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U.S. ARMY TEST AND EVALUATION COMMAND DEVELOPMENT TEST II (ET) - COMMON TEST OPERATIONS PROCEDURE, PROTECTION BY ARMORED VEHICLES AGAINST KINETIC ENERGY PROJECTILES

Army Test and Evaluation Command
Aberdeen Proving Ground, Maryland

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13. ABSTRACT

Describes a computational technique for assessing the protection afforded by an armored vehicle against a specific threat (defined in the applicable ROC, DP, or other military requirements document) by a kinetic energy projectile. The attack conditions are limited to ground attack from conventional weapons. Computation is based on previously obtained ballistic data. Discusses the threat and the protection probability, rationale for the technique, special armor considerations, and prerequisites.

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U. S. ARMY TEST AND EVALUATION COMMAND
DEVELOPMENT TEST II (ET) - COMMON TEST OPERATIONS PROCEDURES

AMSTE-RP-702-101
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PROTECTION BY ARMORED VEHICLES AGAINST KINETIC ENERGY PROJECTILES

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SECTION I
GENERAL

1. Purpose and Scope. This TOP provides a computational technique for assessing the protection afforded by an armored vehicle against a specific threat by kinetic energy projectiles, a threat which is defined in the Required Operational Capability (ROC), Development Plan (DP) or other requirements documents. Other types of threats that may be mentioned in ROC's/DP's are covered in other TOP's as follows:

Fragment threat: TOP 2-2-722, Fragment Penetration Tests of Armor.

Mine threat: TOP 2-2-710, Vehicular Armor.
HEAT and HEP projectile threat: TOP 2-2-710.

Nuclear threat: TOP/MTP 2-2-618, Vulnerability of Vehicles to Nuclear Weapons.

Shock threat: TOP/MTP 2-2-620, Resistance to Severe Shock (Armored Vehicles).

*This TOP supersedes MTP 2-2-715, 19 January 1971.

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Miscellaneous threats: TOP/MTP 2-2-617, Armored Vehicle Vulnerability to Conventional Weapons.

2. Background. Until recently, the protection that an armored vehicle was expected to provide against ballistic threats was expressed only in general terms. Now, many ROC's/DP's definitively state that the vehicle is required to defeat a certain projectile from a certain range with a certain probability.

In this TOP the word "protection" means that the vehicle is able to defeat the attacking projectile in a way that prevents any fragments, from either the projectile or dislodged armor, from entering the vehicle with sufficient velocity to have a potentially injurious effect on personnel and pertinent components such as fuel, engine, and ammunition. Providing protection is synonymous with defeating the threats. This quality in armor is measured by firing projectiles at the armor to obtain a value, expressed in terms of projectile velocity, which is called the protection ballistic limit. The protection ballistic limit and the method of obtaining it are described in TOP 2-2-710. Characteristics of ballistic limit tests are explained in reference 4 (app. A). A study that was made of certain aspects of the procedures contained herein is described in reference 5.

3. Equipment and Facilities. This TOP presumes that test data are already available; thus, no test facilities are required for use of this TOP - only computational equipment. If additional firing data are required, the methods and facilities of TOP 2-2-710 will be used.

SECTION II
TEST PROCEDURES

4. The Threat and the Protection Probability. Protection must be related to a certain threat, the threat being a particular type of attack. An example of a threat coupled with a protection requirement is as follows:

Case I. The armor will provide 95 percent protection against frontal attack with the 14.5-mm AP-I, BS-41 projectile at a range of 100 meters fired along a horizontal plane within 30° of the longitudinal axis of the vehicle.

In effect, this statement says that the projectile can be launched from any point of an arc of a circle (let us call this the "threat line") 100 meters from the vehicle center and confined to 30° either side of the longitudinal axis of the vehicle as measured from the vehicle. The computational procedure assumes equal likelihood of launching from any point on the threat line to any point on the exposed armor of the vehicle. The specified degree of protection in the above example means that under the conditions stated the probability of the vehicle's providing protection against the threat is 0.95.

