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Analysis of Terminal Metallic Armor Plate Free-Surface Bulging

by E. J. Rapacki, Jr.

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An analysis of the bulge formed on the free-surface of the terminal metallic plate of an armor array is shown to lead to reasonable estimates of the armor array's remaining penetration/perforation resistance. Terminal ballistic performance evaluations of penetrators and armors are often performed via statistical analyses to obtain a velocity or obliquity at which the expected probability of perforation is 0.5, or an analytical form relating the residual velocity of the emerging penetrator to the initial impacting velocity in order to determine a "limit velocity." Herein, bulge analysis of rolled homogeneous armor (RHA) plate indicates a plugging/breakout thickness related to the armor material but independent of penetrator material and that bulge extent is a function of penetrator material consistent with the penetrator's cavity formation characteristics. This breakout and bulge size information leads to expressions for remaining penetrable RHA vs. free-surface-bulge height for both tungsten-based-composite and uranium-alloy penetrators.

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Analysis of Terminal Metallic Armor Plate Free-Surface Bulging

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An analysis of the bulge formed on the free-surface of the terminal metallic plate of an armor array is shown to lead to reasonable estimates of the armor array's remaining penetration/perforation resistance. Terminal ballistic performance evaluations of penetrators and armors are often performed via statistical analyses to obtain a velocity or obliquity at which the expected probability of perforation is 0.5, or an analytical form relating the residual velocity of the emerging penetrator to the initial impacting velocity in order to determine a "limit velocity". Herein, bulge analysis of rolled homogeneous armor (RHA) plate indicates a plugging/breakout thickness related to the armor material but independent of penetrator material and that bulge extent is a function of penetrator material consistent with the penetrator's cavity formation characteristics. This breakout and bulge size information leads to expressions for remaining penetrable RHA vs. free-surface-bulge height for both tungsten-based-composite and uranium-alloy penetrators.

INTRODUCTION

The evaluation of kinetic energy (KE) penetrators and vehicular armors is usually posed as simple questions: 1) given a projectile's muzzle velocity and aerodynamic drag and the intended target's range, will the penetrator defeat the target, or 2) the converse question, will the vehicle remain protected if attacked. Research, Development, Test and Evaluation (RDT&E) procedures/protocols have been developed to help answer these questions as early in the materiel acquisition process as possible. R&D experiments may be performed at sub-scale or full-scale, while T&E is usually at full-scale. Late acquisition cycle T&E may also take the form of "live-fire-testing", where a sub-system's (e.g., the armor system(s)) performance is assessed as it may influence overall end-item system performance. For combat vehicles, overall system performance hinges on the ability to effectively engage enemy targets (firepower and mobility), which is critically dependent on survivability.

Some of the protocols developed for armor/anti-armor evaluation are:

1) $V_S - V_R$ formulas [1] where ordered pairs of striking and residual velocities are fitted to:

$$\begin{aligned} V_R &= \begin{cases} 0, & 0 \le V_S \le V_L \\ a\left(V_S^p - V_L^p\right)^{1/p}, & V_S > V_L \end{cases} \end{aligned} \tag{1}$$

where:

a and p are dimensionless fitting parameters subject to the constraints $0 \le a \le 1$ and $1 < p \le 8$, and

V_L is the limit velocity, demarking penetration vs. perforation likelihood

2) statistical V_{50} test method [2] to determine the ~50%-probability-of-perforation velocity by averaging the striking velocity of an equal number of tests that result in a penetration-only (partial penetration – PP) and a perforation (complete penetration – CP), and

3) armor effectiveness measures [3], e.g. spatial effectiveness E_S, areal mass density effectiveness E_M, (and their product $Q^2=E_M \cdot E_S$) for overall effectiveness compared to a notional reference monolithic armor equivalent, usually thick-section RHA [4], by comparing the armor line-of-sight thickness T_{LOS} with a reference depth-of-penetration or perforation, T_{REF}, at the same impact velocity and the post-perforation residual L-O-S penetration R_{REF} in the reference armor material, viz.:

$$\begin{aligned} E_S &= \frac{T_{REF} - R_{REF}}{T_{LOS}} \\ E_M &= \frac{\rho_{REF} \cdot \left(T_{REF} - R_{REF}\right)}{\sum_1^n \rho_i \cdot \left(t_{LOS}\right)_i} \end{aligned} \tag{2}$$

where: $T_{LOS}=\sum(t_{LOS})_i$ (sum-total L-O-S thickness of individual elements i), and ρ_{REF} and ρ_i the respective reference and element mass densities.

