RELATIVE PERFORMANCE OF ANTI-AIR MISSILE WARHEADS[1]

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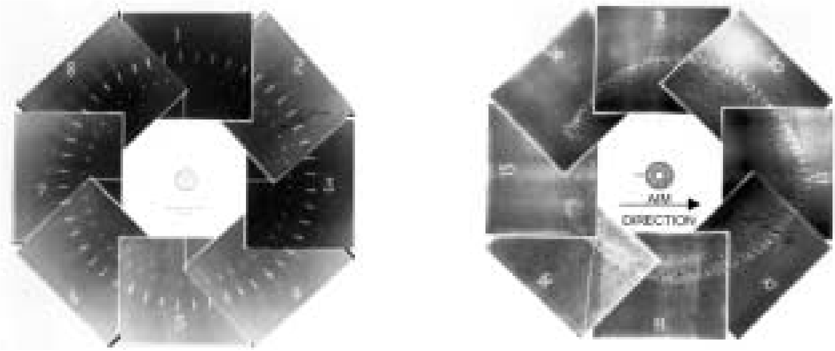
This paper quantifies the relative performance of five types of cylindrical anti-air missile warheads. The warhead performance is quantified in terms of the amount of fragment mass that can be projected at the target as a function of initial velocity on a fixed mass (explosive plus fragment case mass) basis. Performance of the directional warheads is discussed in terms of azimulthal Target Detection Device (TDD) (fuze) requirements.

WARHEAD TYPES AND THEIR RELATIVE PERFORMANCE

Baseline Warhead

The most common type of anti-air missile warhead is a circular cylinder consisting of a central explosive core surrounded by a metal fragmenting outer layer. It is initiated on axis to produce a symmetric fragment pattern about the missile axis, Figure 1(a). Performance can be estimated using the Gurney formula for cylindrical warheads[2], $V = E \cdot (M/C+1/2\,)^{-1/2}$ where V, E, M, and C are the initial fragment velocity, the explosive energy, fragment casing mass, and the explosive mass respectively.



1(a). Axially initiated cylinder 1(b). AI cylinder

Figure 1. Axial view radiographs of fragment pattern.

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Asymmetrically Initiated (AI) Warheads

An AI warhead initiates on a line or lines at the explosive/case interface opposite the direction of aim. This produces a fragment pattern with a 20 to 30% higher velocity in the direction of aim compared to the same warhead initiated along the central axis (Figure 1(b)). The aiming of such a warhead can be accomplished by initiation of 1, 2, or 3 lines of initiators from a warhead containing 4 to 16 equally spaced lines of initiators. An azimulthal sensing TDD would be used to signal the choice of initiator line(s) to direct the enhanced velocity fragments toward the target.

Fragment velocities can again be estimated from the Gurney formula with an additional term to take into account the enhanced velocity in the aim direction, $V=A\bullet E\bullet (M/C+1/2)^{-1/2}$. A is a constant that we will assume as equal to 1.25, thus assuming a 25% velocity enhancement in the aim direction. The enhanced performance through asymmetric initiation is measured by the amount of fragment mass that can be projected at the target at a desired velocity compared to our Baseline.* This relationship is shown in Figure 2. This "Gain" is found by determining the M/C ratio, which gives the desired fragment velocity for each of the two type warheads. For a fixed weight system, the fraction of mass that can be devoted to the case is, M=1/ (C/M+1). The ratio of the "Ms" is the "Gain". It can be seen that the advantage of employing the AI warhead is when the required fragment velocity is high. This occurs when miss distances are large, closing velocities are high and/or when the target is short.

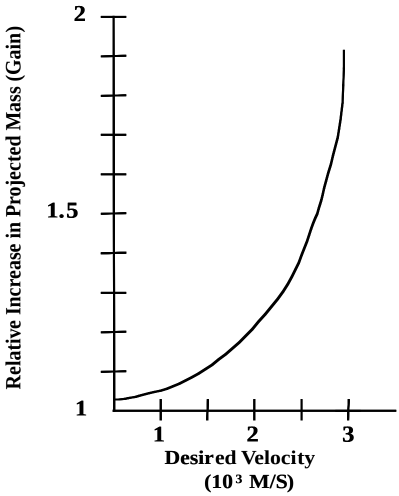

Figure 2. Performance enhancement for AI.

