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Design Philosophy of Variable Mass Preformed Fragmented Missile Warhead

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ABSTRACT

Fragment hit density and hit probability of the warhead are the critical parameters in the selection of a preformed fragment-type missile warhead against ground targets. Hence these factors are to be maximised. The parametric studies of these factors have lead to a new concept of variable mass preformed fragmented (VMPF) warhead. A philosophy was evolved for designing VMPF-type missile warheads. A computer software for generating the external configuration of the VMPF-type missile warhead was developed and basic algorithm is discussed in this paper. With this new design approach, the fragment hit density and hit probability were improved considerably in the shorter ranges, when compared to that of a uniform mass preformed fragmented warhead of conventional design.

NOMENCLATURE

A	target spread area, sqm
A_p	projected area of the fragment, sqm
A_s	area of equal area strip (EAS), sqm
B	maximum stress that can be maintained in the target material without rupturing under conditions of strike, kgf/mm
C_d	drag coefficient
D	assumed warhead diameter, mm
E	specific energy of explosive, foot-lbs/slug
G	Gurney constant, m/s
g	acceleration due to gratvity, m/s
H	height of burst from the ground, m
J	number of the warhead section designated
k	fragment shape factor
L	warhead length, mm
	mass of fragment, g
N	number of EASs
N_r	number of fragment rows
P	point of initiation
R	maximum range, m
R_1	outer radius of EAS, mm
R_2	inner radius of EAS, mm
R_m	mean radius of EAS, mm
r_1	top radius of warhead section, mm
r_2	bottom radius of warhead section, mm
r_m	mean radius of warhead section, mm
t	casing thickness, mm
V_d	dynamic fragment velocity, m/s
V_f	static fragment velocity, m/s
V_m	missile terminal velocity, m/s
V_n	velocity of detonation, m/s
V_0	fragment velocity along the normal, m/s
V_s	fragment striking velocity, m/s
V_l	fragment velocity at range x from the bursting point, m/s
V_2	fragment velocity at any point, m/s
W	width of warhead section, mm
X	distance of point of initiation from base, mm
x	fragment down range, m
Y	warhead section height from ground, m
Y_p	penetration in target plate, mm
ρ_a	air density, kg/cum
ρ_e	explosive density, g/cc
ρ_μ	density of casing material, g/cc
ρ_ϕ	fragment density, g/cc
ρ_τ	target material density, g/cc
α_s	fragment static direction, deg
α_D	fragment dynamic direction, deg
θ_s	fragment static spray angle, deg

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ϕ_1 angle subtended by the section normal with the warhead axis, deg

ϕ_2 angle subtended by line joining the initiation point to the section midpoint with the warhead axis, deg

1. INTRODUCTION

In modern warfare, the movement of wagon lines, vehicles, mobile radar installations, mobile communication centres etc can be effectively deterred by surface-to-surface or air-to-surface missiles equipped with preformed fragmented (PF)-type warheads. These targets will be spread over on a sufficiently large area. To neutralise such a large area, a large number of high velocity lethal fragments are used as a killing mechanism. Conventionally PF-type missile warheads are designed with uniform mass fragments which are laid on the casing containing high explosive. The spatial distribution studies of the fragments in such warheads revealed that in short ranges, the lethality of the fragments is high and tapers off with the distance. This variation in lethality with respect to range can be converted to almost uniform lethality over entire range by using a new concept of variable mass preformed fragment (VMPF) warhead. This paper discusses the evaluation of this concept and outlines the design of such warheads against ground targets.

2. CONCEPT OF VMPF MISSILE WARHEADS

PF-type missile warheads having uniform mass fragments will generate high velocity fragments with higher lethal capabilities at shorter ranges. Fragment distribution studies revealed that these higher lethal fragments at shorter ranges can be replaced by a large number of lower mass fragments with the desired striking energy, increasing the hit density and hit probability for a given mass of warhead and its effective range.