Reference 2 above incorporates specific requirements on the accuracy and precision of the input data; other standards expand on these, specific to their applications, e.g. [5].

Only the V_{50} test method [2] explicitly uses non-perforation data; the $V_S - V_R$ [1] and $E_M - E_S$ [3] methods explicitly require that the target be perforated in order to obtain data for analysis. This may lead to biases in the analyses in the following ways. Experimental data acquisition methods for V_R (usually via flash radiography) require target-free-surface to residual-witness-armor spacing larger than typically specified for obtaining R_{REF}. The residual penetrator may yaw considerably before producing residual penetration, thus, relating V_R and R_{REF} may not produce consistently reliable correlations. Moreover, semi-infinite penetration, finite perforation and residual penetration cannot be easily related over a broad impact velocity range. A long-rod-penetrator in deep penetration has a retarding penetrator-target interface velocity, but as this interface approaches a target free-surface, it accelerates – not by increasing target or penetrator erosion but by forming a plastic bulge on the free-surface. Heuristic quantification of these effects (in thick-section RHA at normal obliquity) is ~4 penetrator diameters from the free-surface the target is still behaving as a semi-infinite medium, and ~1 penetrator diameter can be added to semi-infinite penetration to approximate the finite thickness perforation at the same impact conditions – velocity, acceptable pitch and yaw.

Analysis of the bulged free-surface of a non-perforated terminal armor plate can provide useful information as to the remaining protection that the armor affords, or conversely, the additional capability that the penetrator must have in order to defeat the armor. Previous analytical analyses have been restricted to normal impact conditions to take advantage of the axial symmetry [6]. Nonetheless, comparisons of large-scale numerical simulations [7] with Walker's [6] analytical model are quite favorable. Thus, computational codes should prove quite reliable in predicting depth-of-penetration, bulge growth, target failure, limit velocities of penetrator-target combinations, and behind target ejecta of residual target and penetrator fragments in terms of their mass and velocity vectors. A limitation of the codes, however, is the material model descriptions, especially for failure modes, strengths and deformations. These material model parameters can be improved upon by validating the code predictions with statistically valid three-dimensional experimental results, (and adjusting material model parameters as required).

The purpose of the present work is two-fold. Firstly, an analysis is presented to provide estimates of remaining penetrable RHA protection given a measured free-surface bulge extent. This is different from the usual "penetrator-winner" situation in that this is an "armor-winner" situation. This may be particularly useful in assessing armor or penetrator performance where post-mortem target cross-sectioning is impractical, e.g. live-fire-testing. Secondly, statistically valid ballistic data is provided that may be used to improve material models (e.g.: equation-of-state, constitutive, fracture and failure) for RHA used in the numerical simulation codes. Additionally, the engineering model presented here may be expanded upon to lead to more robust physically-based analytical models.

EXPERIMENTAL

The experiments performed were traditional full-scale terminal ballistics tests of armor-piercing fin-stabilized discarding-sabot (APFSDS) long-rod-penetrators of initial length L_0, diameter $D=f(L)$, mass density ρ_P and strength Σ_P, which impacted targets at velocity V_0 and with pitch α and yaw β sufficiently small such that penetrator performance was not degraded. Penetrators were of uranium-alloy (U-pen) or tungsten-based-composite (W-pen), and initial impact velocity was $1500 < V_0\,(\text{m/s}) < 1700$. The targets consisted of modern-armor-technology "pre-terminal" armors (which defeated most of the penetrator) and a terminal-armor/structure-plate. This last plate was class 3 RHA of Brinell hardness $HB_{30}=321\pm10$[†] and was

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[†] Reference 4 specifies HB_{30} 269-311 for this thickness, however, the measured HB_{30} values were consistently 321±10.