TDD accuracy can be fairly lax for AI warheads. In Figure 1(b), we see that high velocity is maintained over a wide beam width, i.e. 60° or so. If the TDD can sense the relative target position at intercept to within ± 30° of the true position, near maximum fragment striking velocities will occur.

N-Sided Cylinders

There has been discussion throughout the years on using multisided cylindrical warheads with selectable initiation sites to enhance warhead performance. Performance may be enhanced over that of a circular cylindrical warhead due to the possibility of focusing the mass of each face (side). *This analysis will consider the warhead fixed in the missile (rotatable warheads are considered latter).* The warhead has N number of aim directions

* Plotting mass as a function of velocity allows comparison for any damage function in the form of $M\bullet V^{x}$, where X is any value.

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equal to the number of sides. Selection of initiation of the explosive is such that the ejection direction of fragments from a face can be altered so that at least part of the fragment beam is always directed at the target. This allows beam focusing while maintaining 360° coverage. The features of this concept are illustrated in Figure 3.

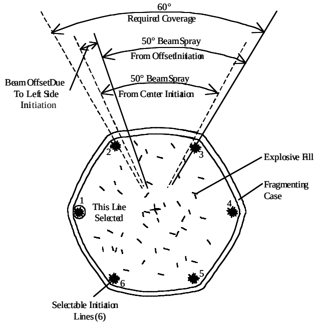

Figure 3. Six-sided cylinder with 6–50° wide beams. Selective initiation used to provide 360° coverage.

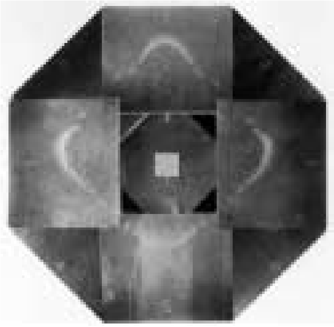

Figure 4. Axial radiograph showing pattern from a 4-sided asymmetrically initiated cylinder.

The measure of merit will be the amount of fragment mass that can be projected at the target at a given velocity compared to that of our Baseline. The analysis approach will be: (1) determine change in ejection angle possible (beam agility); (2) determine beam spray requirements for each face so that 360° coverage is obtained; and (3) estimate enhancement possible as a function of number of sides and required TDD accuracy.

Beam Agility

Altering the explosive ignition point can alter the fragment ejection direction. For example, changing the point of ignition from the center of a cylinder to a side alters the ejection angle of the fragments as shown experimentally in Figure 4. Maximum alteration occurs when the detonation wave strikes the fragmenting case at right angles with respect to the wave direction (bottom side of cylinder in Figure 4). Note the wide beam spray produced. However, velocities from this side are 25% lower compared to those an axially initiated cylinder. For typical fragment and detonation velocities, angle changes of 7 or 8° are possible. For this analysis it was assumed that a 5° change could occur without a reduction in velocity. This is an optimistic assumption, which probably leads to optimistic results. It assumes that a 5° change in angle is possible by initiation on a line at the case/explosive interface 90° from the face being considered (left/right faces of the cylinder in Figure 4 (note how the beam is shifted upward).

Beam Spray Requirements to Provide 360° Coverage

The warhead is fixed in the missile so each face of the warhead must be able to cover at least 360° / N; where N is the number of faces. Since we assume ± 5° beam agility, the inherent beam spray for each face can be 10° less than 360° / N. When the number of faces reaches 36, a zero degree wide beam could theoretically produce 360° coverage. This coverage is possible by providing precise aim control by sequencing two or more lines of initiation.

