

Table 3 shows obtained *Lethal Volume* for tested projectiles. The term is introduced in this paper, and it represents the volume of lethality for individual high explosive projectile, which encompasses space around projectile where density of efficient fragment is equal or greater than 1 frag/m^2. Lethal volume is determined using AutoCAD© mass properties tools for 3D objects and solid bodies.

Table 3. *Lethal volume of tested projectiles*

Projectile	Explosive used	Lethal volume (m^3)
122mm OF-462	TNT	11149
122mm M76	Comp. B	15212
128mm M63	TNT	9643
128mm M87	TNT	12897
128mm M87	Comp. B	15027

Data on lethal volume for tested projectiles (table 3) show that largest lethal volume of efficient fragments has artillery projectile 122mm M76, filled with comp. B. This value is comparable to lethal volume of rocket projectile warhead 128mm M87, also with comp. B explosive charge.

When tables 1 and 3 are compared, it is noticeable that, eventhough shell of warhead 128mm M87 has 2,76 times smaller mass than shell of projectile 122mm M76 and also that projectile 122mm M76 has 1,4 times higher mass of explosive than warhead 128mm M87, their lethal volume is comparable. This means that warhead 128mm M87, filled with composition B, has best performances when scaling projectiles to their relative sizes. Thus, lethal volume can be also one of the terminal effectiveness parameters of HE projectiles.

Influence of projectile impact angle on lethal zone is analyzed using AutoCAD© software, by rotating already obtained 3D models of lethal zone around axis perpendicular to projectile symmetry axis. Analysis is conducted for following impact angles of projectile: 0°, 10°, 15°, 20°, 25° 30°, 45°, 60°, 75° and 90°, regarding to ground plane level.

When 3D models of lethal zones were rotated round axis perpendicular on projectile symmetry axis, intersection technique in AutoCAD© (Section© tool) was used in order to find projection of 3D lethal zone on ground plane level, for different impact angles of projectile. Thus, 2D lethal zones are obtained for different projectile impact angles.

Diagrams of 2D lethal zones of artillery projectiles 122mm M76 and 122mm OF-462, and rocket projectile warheads 128mm M63 and 128mm M87, for different impact angles (0°-90° with incremental step of 15°) are shown in figures 13 and 14, respectivelly.

