TOWARDS A MULTIPLE-HIT CRITERION FOR LIGHT ARMOR (U)

Dr. William S. de Rosset* and LTC Rodney Sturdivant**

*Weapons and Materials Research Directorate
U.S. Army Research Laboratory
Aberdeen Proving Ground, Maryland 21005

**Department of Mathematical Sciences
United Sates Military Academy
West Point, New York 10996

ABSTRACT (U)

(U) Multiple-hit-capable armors are defined and examined for their ability to provide protection against more than two impacts. The formulation of a multiple-hit criterion is proposed, and a model is developed that uses the results of individual ballistic tests to ascertain whether the criterion is met. Examples are provided that show how the model can be used to conduct trade-off studies between competing armor designs, examine parametric variations of a given design, or how variations in striking velocity/range will affect the multiple-hit performance of the armor.

(U) 1. Introduction

(U) While it is the goal for armor designers to defeat all projectile and warhead threats one hundred per cent of the time, certain compromises must be made between protection levels, cost, and vehicle weight such that this goal is rarely attained. This is especially true for lightweight, air-transportable manned ground vehicles that the Army is currently developing as part of the proposed Future Combat System of Systems.

(U) What is required in the process of engineering compromises is a quantifiable ballistic performance criterion that can be used to conduct trade-off studies among such variables as weight, cost, and protection level. The ballistic performance criterion must be related in some way to the battlefield environment that these manned ground vehicles (MGVs) will experience. Currently, the Operations Requirement Document calls for protection against machine guns and fragments (ref. 1). Clearly, the MGVs will experience multiple impacts (likely more than two) from machine guns, and the performance criterion must take this into account.

(U) Multiple-hit capability should not be confused with a multiple-hit criterion. Armor researchers at the Army Research Laboratory are using the term multiple-hit capability to describe the ability of a ceramic-tile-based armor to withstand successive impacts on an armor array. Multiple-hit capability presupposes that the first impact is

(U) Approved for public release; distribution is unlimited.

defeated. Thus, every tile should be capable of stopping a threat round anywhere on the tile surface as well as in the joint between the tiles. Furthermore, the armor array is considered to have multiple-hit capability if, after the first impact is stopped in a tile, a second impact on an adjacent tile is also defeated. Armor performance specifications usually include a specified impact velocity at or below which the armor is not perforated. For impact velocities above this specified velocity, the armor may be perforated. Finally, for sake of discussion here it is assumed that a second impact on the same ceramic tile at the specified impact velocity will result in a perforation of the armor, unless otherwise specified.

(U) An example of a multiple hit criterion might be stated in the following way: the armored vehicle must be able to defeat a burst of seven rounds of 0.50-caliber machine gun fire at a range of 300 meters 95 per cent of the time. Given the weapon system characteristics (muzzle velocity, bullet velocity decrease with range, and dispersion) along with a sufficient amount of ballistic data and the ceramic tile size, a determination can be made as to whether the armor meets the example criterion. The numbers used here are arbitrary. However, the form of the criterion appears to be reasonable, and therefore this particular example criterion will be used in the remainder of the paper for the sake of discussion.

(U) The next section details what ballistic data are needed to ascertain whether a multiple-hit-capable armor array meets the example criterion and shows how it is applied. Section 3 expands on this treatment to include armors that do not have multiple-hit capability. In addition, the effect of having a single ceramic tile capable of defeating two successive impacts is explored to show how the methodology presented here can be used to conduct trade-off studies of different solutions. The final section provides a summary of the paper.

(U) 2. Basic Approach for Multiple-Hit-Capable Armor

(U) In the course of selecting and screening possible armor designs, a ballistic limit velocity or V_{50} is determined. The V_{50} is defined as the projectile impact velocity where there is a 50% probability that a given tile is perforated (or the bullet defeated). For our purposes, the spread in velocities over which perforations and non-perforations both occur (zone of mixed results) will be ignored and it will be assumed that for impact velocities above V_{50} the armor will be perforated. Below V_{50}, the armor will defeat the bullet.