63.5 mm (2-½") normal thickness. The entire armor package was oriented at θ = 30° obliquity (armor normal ← θ → penetrator line-of-flight) and the terminal armor plate spaced ~100 mm normal from RHA witness plates which were also oriented at θ = 30° obliquity.

Post-mortem measurements were: 1) the normal-to-the-free-surface maximum bulge height and 2) the normal remaining target-plate web thickness. The bulge was obtained first using a spanning apparatus and a digital caliper of 0.001" (0.0254 mm) resolution. The "feet" of the apparatus spanned the bulge's plane-of-symmetry at loci beyond any bulge deformation. The web measurement was obtained by saw-cutting the target through the bulge's plane-of-symmetry, and measuring the normal web thickness from the maximum bulge to the penetrator-target interface using a digital caliper. In cases where perforation occurred, but the ejected target plug was wholly recovered, the plug's thickness served as the web thickness measurement, and the maximum normal bulge measurement was obtained by reinserting the plug in the target's exit hole. (Such reinsertion usually requires some modification of the plug's lateral surfaces due to elastic release contraction of the exit hole's dimensions.) The raw-data measurements were normalized by the mean diameter of the estimated aft-end length of penetrator involved in the terminal plate penetration/perforation. For all the data presented herein, $D_{\text{pen aft}}$ is a constant. The data are presented in Figure 1; the uncertainties are smaller than the symbols.

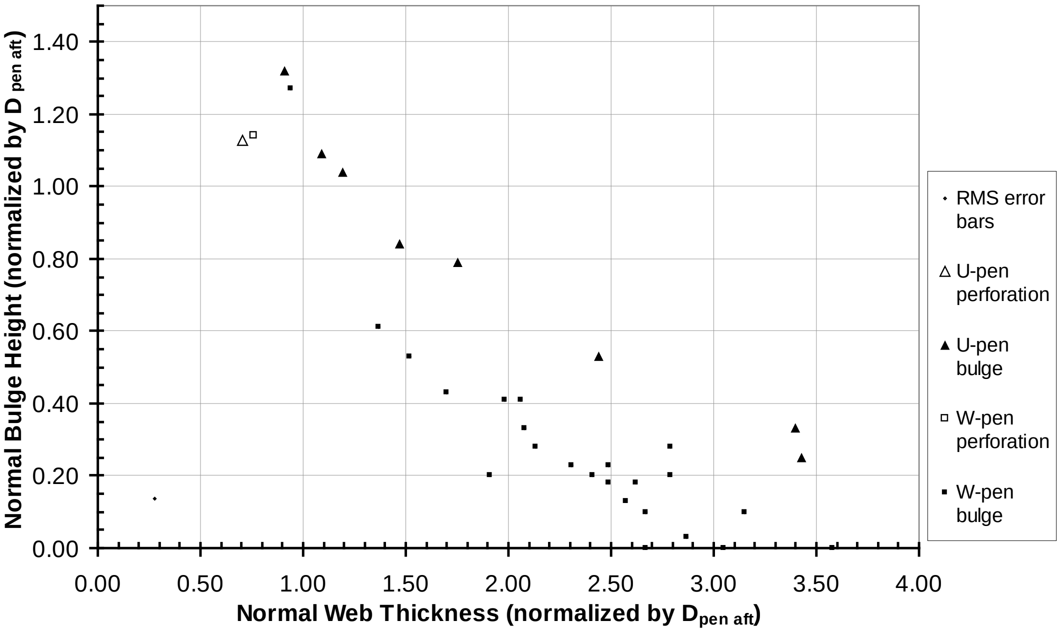

Figure 1. Bulge height vs. web thickness for HB_{30} 321 RHA @ θ=30°, for U-alloy and W-composite penetrators.