Another example of a protection requirement is as follows:

Case II. The armor will provide 95 percent protection against frontal attack with the 14.5-mm AP-I, BS-41 projectile at a range of 100 meters fired within 7.5° of the longitudinal axis of the vehicle.

Since, in this case, horizontal attack is not mentioned, the question arises as to whether horizontal attack was actually intended or whether in fact the statement means that the projectile could be launched from any point on a spherical surface (a "threat surface") 100 meters from the vehicle center and confined to 7.5° (up and down as well as to the sides) from the longitudinal axis. The following rule will be followed: if the threat angle is defined as covering 10° or more, horizontal attack will be assumed;* if under 10° or if the requirement is not specific, it will require resolution with the user and developer before test plan preparation. If a threat surface is intended rather than a threat line (to take into account a mildly pitching vehicle moving over undulating terrain), the threat, instead of being divided into small arcs as in paragraph 8, must be divided into small areas, thus increasing by severalfold the computations involved.

*This assumption is justified in order to prevent vertical obliquities on the vehicle from being unfairly penalized. As an example, a 40° obliquity on an upper slope could be reduced to 30° by an attack launched from 10° above the horizontal.

5. Rationale for Computational Procedure. The computational procedure first determines, for each armored area of the vehicle, the probability of its resisting attack from a particular point on the threat line. These probabilities are weighted in accordance with their associated projected areas of the vehicle and summed. The projected area is a selected area of armor projected to a plane perpendicular to a line connecting the center of the area to the launch point of the threat. The summed, weighted probability is the probability that the armor will defeat the attack from the particular launch point of the threat. The threat line is divided into small arcs each represented by the center point within the arc. The probability of the armor's defeating the threat is computed for each point (arc) on the threat line. These latter probabilities are weighted in accordance with the arc they represent and summed. This latter sum is the probability that the armor will protect against the threat.

6. Special Armor Considerations.

6.1 Openings in the Armor. Openings in the armor envelope often exist to permit the mounting of vision devices and armament. Such openings are undesirable from a protection standpoint but necessary from a system

standpoint. (Consider two vehicles identical in every respect but one: one vehicle has openings, the other none. Clearly the latter would offer better protection.) To adequately describe protection, the openings must be considered in the evaluation. Inclusion of the openings lowers the computed protection and could infer that the armor thickness is inadequate. To avoid misinterpretation, the computation should first be performed assuming the absence of openings. Later, the vulnerable areas of openings are subtracted. This procedure provides a judgement basis for deciding whether the armor material and thickness selection was appropriate. The presence of the opening may permit entry into the vehicle of fragments from the attacking projectile or portions of dislodged armor. The opening thus presents a special problem in the evaluation. For the purposes of this evaluation, a projectile whose center impacts within three quarters of a caliber of an opening shall be considered to have defeated the armor. This rule shall be followed irrespective of the size of the opening or the thickness or type of armor in the area.

6.2 Shielded Armor. Part of the armor of a vehicle is either covered or partially covered by components. For example, the tracks, bogey wheels, and torsion bars partially shield the lower side plates. The analysis shall presume that if the shielding material is composed of sturdy metal, the ballistic limit of that vehicle section is raised by 5 percent for APC projectiles, 15 percent for AP projectiles, and 25 percent for APDS projectiles. If the shielding material is composed of light material - e.g., sheet rubber or thin-gage steel - it is disregarded. If the projectile is small (i.e., cal .30, 5.56-mm or 7.62-mm AP), sturdy shielding shall be presumed to increase the ballistic limits by 25 percent.

7. Prerequisite Data. The procedures described assume the existence of certain ballistic data, thus permitting computational procedures alone to suffice for the evaluation. If firing tests against the vehicle are not needed, the vulnerability analysis may be made very early in the engineering evaluation of the vehicle, thus allowing time for remedial action if required. If the required data are not available and firing tests are necessary, they should preferably be made against samples of the armor material (composites included). Firing against the vehicle for resistance-to-penetration data is usually not desirable. The following must be available in order to perform the evaluation:

a. The protection ballistic limits (V_{50}) for all armor sections on the vehicle. These limits should be available for all thicknesses and obliquities facing the threat, and be for the specified projectile.