Performance Predictions

Since all multi-faced cylinders are nearly circular in cross section and initiation occurs approximately a warhead radius away from the chosen face, they produce fragment velocities approximately equal to that of the Baseline at equal C/M. The performance of these warheads is shown in Figure 5. Gain is simply the inverse of the amount of beam shrinkage, or 1/[1-N/36]. Performance increases with number of faces reaching an infinite value for a 36 faced cylinder (Figure 5).

Minimum Beam Spray Requirements

An azimulthal sensing TDD must be used in conjunction with a multi-faced warhead. Azimulthal TDDs are not precise. They typically employ some scheme to interpolate between two or more sensing beams to define angular positions. TDDs also estimate distance to the target. This measurement along with target/interceptor velocity estimates and some encounter geometry information is used to produce a "time delay" which controls when to burst the warhead. This time delay must also include an estimate of time of flight of the fragments. The uncertainties inherent in all these processes require warhead compensation by producing a wider fragment beam spray. Reference 3 calculates the warhead fragment beam spray required to produce hits on a target as a function of TDD accuracy. Table 1 shows some of these calculations.

Figure 5 plots the probability that the fragment beam spray will intersect the target (P_H) as a function of fuze accuracy and the number of sides of the cylinders†. As the fuzing error becomes large, the probability that the beam strikes the target becomes equal to that for a non-azimulthal sensing fuze, i.e. 1-N/36. Figure 6 plots Gain multiplied by P_H

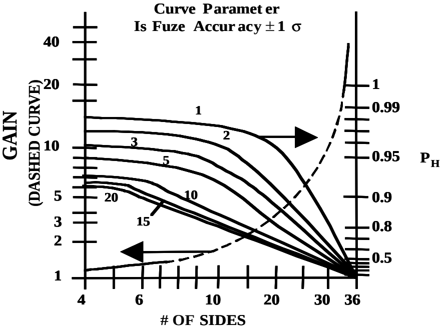

Figure 5. Performance and P_H for multi-sided cylinders.

Table 1. Probability (%) that the beam will intersect the target

TARGET RESOLUTION ± 1 SIGMA	WARHEAD AZIMUTH BEAM WIDTH (DEGREES)								
	1	5	10	20	30	40	50	70	90
PERFECT	100								→
1°	38	99	100						→
2°	20	79	99	100					→
3°	13	59	90	100					→
5°	8	38	68	95	100				→
10°	4	20	38	68	87	95	99	100	→
15°	3	13	26	49	68	82	90	98	100
20°	2	10	20	38	45	68	79	92	97

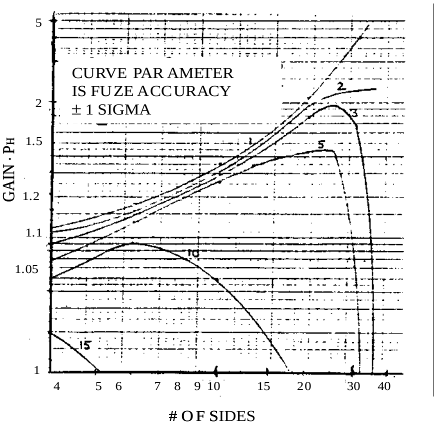

Figure 6. Figure of merit for multi-sided cylinders.

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† PH differs somewhat from those given in Table1 because adjacent beams can come into play

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as a function of fuze accuracy. This results in a figure of merit for the combined effect of fragment focusing and the probability that the focused beam strikes the target. Multi-sided cylinders show significant Gain if very accurate fuzing is available (Figure 6). The product of P_H• Gain is greatest for cylinders with 20 to 30 sides using very accurate fuzes. It should be stated that even though this figure of merit is always greater than 1, it is a poor tradeoff to increase fragment density on target for some encounters at the expense of missing the target entirely in others. This effect becomes exacerbated as the number of sides increases. For example when N=36, the calculated Gain approaches infinity but the P_H is near zero unless the fuzing is perfect. Narrow beams produced by the many sided cylinders are probably impractical for other reasons. Even if the TDD was perfect in placing this beam on target, a certain minimum area of the target surface must be covered to assure a hit on a vulnerable component. *Due to these considerations, fixed-aim concepts based on initiation controlled beam agility concept appear to be impractical.*