(U) Assume that the armor array consists of square ceramic tiles on a backing plate. The edge length of a tile is D. The rounds strike the target randomly inside a circle of radius R and area A. The probability, P_1, that the first round is defeated is 1 by definition of a multiple-hit-capable target. However, one tile has been damaged so that this particular tile cannot defeat a second round if it is impacted. The probability P_2 that the next round is defeated is given by

$$P_2 = (A-D^2)/A. \quad (1)$$

It is assumed that only one tile is destroyed per impact. Also, it is assumed that the number of tiles contained within the area A is large. Given that the second impact is defeated, the third impact will occur in the area that has two ineffective tiles. Thus, its probability for being defeated is given by

$$P_3 = (A-2*D^2)/A. \quad (2)$$

The probability P(3) that all three impacts are defeated is given by the product of the individual probabilities, or

$$P(3) = P_1*P_2*P_3 . \quad (3)$$

It can be shown that in general that the probability P(n) that the first n bullets that strike the target are all defeated is given by

$$P(n) = (1-D^2/A)*(1-2*D^2/A)*(1-3*D^2/A)*\ldots*(1-(n-1)*D^2/A), \quad (4)$$

where it is assumed that the V_{50} for a tile is greater than the specified impact velocity (ref. 2). For the example criterion stated above and for a tile whose edge dimension is 100 mm, P(7) is calculated to be 0.75 or 75%. This assumes that the machine gun has a one-mil dispersion, and that A is related to the dispersion, d, and range, r, by the following relation (ref. 2):

$$A = 8.71* (d*r)^2. \quad (5)$$

The performance of this particular design does not meet the example multiple-hit criterion stated in Section 1.

(U) Conversely, Equation 4 can be used to determine the tile size that insures that the example multiple-hit criterion is met. Rather than solve a high order equation in D, Equation 4 was programmed into a spreadsheet, and D was solved for in an iterative process. The result was that a value of 43 mm for D gives a 95.1 % probability that no perforations will occur for the first seven impacts.

(U) Three additional points should be made about this approach. First, the impacts from a burst-fire weapon generally impact a target according to a bivariate normal distribution. That is, the horizontal and vertical dispersion of the impact locations each

follow a bell-shaped curve. It has been shown that a random distribution of impact locations provides approximately the same result as using the bivariate normal distribution (ref. 2). Therefore, a random distribution will be used for calculations used here. Second, if a vehicle armor is perforated by any given impact, the vehicle is not necessarily defeated. A much more detailed vulnerability/lethality analysis must be performed to determine the effect of a perforating hit. In effect, the value of P(n) represents the lower bound of the probability of vehicle survivability given n impacts from a burst-fire weapon. Third, bullets are assumed to hit at a point. In fact, bullets have lateral dimensions that should be taken into account, especially as the bullet diameter approaches the tile size. For a multiple-hit-capable armor, it makes no difference, in theory, what the bullet dimensions are. However, for non-multiple-hit-capable armor, the bullet dimensions can be accounted for, to some extent, by adjusting the zone of weakness, described below.

(U) The probabilities calculated with this model give a lower bound on P(n) for another reason. The model assumes that a complete tile is removed from A after each shot. In the case where a tile on the periphery of the area A is hit, only part of the tile is removed from A. On average, then, only a fraction of D^2 is subtracted from A to find the probability.

(U) For a large number N of tiles contained within A, the following relation is a good approximation:

$$A = N*D^2. \qquad (6)$$

However, for small values of N, the approximation breaks down. (Small values of N imply that the target is being attacked at very close range.) Consider the case where R=D/2. Here, N ~ ¾. That is, a complete tile is not contained within A. The model would predict a negative value for P(2). If this negative value is interpreted as zero, then the model gives the right answer only if the area A is centered at the mid-point of a tile. The answer will actually vary according to aim point. Consider four possible cases for which P(n) is relatively easy to calculate, based on a random hit location. They are 1) center tile hit, 2) seam hit, 3) triple-point hit, and 4) quadruple-point hit. The seam hit is assumed to occur in the middle of an edge. The triple point is defined as the location where three tiles meet, and the quadruple point is defined as the point where four tiles meet. Table 1 gives the values of P(n) assuming that only the relevant portion of the impacted tile is removed from A after each impact.