b. Standard deviations that measure the normal distribution of the probability-of-penetration curve of each ballistic limit of a, above. The standard formula for a cumulative normal distribution is shown below expressed in projectile velocities.

$$P = 1 - \frac{1}{\sqrt{2\pi}\,\sigma} \int_{-\infty}^{V_s} \epsilon^{-\frac{(V-V_{50})^2}{2\sigma^2}}\, dV$$

where:

P = probability that the armor will provide protection against a projectile impacting at velocity V.
σ = standard deviation (in fps) of the ballistic limit. This is a measure of the spread of the probability-of-penetration curve.
V_{50} = striking velocity (in fps) at which 50 percent of the attacking projectiles will defeat the armor, commonly called the V_{50} ballistic limit.
V_s = striking velocity (in fps).

c. Information on the armor arrangement of the vehicle, from physical examination of the vehicle and drawings, describing the armor material, thicknesses, and geometrical orientations.

d. The striking velocity of the attacking projectile when launched from the range specified in the threat.

8. Computational Procedure. The computational procedure is described below. An example is presented in Appendix B.

a. Divide the exposed surface of the vehicle into areas having like armor characteristics; i.e., composed of the same type of material and of relatively uniform thickness and obliquity. The thickness used in the computation will be the nominal (ordered median) thickness meeting drawing or specification requirements. The size of each area will vary with the particular obliquity and thickness situation. Identify these areas as a_1, a_2, ...a_m.

b. Divide the threat line into arcs. These arcs should be selected so that any point within the arc represents substantially the same attack angle on the vehicle as any other point on the arc. These arcs need not be less than 2° as measured from the vehicle. Identify these arcs as A_1, A_2, ...An.

c. Assume the striking velocity of the projectile to be the same from any threat arc to any portion of the vehicle.

d. Consider attack from A1 against each area a1 to a_m in turn, using the available ballistic penetration data for V_{50} and σ for each area. In the event that data are not available for estimating a σ,

it will be assumed that σ is equal to 2.0 percent of the ballistic limit for homogeneous aluminum or steel armor, and 3.0 percent otherwise.

e. With the V_{50}, σ, and the striking velocity, V_s, determine for each armor area a probability, p, of the armor's providing protection against the projectile. Use the "normal distribution" tables available in textbooks on statistics (ref. 1, table A1, for example). Enter these tables with the argument $(V_s - V_{50}) \div \sigma$, leaving with the probability that the armor will defeat the threat. Associate with each a_i a probability, p_i.

f. Compute each projected area, $\bar{a}_i$, where $\bar{a}_i$ is the projected area of a_i on a plane perpendicular to the line of fire.

g. Compute the probability that the vehicle will defeat the threat from A_1 by the following:

$$P_1 = \frac{\bar{a}_1 p_1 + \bar{a}_2 p_2 + \ldots + \bar{a}_m p_m}{\bar{a}_1 + \bar{a}_2 + \ldots + \bar{a}_m}$$

h. Consider attack from A_2 by repeating the procedure in d through g above. In this manner, keep repeating until P_1, P_2, P_3 ...P_n have been computed.

i. Compute the protection as follows:

$$\bar{P} \text{ (openings neglected)} = \frac{A_1 P_1 + A_2 P_2 + \ldots + A_n P_n}{A_1 + A_2 + \ldots + A_n}$$

Thus, $\bar{P}$ (openings neglected) = the overall probability of providing protection against the threat, with openings in the armor disregarded.

j. For each vehicle area that has an opening, recompute the probabilities of defeating the threat by subtracting the effect of the vulnerable areas caused by openings. Consider each opening to be the area formed when the opening periphery is displaced outward by three-quarters of a caliber of the threat projectile. An opening is considered to be a hole in the armor, whether open or plugged by a nonballistic material such as a telescope. Vision blocks, being designed for ballistic protection, are treated in the same way as the basic armor, and must be evaluated on the basis of data from ballistic tests. Following these determinations, compute a value $\bar{P}$ (openings considered) in the manner described in i above.