In the conventional design of warheads against the ground targets, generally the target spread area will be divided into certain number of equal area strips (EASs) and corresponding sections on the warhead will be designated to neutralise each EAS on the ground[1]. In most of the designs with uniform mass fragments, for having the continuity in the shape of the warhead, higher charge-to-metal mass ratios (*c/m*) will be imposed on the warhead sections intended to neutralise the shorter range EASs while maintaining the optimum *c/m* ratios for other sections intended for longer range. Hence the fragments will have higher lethal capabilities than required in the sections intended for shorter ranges. As pointed earlier, these higher lethal fragments can be replaced by a large number of lower mass fragments bringing down the energy of the fragments to the desired level. This will lead to increase in the fragment numbers in those sections and hence increase in the hit density and hit probability in the shorter ranges. Thus for each EAS, the fragment size required will be different. Hence, theoretically in the VMPF warhead design, there can be large number of different mass fragments intended for different lethal ranges in the target spread area.

3. DESIGN PHILOSOPHY

Five steps which are identified for designing a VMPF warheads are explained in the following sections.

3.1 Selection of Explosive

The warhead designer has to select an explosive from various options available based on its characteristics like velocity of detonation, blast parameters, processibility, and role of the warhead, etc.

3.2 Selection of Fragment Material and Shape

The size of these fragments should be minimum so as to accommodate larger number of fragments in the warhead to increase the hit density and hit probability of the target. Thus the density of the fragment material chosen should be high. The brittleness of the material should be low so as to withstand the impact force on the target.

Factors to be considered in the selection of the shape of the fragment are: (i) the fragments chosen should have sufficient energy at the terminal end to cause desired damage to the target; (ii) the shape and roughness factors, and drag characteristics shall be low, so as to carry the fragment to a longer range; and (iii) the type of the target to be damaged because the selection of the shape of the fragment depends to a greater extent on this.

Conventionally cubical, spherical and right cylindrical fragments are being used in the PF-type missile warheads because of their known drag characteristics.

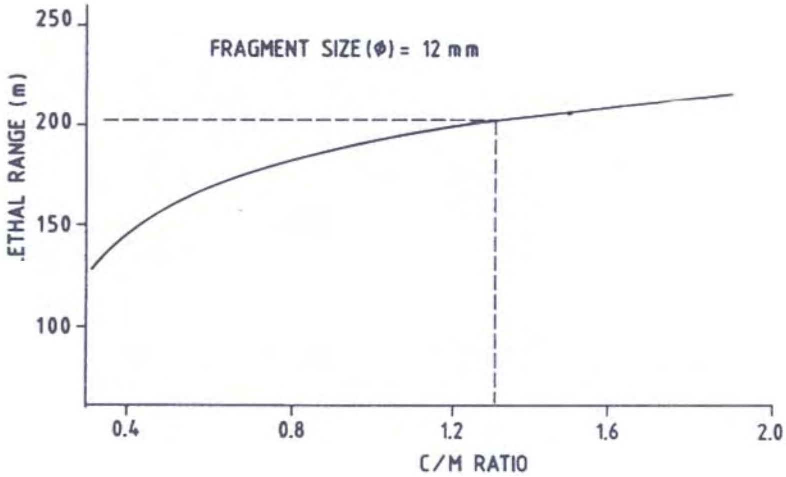

Figure 1. *c/m* **ratio vs lethal range.**

3.3 Selection of Maximum Fragment Size

The lethal range of the fragment increases with *c/m* ratio as shown in Fig.1. However, it can be observed that the gain in lethal range is marginal after a certain c/m ratio. Hence this *c/m* ratio and the corresponding lethal range are considered for the selection of maximum fragment size. The maximum range in the target spread area is determined from the following relation.

$$\text{Maximum range } [R] = (A/\pi)^{0.5} \quad (1)$$

3.4 Selection of Other Fragment Sizes

The designer in principle can have all the fragment sizes upto the maximum size calculated above in the VMPF warhead. But due to fragment fabrication and laying limitations, it is suggested that the designer should choose only three or four sizes of fragments for the warhead. In this regard, the following two approaches are suggested.

3.4.1 Equal Area Approach

In this approach, the target area is divided into three or four EASs and corresponding radii are determined. For each radius a fragment size is chosen while maintaining the *c/m* ratio corresponding to the maximum fragment size selected earlier.

3.4.2 Equal Range Approach

In this, the target range is divided into three or four equal segments and the fragment sizes are selected for each range segment in the same way as in the case of equal area approach.