Deformable Warheads

The deformable warhead consists of an explosively filled fragmenting cylinder surrounded by a layer of explosives divided radially and buffered so that the resulting strips can be initiated independently (Figure 7). In operation the TDD senses the desired direction of aim, a number of the outer explosive strips, deforming charges, are initiated (3 out of 12 shown in Figure 7). Detonation of the strips causes deformation of the fragmenting case so that at some later time a large portion of the case is flattened at which time the main charge is initiated by a line initiator on the side opposite case deformation. The flattened portion of the case is projected at the target (typically 30% of the circumference) at high velocity. As a first order approximation, fragments are ejected in a direction normal to their outer surface; the fragments originating from the flattened portion of the case can be projected in a tight beam at the target. The beam tightness can be controlled and is optimized to the azimulthal resolution of the TDD.

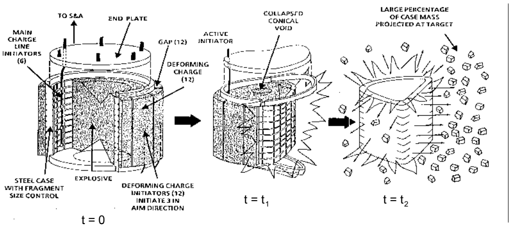

Figure 7. Sequential operations of a deformable warhead.

Figure 8 illustrates the fragment pattern produced from a deformable warhead. Fragment velocity can be predicted from the Gurney formula using a value of 1.15 for A, assuming asymmetrical initiation. The value for the explosive energy, E, however, must be reduced by approximately 15% to take into account the requirement to use the shock insensitive explosive, Navy designated PBXN-

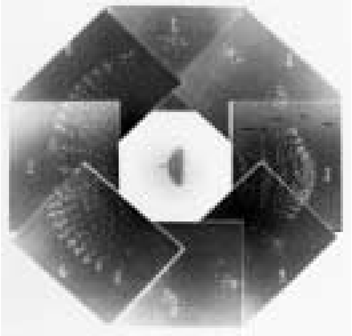

Figure 8. Axial view radiograph of a performance warhead fragmentation pattern.

128. This explosive contains more inert binder than is normally used for air target application accounting for the decrease in energy. For comparison purposes, the Deformable warhead incurs a 25% weight penalty due to the additional weight of the deforming charges. Because of the offsetting nature of asymmetric initiation and lower energy explosive, the relationship of velocity with M/C is the same as that of the Baseline. Therefore Gain is calculated as 108° (the sector of the Baseline which contains 30% of the case mass) divided by the desired azimulthal beam spray multiplied by 0.75 to account for parasitic weight. Representative Gains are 8.1, 4.05, 2.7, 1.8, and 1.35 for beam widths of 10, 20, 30, 45, and 60° respectively. Table 1 can be consulted to determine fuze accuracy's compatible with these beam widths.

Fixed-Aim Warheads

Studies were conducted to show the performance potential of Fixed-aim warheads that require missile roll or some internal mechanism to aim the warhead.[4] One example is the square cylindrical warhead shown in Figure 4. Some mechanism is required to roll the warhead up to 45°. Test results indicate that maximum velocity in the aim direction can be predicted using the same equation for velocity used for AI warheads. As shown in Figure 4, fragment velocity decreases approximately 25% towards the edges of each face of the cylinder. For comparison purposes it was assumed that the sides of the cylinder could be tapered uniformly to the center of each side so a uniform velocity could be obtained. The required taper results in the edge being 33% the thickness of the center and results in a fragment with 67% of the original mass. The equation for velocity becomes: $V=1.25 \bullet E \bullet [(1/0.67) \bullet M/C+1/2]^{-1/2}$. The relative performance of the square warhead is shown by the solid curves in Figure 9. It was assumed that the sides of cylinder could have a curvature to provide the beam spray desired. The gain in performance with the narrower beam sprays is probably not practical because of precise aiming and fuzing requirements, the 2 to 3+ gains at 30 and 45° are probably useable. At a 90° beam spray the performance enhancement is minimal and an AI warhead would be a better choice.