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APPENDIX A
REFERENCES

1. AMCP 706-114, Engineering Design Handbook, "Experimental Statistics, Sec. 5 - Tables," June 1962.

2. AMCP 706-170, Engineering Design Handbook, "Armor and Its Applications" (U). (To be printed in six volumes (U to S) late in 1973.)

3. "Final Report on Research Test of Vulnerability Analysis Technique for MBT-70" (TECOM Project No. 0-7-1006-02), Aberdeen Proving Ground, Md., Report No. DPS-2558.

4. Feroli, John A., "The Accuracy and Reproducibility of Several Methods for Obtaining Ballistic Limits of Armor," First Report on Project 7B4-005D (AD-1200), Aberdeen Proving Ground, Md., Development and Proof Services, July 1957.

5. Feroli, John A., "Special Study of Procedures for Evaluating Protection of Vehicles Against Projectiles and Fragments" (TECOM Project No. 9-CO-001-000-054), Aberdeen Proving Ground, Md., Report APG-MT-4362, October 1973.

APPENDIX B
EXAMPLE OF COMPUTATIONAL PROCEDURE*

NOTE: To concentrate the attention on the method rather than on a large number of detailed calculations, a simple boxlike arrangement of armor was chosen to serve as the vehicle. The armor material is unspecified and the ballistic limit data are fictitious.

1. GIVEN INFORMATION

1.1 Vehicle

The armor consists of plate arranged according to the sketch in figure 1. The sides are perpendicular to the horizontal plane.

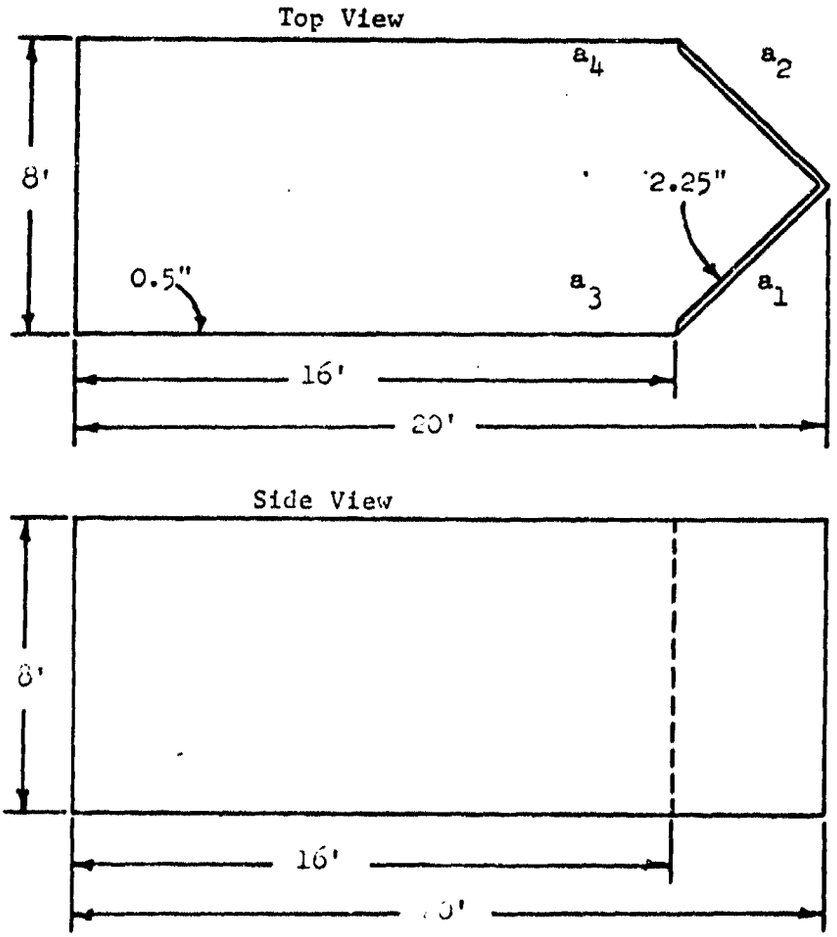


Figure 1. Armor Arrangement and Dimensions.

*Based on ref. 3 (app. A).