3.5 Design of External Configuration

The basic design steps for determining the warhead configuration are enumerated below and the computer flow chart is shown in Fig.2. The basic inputs for the design alogrithm are : point of initiation, P (base, nose and any point on the warhead axis); explosive characteristics G, ρ_e and V_n; warhead characteristics t and ρ_m; fragment characteristics like fragment shape, size, optimum c/m, lethal range for various fragments selected, ρ_f and N_r; target damage criteria; warhead orientation (normal to the ground); and other parameters like H, A, D, L, X and V_m.

Step 1: Compute maximum lethal range, R, from target spread area, A, using Eqn (1).

Step 2: The area, A, into N number of EAS. Each EAS has to be neutralised by suitable fragments of one of the N sections of the warhead when detonated at height, H. Area of EAS, A_s is given by

$$A_s = A/N \quad (2)$$

Step 3: Compute width, W, of each warhead section when L is the length of warhead.

$$W = L/N \quad (3)$$

Step 4: Calculate inner radius, R_2 and mean radius, R_m, of the first or outermost EAS to be covered by the first or topmost section of the warhead when outer radius of the said EAS, R_1, is equal to R

$$R_2 = (R^2 - (R^2/N)^{0.5}$$

$$\text{and } R_m = 0.5(R + R_2) \quad (4)$$

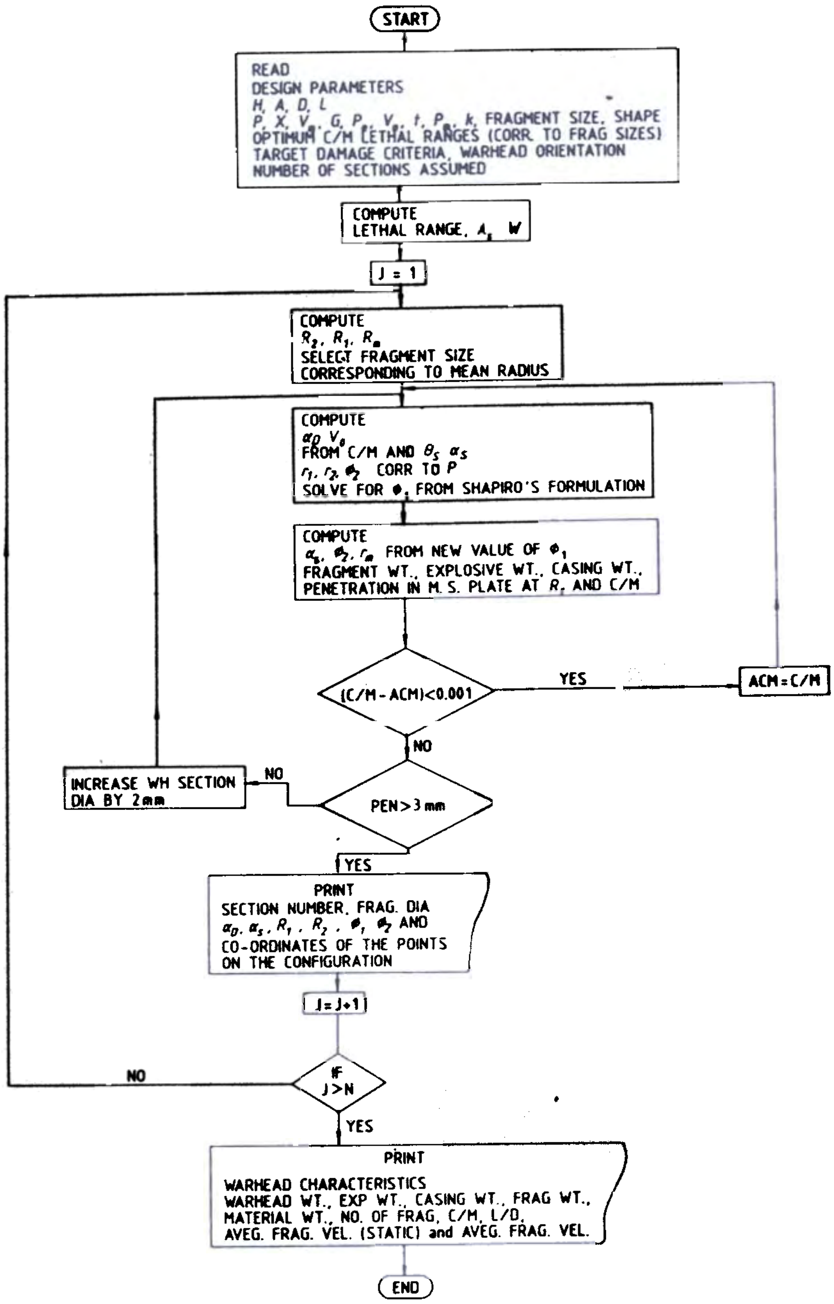

Figure 2. System flow chart of warhead configuration code.

Step 5: Select the fragment size depending on R_m and target damage criteria.

Step 6: Compute fragment dynamic direction, (a_D), with reference to warhead axis (Fig. 3)

$$a_D = -\tan^{-1}(R_m / Y) \tag{5}$$

wherein Y is determined from

$$Y = H + L - (J - 0.5)\ W \tag{6}$$