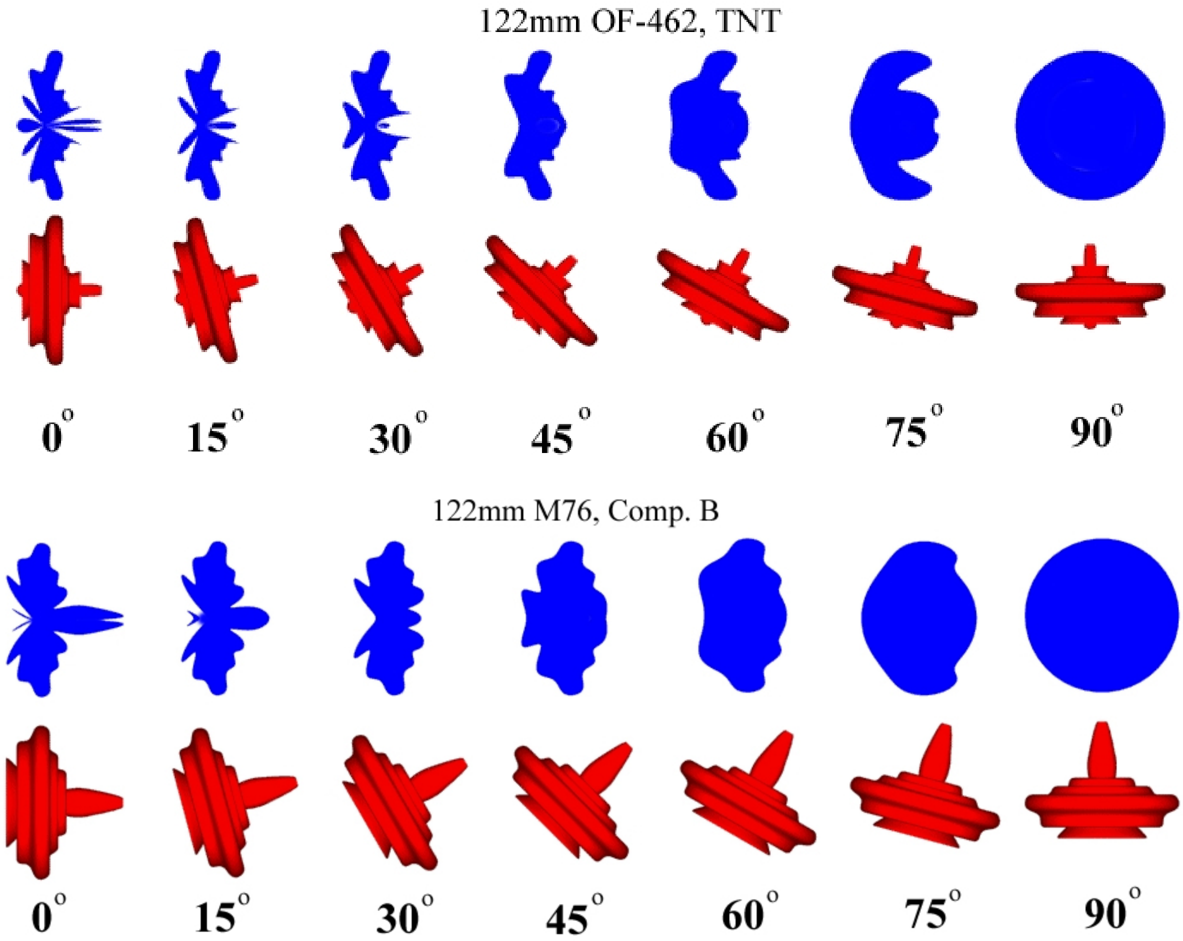

Fig 12. 2D lethal zones for different impact angles of artillery projectiles 122mm

It is clearly seen from fig. 13 and 14 how increase in impact angle leads to signifficant increase of total 2D lethal zone of all projectiles. Obviously, 2D lethal zone has miximum value for highest possible impact angle, hence 90° projectile impact angle is desirable parameter when considering terminal effectiveness of projectile. Projection of lethal zone for 90° projectile impact angle has always circular shape.