1.2 Threat

The vehicle is subjected to frontal attack by caliber .50 armor-piercing projectiles. The attacking weapon is 200 meters from the vehicle and may be at any location along an arc extending 30° on each side of the centerline. See figure 2 for a sketch of the threat region. The remaining projectile velocity at a distance of 200 meters from the muzzle is 2850 fps.

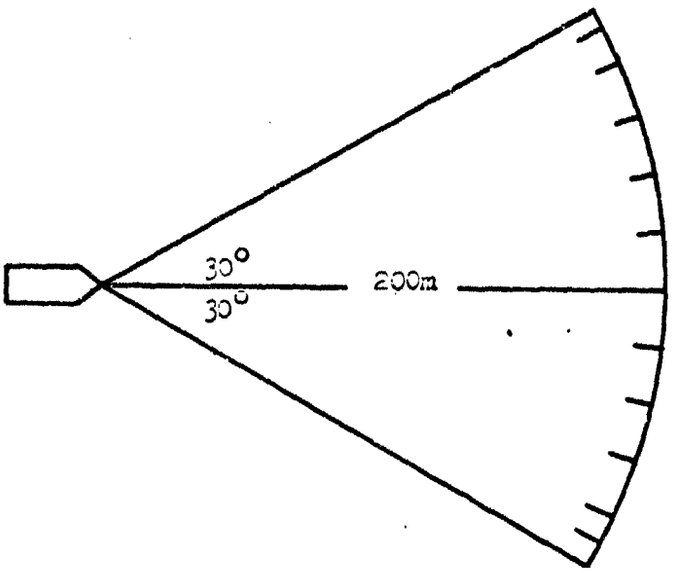


Figure 2. Threat.

1.3 Penetration Data

Curves of ballistic limit versus armor thickness and obliquity are contained in figure 3. The standard deviation associated with the probability-of-penetration curve is 1.5 percent of the ballistic limit based upon available data for this particular armor-projectile combination.