Table 1(U). P(n) versus Aim Point for R=D/2

Aim Point	P(1)	P(2)	P(3)	P(4)	P(5)
Center of tile	1	0			
Seam	1	0.5	0		

Triple Point	1	0.625	0.375	0	
Quadruple Point	1	0.75	0.375	0.093	0

(U) 3. Non-Multiple-Hit-Capable Armor

(U) Difficulties in making a multiple-hit-capable ceramic tile armor increase as the tile dimensions decrease. It may be decided that for some reason (cost, manufacturability, etc.) a non-multiple-hit-capable armor is the best choice. Or it is possible that after a multiple-hit-capable armor is fielded a new threat overmatches the armor at, for instance, the region between tiles. The approach outlined here can be extended to include non-multiple-hit-capable armors.

(U) As an example, consider the same square tile array as in Section 2. Assume now that there is a zone of weakness near the edge of each tile. That is, an intact tile can defeat an incoming bullet everywhere except in the zone of weakness. Let the width of this zone be δ. It can be shown (ref. 1) that the probability P(n) that n impacts from a burst-fire weapon are defeated is given by

$$P(n)= (1-D^2/A)*(1-2*D^2/A)*(1-3*D^2/A)*\ldots*(1-(1-n)*D^2/A))*(1-2*\delta/D)^{2n}. \quad (7)$$

Ballistic data would need to be generated to establish the actual value of δ for the armor array.

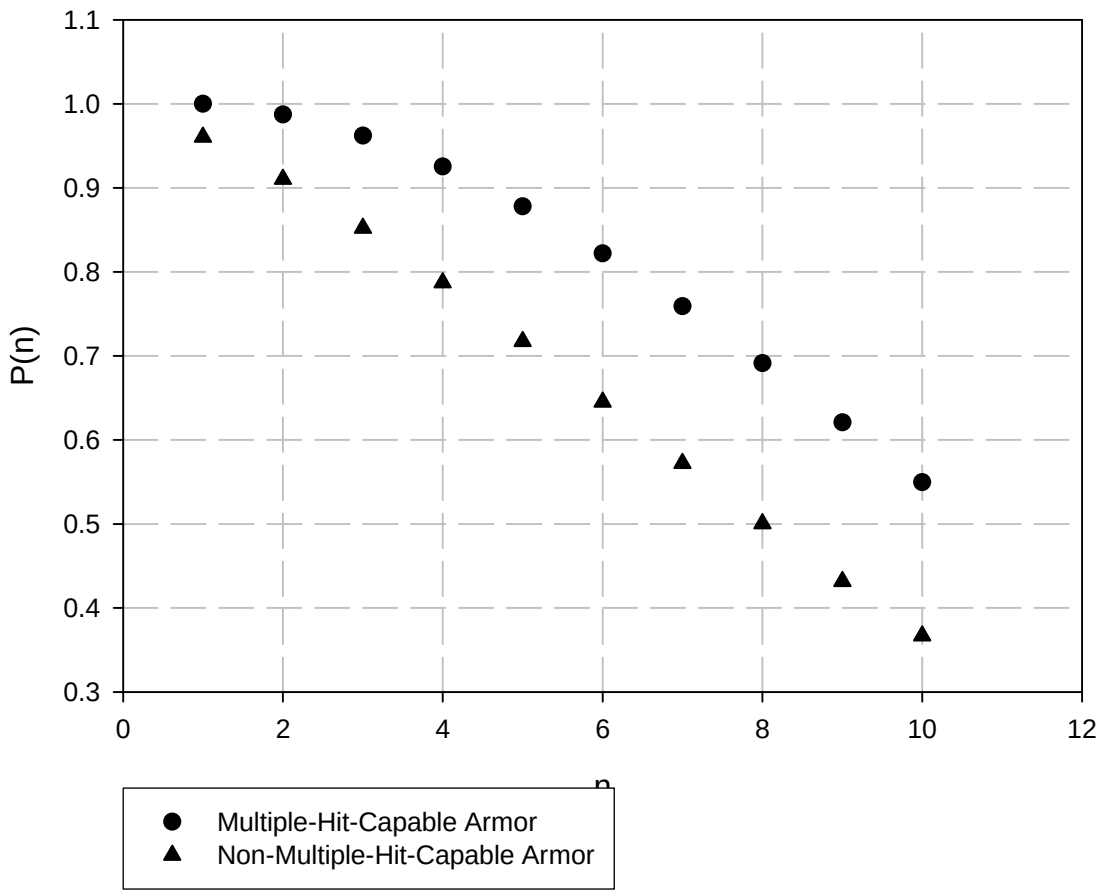
(U) The importance of having multiple-hit capable armor can be demonstrated by comparing P(n) for two cases. The first is a multiple-hit-capable square tile array whose tile edge length is 100 mm. The second is the same tile array that has a zone of weakness 1 mm thick at the edge of each tile. Figure 1 compares P(n) as a function of n for these two cases when attacked by a 0.50-caliber machine gun at 300 meters range, assuming a 1 mil weapon dispersion. Even with a very small weak zone there is a significant difference in P(n) between the two cases. This difference increases dramatically with increasing values of δ.