ANALYSES & RESULTS

Some qualitative observations of the data in Figure 1 are: 1) there were a paucity of data available for the limiting conditions of maximal bulge and minimal web, likely due to the instability and stochastic nature of the limit condition; 2) the perforation data (open symbols) were clearly demarked from the bulge data in both abscissa and ordinate, and U-pen and W-pen were only marginally different, likely due to the somewhat contrived nature of these data points (reinserted plug), but their similar values for both penetrator materials indicated that the plugging and break-out was primarily a function of target material strength and failure; and 3) the bulge data (filled symbols) appeared as two families of response function (U-pen and W-pen) and appeared to converge as they approached a demarcation of penetration/ bulging and perforation/plugging.

These qualitative observations lead to restrictions and questions in order to obtain quantitative results. The small sample sizes required small-sample statistics, i.e. Student's *t*-distributions, and appropriate hypothesis testing, q.v. e.g. [8]. The first question posed is: "Is there a difference in target performance near the limit condition depending on the penetrator material?" Quantitatively, the proposed null hypothesis (H_0) was:

$$H_0 : \left|\mu_U - \mu_W\right| - \Delta_{meas} = 0 \tag{3}$$

where:

μ_X – mean of <u>webs</u> of largest bulges and smallest <u>plugs</u> for a material X[††],
Δ_{meas} – root-mean-square uncertainty of the difference of the two means.

Statistically, H_0 could not be rejected, thus the means μ_U and μ_W were indistinguishable, and the grouped mean – $\mu_{w\text{-}RHA}$, provided a 50%-probability demarcation web thickness (normalized by $D_{pen\ aft}$) value between penetration/bulging and perforation/plugging of 0.830 (90% confidence interval: $0.698 \le \mu_{w\text{-}RHA} \le 0.962$). The penetration versus perforation probabilities vs. normal web thickness are illustrated in Figure 2.

The bulge-only data shown in Figure 1 suggested an exponential decay engineering model for each penetrator material X (U or W), viz.:

$$B_X = A_X \cdot exp\left(-c_X w\right) \tag{4}$$

where: A_X and c_X are data fitting parameters; w is normal web thickness and B_X the normal bulge height, both normalized by $D_{pen\ aft}$.

Analytical and statistical results are shown in Table I, where the ± uncertainties were calculated at the 90% confidence level, and R_{adj} determined from a linearized form of Equation 4. Note that $w_\cap$ (q.v. Table I) and $\mu_{w\text{-}RHA}$ were statistically equivalent, which corroborated the remaining normal web thickness equivalence at maximum bulging <u>and</u> plugging, and compared favorably with a value derived from data that Leavy reports for W-composite penetrators vs. RHA, viz.: 0.849 [9].

[††] For n_X data points, $n_X/2$ should be plugs and $n_X/2$ should be bulges; in the present work n_X=2.