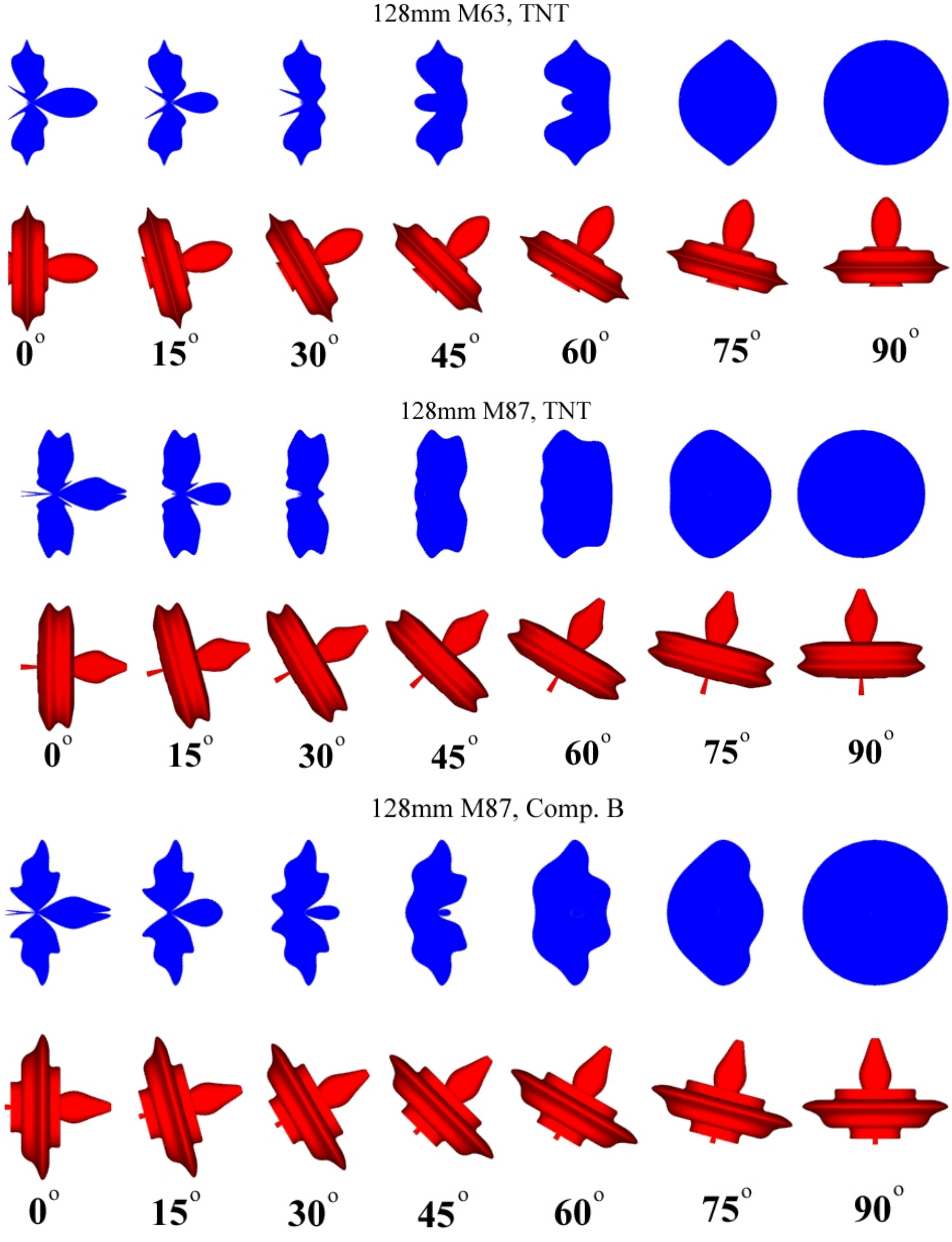

Fig 13. 2D lethal zones for different impact angles of tested rocket projectile warheads 128mm

Diagrams (fig. 13 and 14) show that for 0° impact angle of projectile, 2D lethal zone has very stohastic shape, and possesses many areas with posible no-hit scenario. With higher impact angles, however, lethal zone projection becomes more uniform, tending towards circle shape.

Figures 13 and 14 show diagrams which are great visual tools for preliminary and qualitative analysis of projectile terminal effectiveness. However, quantitative analysis is needed, in order to perform comparation of individual cases.

CAD software (AutoCAD© in our case) can easily calculate an area of these 2D lethal zones, since they represent surfaces made by intersecting 3D lethal zones with particular planes. Perimeter of lethal zones can also be determined, should we wish to do so. Procedure of determination of 2D lethal zone real area A_s is conducted in CAD software using Area© tool. Table 4 shows 2D lethal zone real area A_s, determined in AutoCAD©, for tested projectiles and rocket warheads with different impact angles.

Table 4. *2D lethal zone real area A_s for different impact angles of projectile*

Projectile	**2D Lethal zone real area A_s (m^2)**									
	0°	**10°**	**15°**	**20°**	**25°**	**30°**	**45°**	**60°**	**75°**	**90°**
122mm OF-462,TNT	398	387	375	384	402	426	471	684	831	1356
122mm M76,Comp.B	585	557	542	533	537	556	753	836	1104	1568
128mm M63,TNT	432	401	373	343	328	350	437	574	872	1304
128mm M87,TNT	525	484	461	430	422	440	564	768	994	1335
128mm M87,Comp.B	584	550	539	536	540	554	584	849	1094	1856

Very important data are given in table 4. Lethal zone real area A_s first decreases slighty up to average 25° impact angle, and then increases with further increase of impact angle.

Phenomennon of minimum lethal zone (for approximate 20° projectile impact angle) is somewhat new and surprising discovery. Since this decrease is present for all tested projectiles, conclusion may arise that for every projectile there is an impact angle that gives smallest lethal zone area, and it is not 0° impact angle, as one would think, rather around 20° impact angle. Further Arena testing are needed to confirm this interesting discovery.