(U) The approach used for single impacts on tiles can be expanded to the case where an individual tile can defeat two (or more) bullet or fragment impacts. This might occur when a tile is struck at such a long range that not a great deal of damage is done on the first impact. It could also apply in the case where the armor is attacked by a much less potent threat than it was originally designed to defeat. The calculation of P is more complicated for multiple hits on the same tile, and to date no simple closed form solution has been found for the general case (ref. 3). However, P can be calculated for any specific case of interest. Suppose, for instance, that a single tile can defeat two threat rounds at a specified velocity. It can be shown (ref. 3) that the probability that seven hits on this armor in an area A are all defeated is given by

$$P(7) = 1-35/N^2 + 105/N^3 - 56/N^4 - 105/N^5 + 90/N^6, \qquad (8)$$

where N is the number of tiles contained in the area A. The mathematical development ignores the assumption that the area over which the bullets strike is in the form of a circle, whereas the tiles are squares. If $A/D^2 = N >> 1$, then a large number of tiles fit within A, and the use of an integer for N does not introduce a large error. Note, too, that P(7) = 0 for N=1, N=2, or N=3.

UNCLASSIFIED



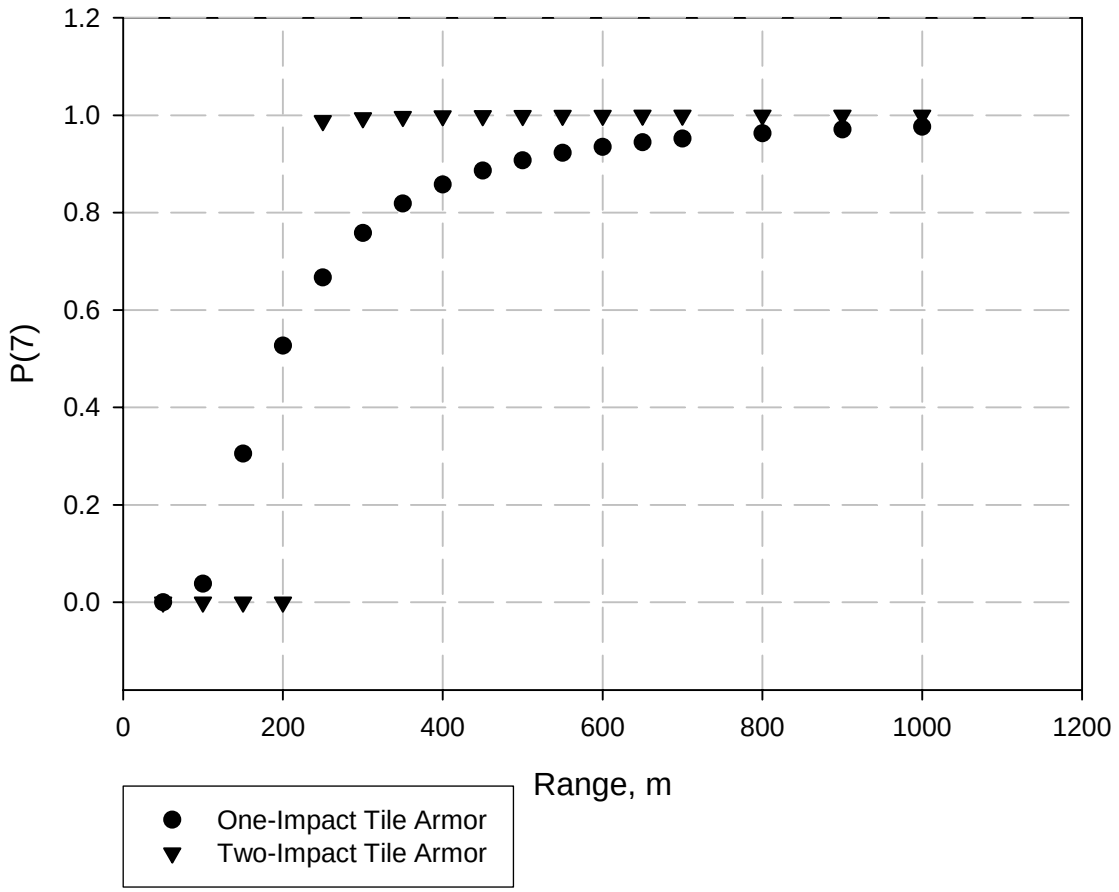
UNCLASSIFIED

Figure 1 (U). Comparison of Performance between Multiple-Hit-Capable Armor and Non-Multiple-Hit-Capable Armor (tile dimensions 100 mm by 100 mm and zone of weakness 1 mm wide)

(U) Equation 8 can be used to examine a hypothetical choice between two competing armor designs. The first is a multiple-hit-capable armor whose tiles can defeat a single impact of a 0.50-caliber bullet at 900 m/sec. The next impact on that same tile perforates the armor. The second armor design is a multiple-hit-capable armor whose tiles can defeat two impacts of a 0.50-caliber bullet at a velocity of 800 m/sec or below. The third impact on that same tile results in a perforation. The value of D for both armors is 100 mm. Weapon dispersion is taken as 1 mil. The value of P(7) as a function of range can be

calculated for both armors, using the range-velocity data for the AP-M2 machine gun round (ref. 4). This comparison is shown in Figure 2.

UNCLASSIFIED



UNCLASSIFIED

Figure 2 (U). Performance comparison of one- and two-impact tile armor as a function of range