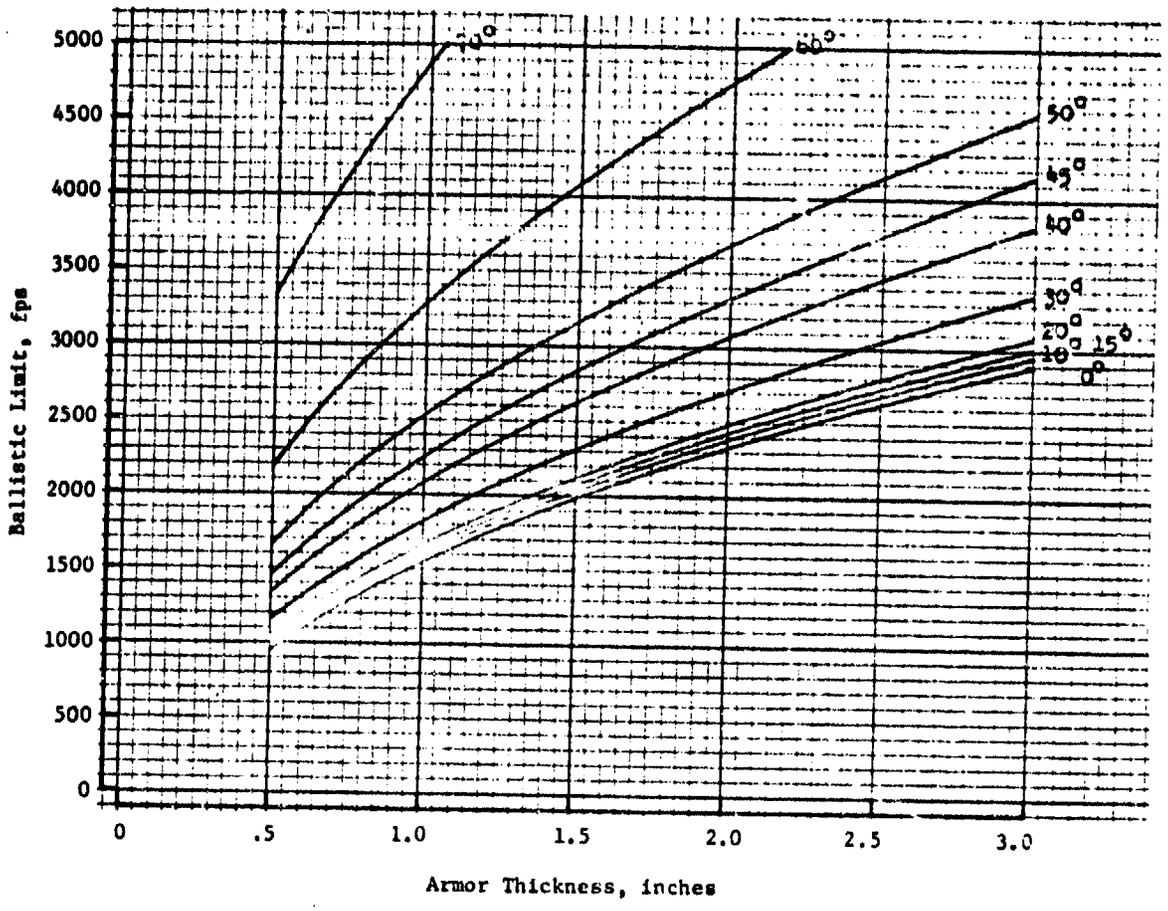


Figure 3. Ballistic Limit Versus Armor Thickness and Obliquity.

2. PROBLEM

To calculate the probability that the armor will provide protection against the threat described above.

3. SOLUTION

Specified interpretations of the given information concerning the threat are required in order to proceed with the analysis:

a. The attacking weapon and the vehicle are situated on the same horizontal plane.

b. The trajectory of the projectile is essentially flat. Because the sides of the vehicle are perpendicular to the horizontal plane, the angle of impact of the projectile on the plate is simply the angle measured in a vertical plane.

c. The trajectories of projectiles fired from a given location of the weapon can be considered parallel because the distance between weapon and vehicle is large relative to the size of the vehicle.

d. The threat line in this situation is an arc of a circle centered at the vehicle. This arc lies in front of the vehicle and extends 30° on each side of the longitudinal axis of the vehicle.

The exposed surface of the vehicle is divided into four areas within which the thickness and obliquity are constant. (At most, three surfaces are exposed to the threat at any one time.) These are labeled a_1, a_2, etc., in figure 1. The projected areas (projected in a plane perpendicular to the line of fire) and the obliquities vary with the location of the weapon and can be easily computed from the given dimensions and angles.

The threat line (i.e., arc of d above), is divided into smaller arcs varying from 1° to 6°. Preliminary scanning of the data indicated that, for some regions of the threat, the probability of defeating the threat would be either zero or one. The wider intervals could be used in those regions and the amount of computation reduced. The weapon is considered to be at the midpoint of the interval, and the various quantities calculated for the weapon at that location are assumed to apply to the entire interval.

A table to facilitate computation is constructed as in table 1. (Because, in this application, there is symmetry of the armor and of the threat arc about the longitudinal axis of the vehicle, the computations for the left half of the threat are the same as for the right half. Therefore, only the one half appears in the table.) The entries for the table are described in detail for the first threat region, 0° to 4° beginning at the axis.

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Table 1 - Table of Computations