Table 5. *2D lethal zone real area A_s presented in relative form (scaling data)*

Impact angle (°)	**122mm OF-462, TNT**	**122mm M76, Comp. B**	**128mm M63, TNT**	**128mm M87, TNT**	**128mm M87, Comp.B**
	A_s/A_0	**A_s/A_0**	**A_s/A_0**	**A_s/A_0**	**A_s/A_0**
0	1.000	1.000	1.000	1.000	1.000
10	0.973	0.952	0.928	0.921	0.942
15	0.941	0.927	0.862	0.878	0.924
20	0.965	0.910	0.792	0.818	0.918
25	1.009	0.917	0.758	0.803	0.925
30	1.069	0.951	0.809	0.838	0.949
45	1.183	1.286	1.010	1.074	1.001
60	1.719	1.429	1.327	1.463	1.454
75	2.089	1.887	2.017	1.894	1.874
90	3.407	2.679	3.017	2.543	3.181

When 2D lethal zone real area A_s is presented in its relative form, dividing lethal zone real area A_s with an initial value A_0 (lethal zone real area for 0° impact angle), analysis of relative increase of lethal zone for individual projectile can be made. Results are shown in table 5, for different impact angles.

It is interesting to see (table 5) relative increase of lethal zone area A_s for tested projectiles. Increase of A_s i.e. for artillery projectile 122mm OF-462, filled with TNT, is overwhelming 240%, comparing lethal zones for 0° and 90° impact angle.

In order to predict aproximative function of lethal zone area A_s vs projectile impact angle, MatLab Curve Fitting Tool©, an interactive environment for fitting curves to one-dimensional data, was used.

Regression analysis is done using several types of fit (exponential, fourrier, gaussian, polynomial, power, rational and weibull) and custom exponential function (fig. 14) of following form gave the best results (highest correlation coefficient):

$$A_s = A_0 \cdot e^{(b \cdot \alpha + c)} + d \tag{9}$$

where A_0 is lethal zone area for 0° projectile impact angle, b, c and d are constant determined from regression analysis, and α is projectile impact angle.

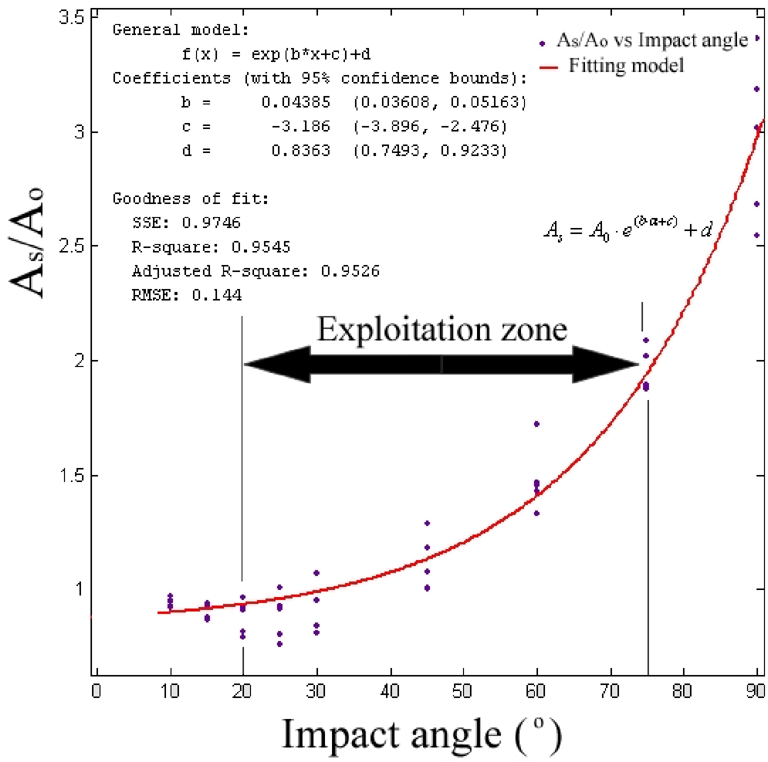

Fig 14. Aproximation functions of lethal zone area vs projectile impact angle for tested artillery projectiles and rocket projectile warheads

From the data in table 5 and fig. 14 it is obvious that larger impact angles of projectile lead to significant increase in lethal zone area.

However, one must consider exploitation conditions (fig. 14) for projectile when considering terminal effectiveness. From firing tables largest impact angle for artillery projectiles 122mm, fired from howitzer, is around 75°, and for rocket projectiles 128mm, fired from multiple rocket launcher, is around 60°. So analysis is only realistic when considering angles lower than maximum impact angles given in firing tables for individual projectile.

In fig. 15 and 16, diagrams of individual influence of projectile design and explosive type used on terminal effectiveness for tested rocket projectile warheads.