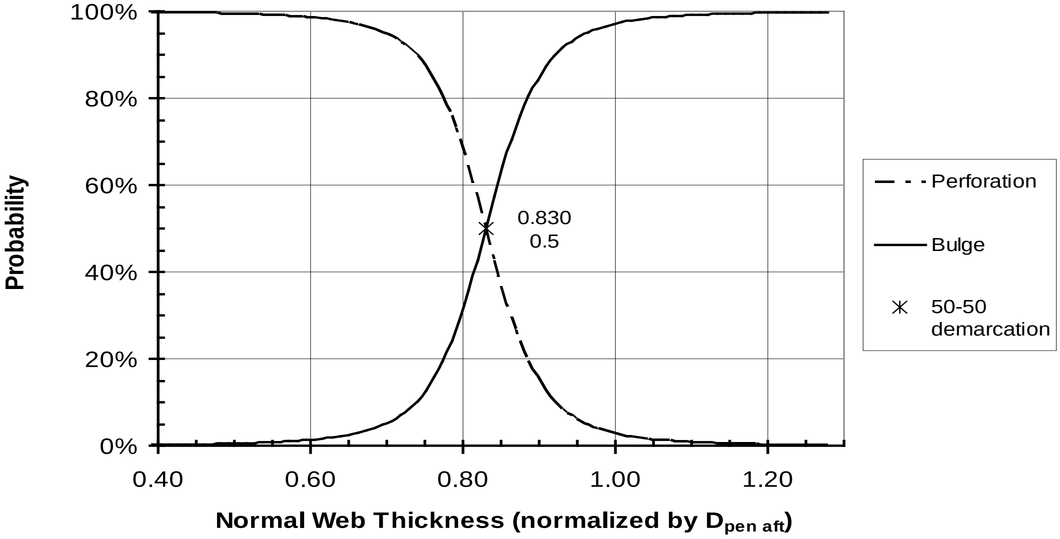

Figure 2. Perforation versus bulging probabilities vs. web thickness for $HB_{30}=321$ RHA @ $\theta=30°$ obliquity, for U-alloy <u>and</u> W-composite penetrators.

TABLE I. ANALYTICAL FITTING PARAMETERS FOR EQUATIONS (4) & (5), AND STATISTICAL RESULTS for $HB_{30}=321$, 63.5 MM THICK RHA @ $\theta=30°$ OBLIQUITY; FREE-SURFACE BULGED BY U-ALLOY or W-COMPOSITE PENETRATORS.

pen mat'l **X**	A_X	c_X	adjusted coeff. of determination, R_{adj}	U & W model's intersection, $w_{\cap}$	max bulge, B_{max}
U	2.1196 (+0.3121/ -0.2721)	0.58333 (±0.063084)	0.99174	0.8002 (+0.2065/-0.1808)	1.3290
W	3.4330 (+0.1877/ -0.1780)	1.18595 (±0.023068)	0.95170		

In order to provide a simple means to estimate the remaining penetrable RHA within the bulged terminal plate, the engineering model must be inverted and the plugging/break-out thickness subtracted from the resulting expression for normal web thickness, and adjusting for obliquity, viz.:

$$\frac{T_{\text{LOS RHA}}}{D_{\text{pen aft}}} = \left(\frac{\ln A_X - \ln B_X}{c_X} - \mu_{w-\text{RHA}} \right) \Big/ \cos\theta \qquad (5)$$

Equation (5) relates a normalized measured maximum normal bulge height (B_X) to a normalized remaining L-O-S penetrable thickness. Note that the first term in the numerator applies to a specific penetrator material X (U or W in the present work) and target material, and the second term applies to a specific hardness and thickness terminal armor plate at a specified obliquity (RHA, $HB_{30}=321$, and 63.5

mm thick @ θ=30° obliquity in the present work). Plots of example calculations of the present work are shown in Figures 3-5. It is clear that a large bulge means little remaining armor protection. In Figure 5, for a given ordinate, the U-pen shows a higher bulge, the lower bulge of the W-pen was likely accompanied by greater lateral extent of bulge, however, neither bulge lateral extents nor residual penetrator length or mass were measured in the present work.

DISCUSSION

Traditional methods [1-3] of armor-penetrator terminal ballistic performance assessment usually rely on perforation of the target (i.e. require residual velocity or residual penetration), and usually require a number of experimental results. Only the $E_M - E_S$ [3] method allows a "one-shot" assessment (provided the reference information is available). With the method provided herein, a similar "one-shot" assessment can be performed where the target is <u>not</u> perforated, and a simple exterior target measurement provides the data, however, the fitting parameters of Equation (5) for specific materials and geometries must be determined apriori.