(U) At short ranges, the one-impact cell armor outperforms the two-impact cell armor. However, above 200 meters range (actually 223 meters) the two-impact cell armor has a higher value of P(7). The value of having a one-impact cell armor with a high limit velocity is negated to some extent at very close range due to the multiple impacts hitting a small area.

(U) It is clear that there are many different types of comparisons that can be made between armors with various performance characteristics. However, unless there is a well-posed performance criterion, the methodology presented here is of little value. Taking the multiple hit example criterion stated in the Introduction, it can be easily seen that the two-impact cell armor meets the criterion while the one-cell impact armor does not.

(U) 4. Summary

(U) The goal of the armor designer has always been to defeat any and all threats. While this is a worthy goal, it must be recognized that light armor attacked by automatic weapons fire can be defeated under some circumstances. Consequently, realistic performance criteria need to be decided upon.

(U) Characteristics of multiple-hit-capable armor were presented. A way to relate ballistic data on individual ceramic armor tiles to the overall performance when an armor array is attacked by automatic weapons was presented. That is, simple calculations were performed to determine the probability that multiple-hit-capable armors would be perforated after a given number of impacts. The calculations were extended to armors that did not have multiple-hit capability. The importance of achieving multiple-hit capability was demonstrated. In addition, the effect of allowing the armor tiles to defeat more than one impact was investigated. An example was shown how the approach could be used to compare one-cell-impact and two-cell-impact armors. The main point demonstrated is that the approach can be used to conduct trade-off studies when engineering compromises must be made.

(U) References

1. "Army Future Combat Systems Unit of Action Book," Version 3.0, US AMSAA, 22 May 2003 (UNCLASSIFIED)
2. W.S. de Rosset and J.K. Wald, "Analysis of Multiple-Hit Criterion for Ceramic Armor," US Army Research Laboratory TR-2861, September 2002 (UNCLASSIFIED)
3. W.S. de Rosset, "Patterned Armor Performance Evaluation for Multiple Impacts," US Army Research Laboratory TR-3038, August 2003 (UNCLASSIFIED)
4. F.S.Mascianica, " Ballistic Technology of Lightweight Armors," AMMRC TR 76-15, May 1976 (CONFIDENTIAL)