Diagram in fig. 15 describes influence of warhead design on terminal effectiveness. Dependance of area of lethal zone A_s vs projectile impact angle is shown for two rocket projectile warheads, 128mm M63 and 128mm M87, both filled with TNT. Hence, one can see that improved warhead design (model M87) exhibit better effectiveness (larger area of lethal zone) for all impact angles. Change in area of lethal zone for model M87 is very similar as one obtained for model M63. Greatest difference in lethal zone area is obtained for impact angle of 60°, as shown in fig. 15.

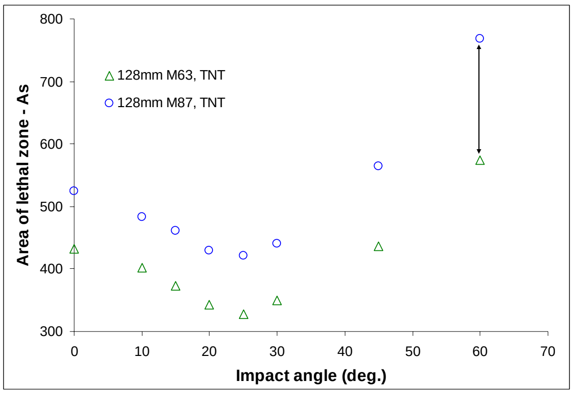

Fig 15. Influence of projectile design on terminal effectiveness (rocket projectile warheads)

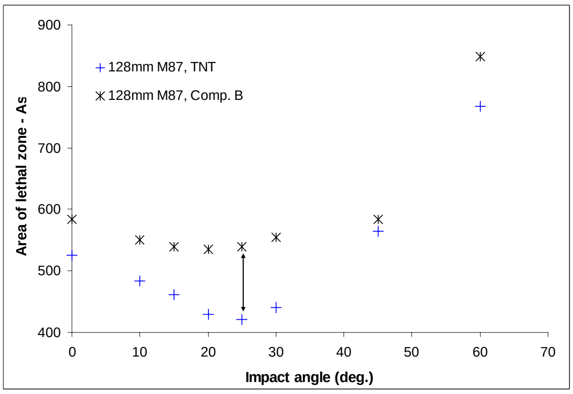

Fig 16. Influence of explosive type used projectile terminal effectiveness (rocket projectile warheads)

Influence of explosive type on terminal effectiveness for rocket warheads 128mm M87, one filed with TNT and other with comp. B, is shown in fig. 16. Greatest difference in lethal area is obtained for impact angles around 25°. It is obvious how more energetic explosive (comp. B) leads to increase of lethal area for all projectile impact angles. Also, smaller function gradient of lethal area vs impact angle is present for model M87 with comp. B, which means this model is less sensitive for lethal area changes with lower impact angles.

Diagrams in fig. 17 and 18 show influence of both projectile design and explosive type used on terminal effectiveness for tested artillery projectiles and rocket projectile warheads.

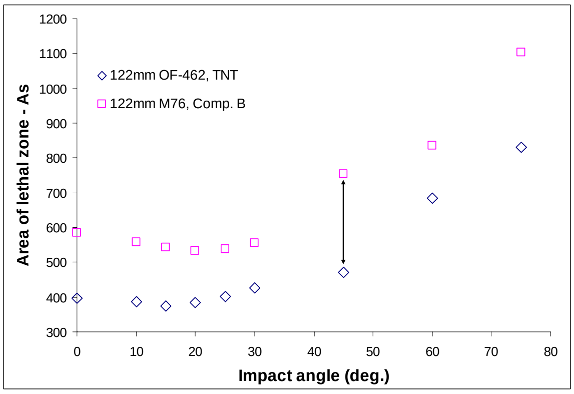

Fig 17. Influence of projectile design and explosive type on terminal effectiveness (artill. projectiles)

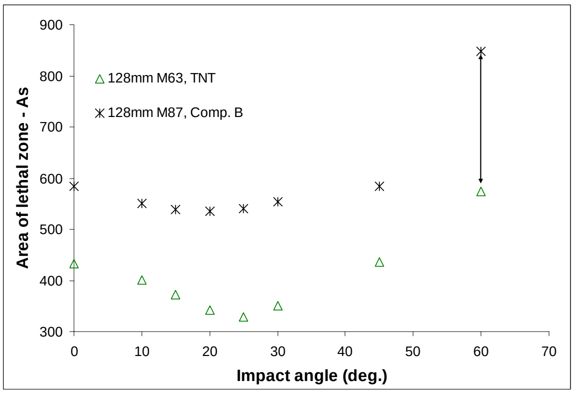

Fig 18. Influence of projectile design and explosive type on terminal effectiveness (rocket warheads)