Threat Region, deg	A_i, deg	Armor Surf. a_j	Armor Thick., in.	Obl., deg	Projected Area, $\bar{a}_j$, sq. ft.	V_{50}, fps	$\frac{V_s - V_{50}}{\sigma}$	p_j	$\bar{a}_j p_j$	P_i	$A_i P_i$
0-4	4	a_1	2.25	43	33.16	3436	-11.37	1.0000	33.16		
		a_2	2.25	47	30.92	*		1.0000	30.92		
		a_3	0.50	88	4.47	*		1.0000	4.47		
					68.55				68.55	1.0000	4.0000
4-8	4	a_1	2.25	47	35.23	3226	-7.77	1.0000	35.23		
		a_2	2.25	51	28.53	*		1.0000	28.53		
		a_3	0.50	84	13.38	*		1.0000	13.38		
					77.14				77.14	1.0000	4.0000
8-12	4	a_1	2.25	35	37.14	3055	-4.50	1.0000	37.14		
		a_2	2.25	55	20.00	*		1.0000	20.00		
		a_3	0.50	80	22.23	*		1.0000	22.23		
					95.37				85.37	1.0000	4.0000
12-16	4	a_1	2.25	31	38.80	2914	-1.46	0.9278	36.05		
		a_2	2.25	59	23.35	*		1.0000	23.35		
		a_3	0.50	76	30.97	*		1.0000	30.97		
					93.13				90.37	0.9698	3.8792
16-20	4	a_1	2.25	27	40.33	2793	1.21	0.1132	4.57		
		a_2	2.25	63	20.58	*		1.0000	20.58		
		a_3	0.50	72	33.55	*		1.0000	39.55		
					100.32				64.70	0.6437	2.5748
20-21	1	a_1	2.25	24.5	41.25	2656	2.73	0.0032	0.13		
		a_2	2.25	65.5	18.80	*		1.0000	18.80		
		a_3	0.50	89.5	44.82	3243	-8.20	1.0000	44.82		
					104.87				63.75	0.6079	0.6079
21-22	1	a_1	2.25	23.5	41.58	2675	3.26	0.0006	0.02		
		a_2	2.25	66.5	18.08	*		1.0000	18.08		
		a_3	0.50	89.5	46.91	3093	-5.24	1.0000	45.91		
					106.57				65.01	0.6100	0.6100
22-23	1	a_1	2.25	22.5	41.89	2694	3.86	0.0000	0.00		
		a_2	2.25	67.5	17.35	*		1.0000	17.35		
		a_3	0.50	87.5	48.35	2950	-2.26	0.9881	48.40		
					107.22				65.75	0.6075	0.6075
23-24	1	a_1	2.25	21.5	42.19	2675	4.36	0.0000	0.00		
		a_2	2.25	68.5	16.62	*		1.0000	16.62		
		a_3	0.50	89.5	51.04	2920	0.71	0.2389	12.19		
					109.84				28.81	0.2623	0.2623
24-30	6	a_1	2.25	19	43.12	2814	0.02	0.0000	0.00		
		a_2	2.25	72	14.01	*		1.0000	14.01		
		a_3	0.50	83	58.11	2444	11.07	0.0000	0.00		
					115.24				14.01	0.1216	0.7296
	30										21.2715

$\bar{P}$ (openings neglected) $= \frac{2\Sigma A_i P_i}{2\Sigma A_i} = \frac{2(21.2715)}{2(30)} = 0.709$.

*Denotes a ballistic limit (V_{50}) of 3500 fps or greater and $\frac{V_s - V_{50}}{\sigma} < -12.38$.

See notes on p. B-6.

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NOTES: $A_1 = 4°$. For this threat region the exposed armor surfaces are listed.

The obliquity and projected area ($\bar{a}_j$) of each armor area is calculated.

The ballistic limit (V_{50}) corresponding to the thickness and obliquity is obtained by reference to the curves in figure 3. (Interpolation between obliquity curves may be necessary.)

The expression $(V_s-V_{50})/\sigma$ is calculated for each armor area and referred to tables of normal probability to find the probability of defeating the threat (p_j). This is the area under the normal curve situated to the right of $(V_s-V_{50})/\sigma$.

Next, p_j is multiplied by the projected area to form the product $\bar{a}_j p_j$.

The $\bar{a}_j p_j$ are summed and the $\bar{a}_j$ are summed. The quotient, sum $\bar{a}_j p_j$ divided by sum $\bar{a}_j$, is entered as P_1 in the column headed P_i. The product A_1P_1 is in the column headed A_iP_i. P_1 is the probability of defeating the threat given that the attacking weapon is located in the first threat region.

The above six steps are repeated for each threat region until all have been considered. The columns of A_i and A_iP_i are then summed, and multiplied by 2 to account for both right and left halves of the threat. The quotient, sum A_iP_i divided by sum A_i, is denoted by $\bar{P}$. $\bar{P}$ represents the probability of providing protection against the threat of the attacking projectile, assuming that the weapon is located at random in the threat region as defined.