Step 7: Evaluate the static fragment velocity, V_f, assuming *c/m* of the warhead section as that of the maximum fragment size selected for achieving specific penetration by the fragments at desired radial range and the fragment static spray angle of the section, θ_s

(say 2 degrees). The fragment velocity[2], V_0 , along the normal to the section is computed from the following formulation.

$$V_0 = [2E(c/m)/(1+0.5(c/m))]^{0.5} \tag{7}$$

then

$$V_f = V_0 \cos \theta_s$$

Step 8: Compute fragment static direction, a_s, with respect to warhead axis for the same section.

$$a_s = a_D - \psi \tag{8}$$

where ψ is computed applying the sine rule

$$\psi = \sin^{-}\ [(V_m / V_f)\ \ \sin a_D]$$

Step 9: Compute top radius, bottom radius and mean radius of the warhead section assuming warhead generating diameter D; the angle subtended by the section normal with warhead axis, ϕ_1 (say 85 degrees); and $r_1 = D/2$ for the first section (J=1). From geometry

$$r_2 = r_1 + W.\ \tan(90-\phi_1) \tag{9}$$

and

$$r_m = 0.5\ (r_1 + r_2) \tag{10}$$

Step 10: Compute angle ϕ_2 , the angle subtended by line joining the initiation point to the section midpoint with respect to warhead axis. From geometry, depending upon the point of initiation P lies above or below the section under consideration we have for point P below the section (Fig. 3(a))

$$\phi_2 = \tan(R_m / b_1)$$

For point P above the section (Fig. 3(b))

$$\phi_2 = 180 - \tan\ (R_m/b_2)$$

where in

$$b_1 = X - (J-0.5)W \quad \text{and}$$

$$b_2 = (J-0.5)W - X$$

Step 11: Compute fragment static spray angle from Shapiro's formulation[2].

$$\theta_s = \tan^{-1}(V_0 \cdot \cos(90 + \phi_2 - \phi_1) / 2V_n)$$
$$= \tan^{-1}(K \cdot \sin(\phi_1 - \phi_2))$$

where $K = V_0 / 2V_n$

Step 12: Calculate θ_s from geometry which depends on the position of initiation point P either below or above the warhead section under consideration and equate