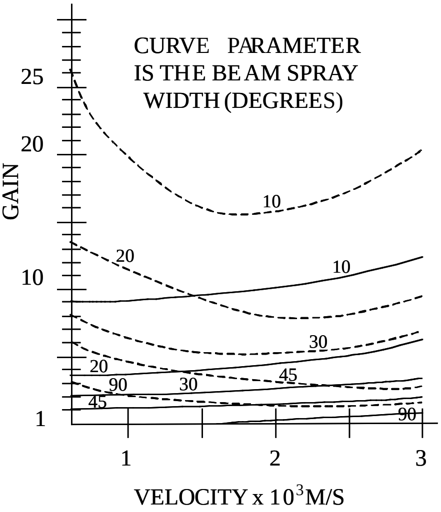

Figure 9. Gain for fixed-aim warheads.

Performance of single sided warheads has also been analyzed.[5,6] The warhead was to fit a circular cylindrical contour of a missile body. Parameters varied were fragment layer thickness, w, confinement thickness, t, and height of the free volume, h, illustrated in Figure 10. The Hydrocode CTH was used to evaluate the velocity of the fragment layer. This layer was modeled as steel with a very high strength value to keep it intact so that a single average velocity could be obtained. The results indicate that on a constant mass ba-

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sis, a zero confinement thickness maximizes the amount of fragment mass that can be projected at any required velocity. The amount of fragment mass is fairly insensitive to this parameter up to values of 0.03. Fractional fragment mass at a given velocity increases with h (large h values are unrealistic because of their poor volume efficiency). Figure 11 plots the fractional fragment mass at a t value of 0.01 for different values of h. For this analysis a volume efficient h value of 0.25 was used along with a nominal confinement value t of 0.01, which functions as the explosive container. It is assumed that the plate can be contoured to project the fragments into the width azimulthal zone desired. The gain in projected mass compared to our Baseline is shown in Figure 10 as the dashed curves. The Gain is plotted as a function of beam angle and the same comments apply as to their practicality as in the case of the four-sided device. The potential gains for the single-sided warhead are large. The Gains are three times that of the four-sided cylinder. The technical problem is developing a method of aiming such a warhead.

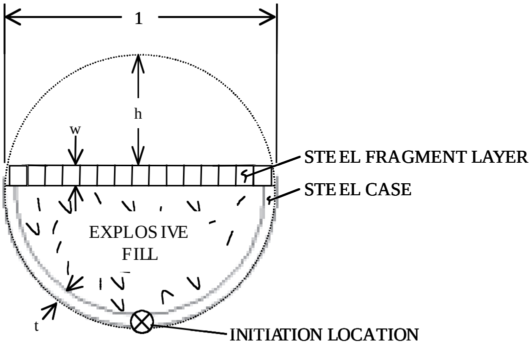

Figure 10. Single-sided fixed aim parameters.

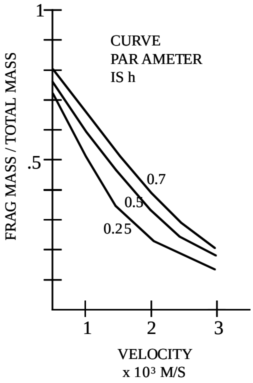

Figure 11. Fractional fragment mass for single-sided fixed-aim.

SUMMARY

This paper examines the relative performance of several different anti-air warheads. Performance is defined as the amount of fragment mass that can be projected at a target compared to an axially initiated circular cylindrical warhead of equal mass. Modest gains in performance are possible for warheads for which aiming is accomplished by control of the position of explosive initiation. Large gains in performance are possible for warheads with a single-side or four-sides if there is some means of aiming the/a side at the target. The method of this aiming is not addressed in this paper. For all warheads and especially those with selectable beam sprays, the beam width must be compatible with fuzing accuracy.

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