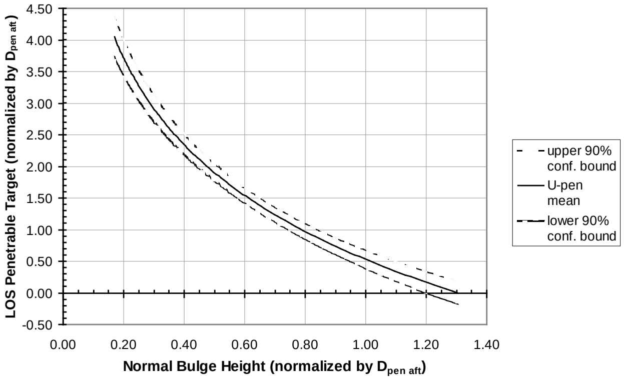

Figure 3. Equation (5) predictions for U-alloy penetrators (w/90% confidence bounds).

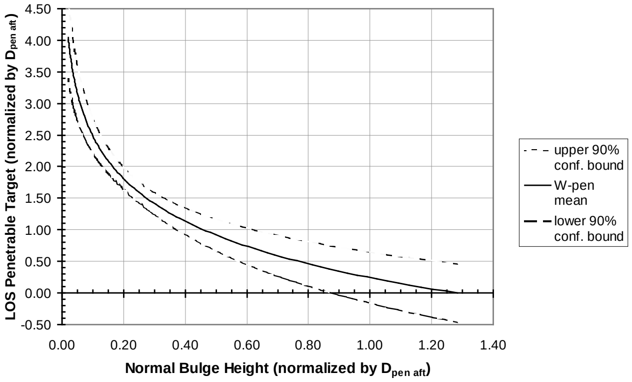

Figure 4. Equation (5) predictions for W-composite penetrators (w/90% confidence bounds).

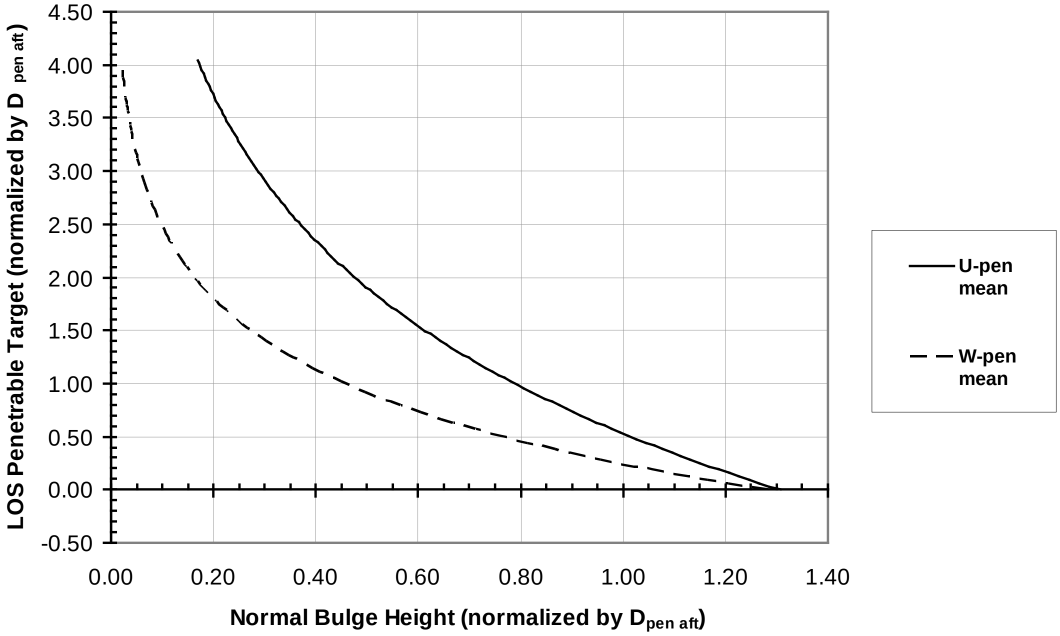

Figure 5. Comparison of remaining LOS penetrable target vs. bulge height for HB_{30}=321 RHA @ θ=30° obliquity for U-alloy and W-composite penetrators.