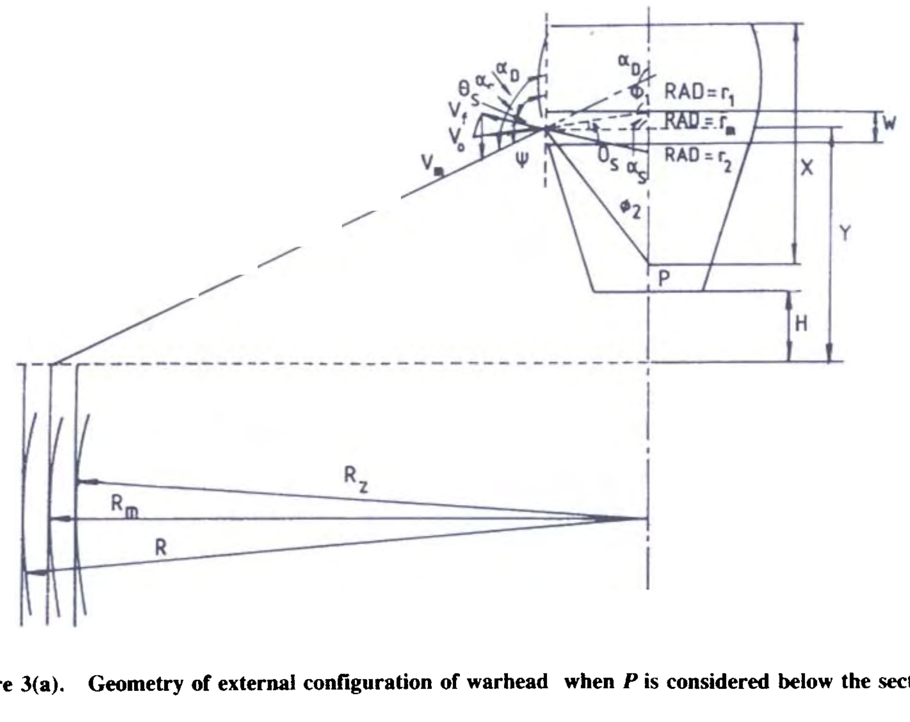

Figure 3(a). Geometry of external configuration of warhead when *P* is considered below the section.

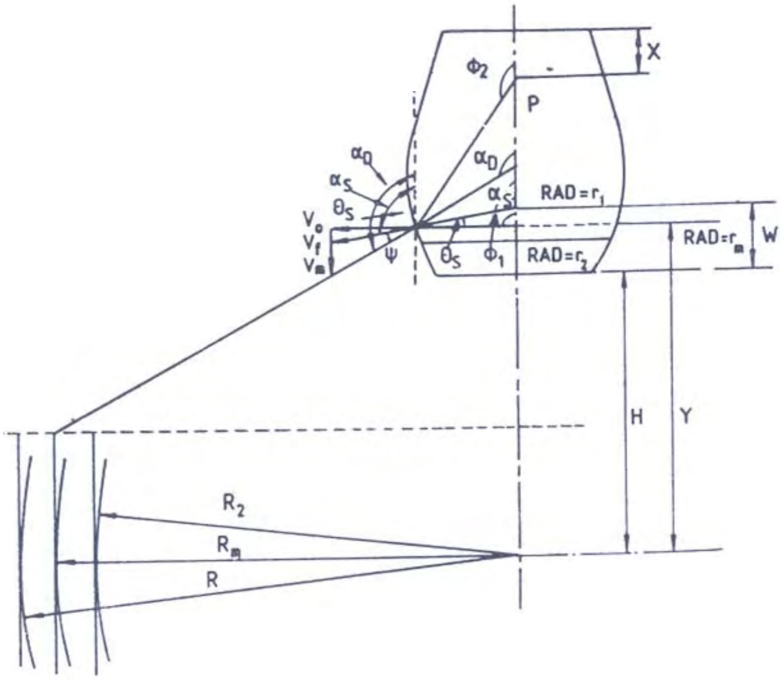

Figure 3(b). Geometry of external configuration of warhead when *P* is considered above the section.

with θ_s computed from Shapiro's formula to solve for From geometry we have

$$\theta_s = \alpha_s - \phi_1 \quad \text{for } P \text{ above the section; and} \tag{15}$$

$$\theta_s = \phi_1 - \alpha_s \quad \text{for } P \text{ below the section} \tag{16}$$

Let $P = \tan\theta_s$ and $Q = \text{K}.\sin(\phi_2 - \phi_1)$ which leads to the condition

This leads to the condition

$$P + Q = 0 \tag{17}$$

If $P + Q \neq 0$, depending on the value of $P + Q$ increase or decrease the assumed ϕ_1 value by a small angle(δ)

Step 13: With the new value of ϕ_1, compute r_m and ϕ_2 as in step 9 through 12 till $P + Q$ value becomes zero.

Step 14: Compute explosive weight, fragment weight, casing weight and determine *c/m*.