Both diagrams (fig. 17 and 18) confirm high impact of both projectile design and explosive type used on overall terminal efectiveness of ammunition. This is more pronounced for rocket warheads 128mm M63 and 128mm M87 (fig. 18) where application of new (optimized) desig and use of comp. B instead of TNT leads to signifficant increase of lethal area for all impact angles, and greatest increase is noted for impact angle of 60°.

When considering influence of projectile design and explosive type on terminal effectiveness of artillery projectiles (fig. 17), one can see that general trend of lethal area increase for model 122mm OF-462 is followed by model 122mm M76, and in this case greatest increase in lethal areas of these projectiles is noted for impact angle of around 45°.

Data from table 4 can be interpreted differently. If the density of human targets σ is defined as in eight man infantry squad on line (infantry deployed in 10 x 50 meter area - density of soldiers 0,016 soldiers/m^2), then in table 6 results are given for expected number of casualties N_c, and taking into account exploitation characteristics of individual projectiles, hence data are given up to an impact angle of 75° for artillery projectiles, and up to 60° for rocket projectile warheads.

Values of N_c in table 6 are obtained when lethal zone real area A_s is multiplied by density of human targets σ. Thus, total number of incapacitated soldiers in the battlefield is obtained for different projectile impact angle, using CAD technique. If the tables 2 and 6 are compared, one can see that approach of determination of expected number of casualties using equation (1) and our approach using CAD technique gives results that are comparable, for given impact angle of projectiles.

Table 6. *Expected number of casualties N_c using CAD technique*

Projectile	**Expected number of casualties N_c**									
	0°	**10°**	**15°**	**20°**	**25°**	**30°**	**45°**	**60°**	**75°**	**90°**
122mm OF-462, TNT	6	6	6	6	6	7	8	11	13	-
122mm M76, Comp.B	9	9	9	9	9	9	12	13	18	-
128mm M63, TNT	7	6	6	5	5	6	7	9	-	-
128mm M87, TNT	8	8	7	7	7	7	9	12	-	-
128mm M87, Comp.B	9	9	9	9	9	9	9	14	-	-

Considering exploitation conditions for projectiles, it is obvious that highest number of expected number of casualties (18) is to be expected from artillery projectile 122mm M76, for maximum impact angle. Rocket projectile warhead 128mm M87, filled with comp. B, can incapacitate 14 soldiers, when impact angle is close to its maximum value (60°).

Obtained results and performed analysis show that expected number of casualties is interrelated with lethal zone area, and parameters such as projectile or warhead design and explosive type greatly affects expected number of casualties in the battlefield.

5. CONCLUSION

Prediction of expected number of casualties using modified US Vulnerability Model, and analysis of lethal zones dependance on projectile impact angle, was based on semicircular Arena tests for artillery (122mm) and rocket projectile warheads (128mm).

Analysis of projectile design and explosive type influence on terminal effectiveness, for different projectile impact angles, was made using CAD method.

Results show that increase in projectile impact angle leads to dramatical increase in lethal zone area.

Considering exploitation conditions for different projectile types, maximum increase of lethal zone area for artillery projectiles is around 2 times (75° impact angle), and maximum increase of lethal zone area for rocket warheads is around 1,5 times (60° impact angle).

For tested projectiles and warheads small decrease of lethal zone area was observed from 0° to around 25° impact angle. Further tests are needed to confirm this discovery.

Aproximative function that best fits lethal zone area vs. projectile impact angle for tested projectiles and warheads has following exponential form: $A_s = A_0 \cdot e^{(b \cdot \alpha + c)} + d$.

Expected numbers of casualties determined using CAD method show similar trend as results obtained with modified US Vulnerability model.

It was observed that best terminal effectiveness (highest expected number of casualties, largest lethal zone area) can be achieved by optimizing external and internal projectile surface (new, optimized design), applying new casing material, and using more energetic explosive material as main charge.

Recomendation for further work are pointed toward research of influence of different presented areas of target and detonation above ground on lethal zone, and unification of models in one universal software for prediction of lethal zone for high explosive projectiles.

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