If the deviation between the calculated *c/m* and the assumed *c/m* is small, then proceed to step 7 substituting assumed *c/m* by calculated c/m for the same section, otherwise proceed to step 15.

Step 15: Compute the dynamic fragment velocity[3]

$$V_d = [\,V_f^2 + V_m^2 - 2.V_f \,.\, V_m \cos(\alpha_s)\,]^{0.5} \tag{18}$$

Step 16: Calculate the striking velocity[2] V_s of the fragment in the section under consideration at the outer radius of the corresponding EAS using iterative method in velocity decay formulation.

$$V_2 = V_1 \exp\,(-C_d \,.\, \rho_a \,.\, A_p \,.\, x/m) \tag{19}$$

Step 17: Calculate the penetration on target plate[2] made by the fragment in the section under consideration with velocity V_s as obtained in step 16 using Poncelet formulation given below.

$$Y_p = k \,.\, m^{1/3} \,.\, \rho_f^{2/3} \,.\, \ln(1 + \rho_t\, V_s^2 / B \,.\, g) / 2.\rho_t \tag{20}$$

For the first section of the warhead it has to be checked (i) if target penetration Y_p is matching the equivalent damage criteria of target in terms of penetration then proceed to step 18; and (ii) if target penetration Y_p is more or less than required, reduce or increase the warhead generating diameter *D* and repeat all the steps from 9 to 17.

Step 18: Compile all the section parameters and fragment parameters for the section and go to the next section of the warhead by putting $J = J + 1$ while updating the section parameters.

Step 19: Repeat all the steps from (1) to (6) till $J = N$.

Step 20: Compute explosive weight, fragment weight and casing weight.

After obtaining the parameters of various sections on the warhead, these sections will be stacked together and treated as single warhead. Thus, obtained shape is the external configuration of the warhead.

3.6 Acceptance Criteria

The following aspects have to be taken into account before finalising the external configuration of the warhead.

(a) The warhead length to diameter ratio should lie in boundary values from 1.25 to 2.5. In general, length to the diameter ratios less than 1.25 will seriously reduce the average fragment velocity, whereas the ratios higher than 2.5 do not yield any significant improvement in the fragment velocities[3].

(b) For filling of the explosive, there can be a constraint on the warhead nose or base diameter depending on the processibility of the explosive.

(c) By choosing different combinations of fragment sizes, the number of fragments in the warhead should be maximised.

4. RESULTS AND ANALYSIS

A hypothetical warhead of 250 kg weight with a missile mission of 50 km land range has been considered for the analysis of design features. It was assumed that this warhead has to neutralise the targets like soft skinned vehicles, personnel, mobile radar installations etc. in a circular area of 150 m radius with 0.1 per cent of circular error of probability (CEP) when it is detonated at 25 m height with the terminal missile velocity of 300 m/s.

For analysis purpose spherical fragments made of mild steel were chosen as kill mechanism. An explosive, with Gurney constant of 2309.52 m/s, velocity of detonation of 7780 m/s and density of 1.72 g/cc is considered for this hypothetical warhead. A penetration of 3 mm in mild steel plate is assumed as an effective kill or damage criteria for the specified targets.

For maximum lethal range of 200 m (including CEP of 50 m), 12 mm mild steel (MS) spherical fragment is chosen from *c/m* ratio consideration as shown in Fig. 1. The thickness of warhead casing on which two rows of preformed fragments are laid is assumed as 2 mm of MS, keeping in view of the stresses developed in the structure due to transportation and missile flight.

Thus in the uniform mass preformed fragmented (UMPF) warhead design, the 12 mm diameter fragment is considered to achieve the lethal range of 200 m. A design of such a warhead was generated through the computer code discussed above and presented in Fig. 4(a) and design details are given in Table 1.

For designing the VMPF warhead, the equal range approach and equal area approach discussed earlier are considered for the analysis purpose. In equal area approach, the lethal range 200 m is first divided into three equal segments and the corresponding radii are calculated as 115 m, 163 m and 200 m. The slant ranges for the height of burst of 25 m, corresponding to the above radii, were determined as 118 m, 163 m, and 202 m. 8 mm, 10 mm and 12 mm diameter fragments were selected corresponding to the above calculated slant ranges. Using these fragments, a VMPF warhead was designed and presented in Fig. 4(b) and design details are given in Table 1.

In equal range approach, the lethal range 200 m is first divided into three equal segments and the corresponding radii are calculated as 66 m, 132 m and 200 m. The slant ranges for the height of burst of 25 m, corresponding to the above radii, were determined as 71 m, 134 m, and 202 m. Corresponding to these slant ranges 6 mm, 9 mm and 12 mm diameter fragments were selected. Using these fragments, a VMPF warhead was designed and presented in Fig. 4(c) and design details are given in Table 1.

The performance analysis of these designs was carried out. Spatial distribution of the fragments and the hit density at various ranges were determined through computer analysis and presented in the Fig. 5. Number of hits on a soft skinned vehicle at various ranges were computed and presented in Table 2. The lethality in terms of penetration in MS plates at various ranges is calculated and presented in graphical form in Fig. 6.

From Table 1, it can be obsereved in the VMPF design the number of fragments are approximately 54 per cent more than that of in the UMPF design. From Fig. 5, it is evident that the number of useful

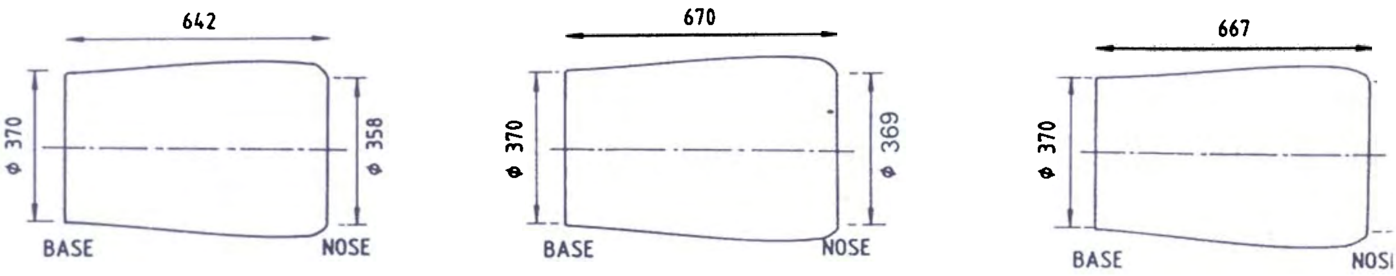

Figure 4. Design sketches of external profiles of warhead configuration; (a) UMPF, (b) VMPF/area, and (c) VMPF/range.

Table 1 Design parameters of hypothetical missile warheads

[(1) Height of burst : 25 m;(2) lethal range : 200 m; (3) missile terminal velocity : 300 m/s; (4) warhead mass : 250 kg and (5) point of initiation : base]

Design parameter	Warhead configuration		
	UMPF	VMPF/area	VMPF/range
Base dia (mm)	370	370	370
Nose dia (mm)	368	369	368
Maximum dia (mm)	438	442	442
Fragment size (mm)	12	12/10/8	12/9/6
Section length (mm)	642	313/178/179	400/222/45
Fragment Nos.	12404	5730/5220/8243	7478/8183/3482
Total No. of fragments	12404	19192	19143
Length (mm)	642	670	667
L/D ratio	1.46	1.52	1.51
CG from base (mm)	335	341	339
Average c/m	1.42	1.63	1.63

fragments in VMPF configurations is 50 per cent more compared to UMPF configuration. From Fig. 6, it is seen the lethality in UMPF design is much higher than desired (3 mm penetration in MS) whereas in VMPF designs the lethality is brought nearer the desired level. Further, in selecting the VMPF design the fragment energy losses due to higher lethality have been considerably reduced in comparison with UMPF design. By increasing the number of types of different size fragments in the design, the lethality can further be brought nearer to the desired level. From Table 2, it is clear that the hit density (number of hits per target) in shorter ranges is much higher in VMPF design than in UMPF design. In longer ranges too, considerable improvement is observed in the hit density. It means, in general, the hit probability of the target at various ranges is considerably higher in the case of VMPF design when compared to conventional UMPF design.

5. CONCLUSION

The VMPF-type missile warheads are more effective in terms of hit density and hit probability of the target compared to the conventionally-designed UMPF warheads for a given weight and lethal range, especially for longer lethal ranges. The fragment energy losses due to higher lethality in UMPF design could be considerably minimised by opting VMPF design. However in the design of warheads for aerial targets the advantages of VMPF design are less significant.

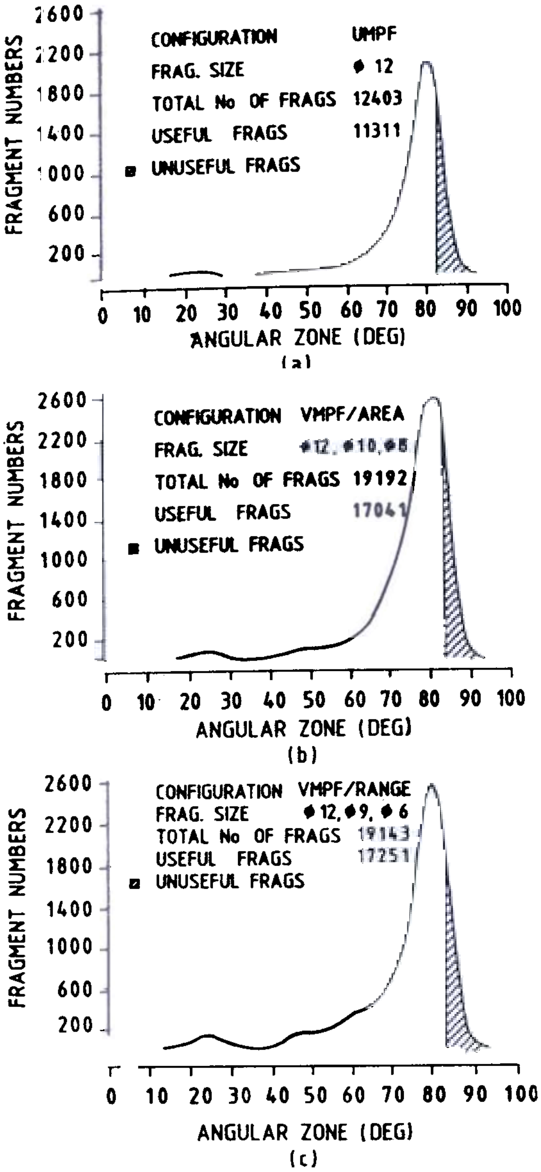

Figure 5. Fragment spatial distribution profiles.

Table 2. Fragment hit density over target

Target area : 15 sqm; height of burst : 25 m, and missile terminal velocity : 300 m/s

Land range (m)	Fragment hit density (numbers/target)		
	Warhead configuration		
	UMPF	VMPF/area	VMPF/range
0–10	4	9	16
10–20	4	10	14
20–30	2	5	8
30–40	3	6	11
40–50	3	7	11
50–60	4	11	10
60–70	6	13	11
70–80	6	14	11
80–90	7	14	12
90–100	8	15	12
100–110	9	14	13
110–120	9	14	13
120–130	8	10	10
130–140	8	10	10
140–150	5	6	5
150–160		6	
160–170		6	
170–180	5	6	
180–190	2	2	
190–200	2	2	
Mean fragment hit density	5.2	9.0	

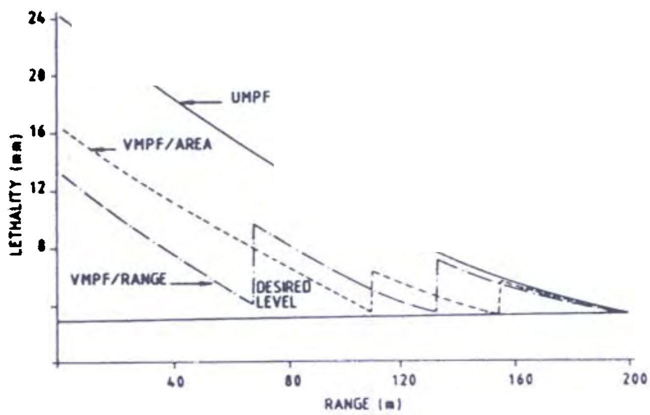

Figure 6. Range vs lethality

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