REFERENCES

1. Lambert, J. P. and G. H. Jonas, January 1976, "Towards Standardization in Terminal Ballistics Testing: Velocity Representation," US Army Ballistics Research Laboratories Report No. 1852, Aberdeen Proving Ground, MD 21005, USA.
2. AMSRD-ARL-WM-M, 18 December 1997, "V_{50} Ballistic Test for Armor," Department of Defense Test Method Standard, Mil-Std-662F, Aberdeen Proving Ground, MD 21005, USA.
3. Frank, K., March 1981, "Armor-Penetrator Performance Measures," US Army Ballistics Research Laboratories Memorandum Report No. ARBRL-MR-03097, Aberdeen Proving Ground, MD 21005, USA.
4. AMSRD-ARL-WM-MC, 20 July 2007, "Military Specification-Armor Plate, Steel, Wrought, Homogeneous (for use in combat-vehicles and for ammunition testing)," USA MIL-A-12560H (MR) w/Interim Amendment 4, Aberdeen Proving Ground, MD 21005, USA.
5. Office of Law Enforcement Standards (OLES) of the National Institute of Standards and Technology (NIST), June 2001, "Ballistic Resistance of Personal Body Armor NIJ Standard-0101.04 Revision A," National Institute of Justice, Office of Science and Technology, Washington, DC 20531, USA.
6. Walker, J. D., 1999, "An Analytic Velocity Field for Back Surface Bulging," Proceedings – 18th International Symposium on Ballistics, San Antonio, TX, 15-19 November 1999, pp. 1239-1246.
7. McGlaun, J. M., S. L. Thompson and M. G. Elrick, 1990, "CTH: A Three-Dimensional Shock Wave Physics Code," *Int. J. Imp. Engng.*, 10: 351-360.
8. Montgomery, D. C. and G. C. Runger, 2007, *Applied Statistics and Probability for Engineers, 4th ed.*, John Wiley & Sons, Inc.
9. Leavy, R. B., March 1996, "Improved Rolled Homogeneous Armor (IRHA)," US Army Research Laboratory Contractor Report No. ARL-CR-285, Aberdeen Proving Ground, MD 21005, USA.

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J LASALVIA
B SCOTT
AMSRD ARL WM SG
T ROSENBERGER
AMSRD ARL WM T
P BAKER
B BURNS
N GNIAZDOWSKI
D WEEKS
AMSRD ARL WM TA
M ATKIN
M BURKINS
P BARTKOWSKI
R DONEY
M DUFFY
R FREY
W GOOCH
D HACKBARTH
T HAVEL
V HERNANDEZ
C HOPPEL
E HORWATH
S HUG
T JONES
M KEELE
D KLEPONIS
C KRAUTHAUSER
R B LEAVY
M LOVE
H MEYER
P NETHERWOOD
J RUNYEON
S SCHOENFELD
D SHOWALTER
K STOFFEL
AMSRD ARL WM TB
S AUBERT
N ELDREDGE
F GREGORY
S KUKUCK
G RANDERS-PEHRSON
AMSRD ARL WM TC
J BARB
G BOYCE
N BRUCHEY
T EHLERS
T FARRAND
M FERMEN-COKER
E KENNEDY
K KIMSEY
J KINEKE
L MAGNESS
R MUDD
R PHILLABAUM
D SCHEFFLER
S SCHRAML
B SCHUSTER
S SEGLETES
R SUMMERS
A TANK
W WALTERS
G WATT
C WILLIAMS
AMSRD ARL WM TD
S BILYK
T BJERKE
D CASEM
J CLAYTON

NO. OF COPIES	ORGANIZATION
	D DANDEKAR M GREENFIELD C A GUNNARSSON Y HUANG R KRAFT B LOVE M RAFTENBERG E RAPACKI (5 CPS) M SCHEIDLER T WEERASOORIYA
	AMSRD ARL WM TE P BERNING D ECCLESHALL C HUMMER T KOTTKE A NIILER J POWELL B RINGERS G THOMSON
	AMSRD ARL SL R COATES
	AMSRD ARL SL BA M ENDERLEIN E HUNT J PLOSKONKA
	AMSRD ARL SL BE A DIETRICH
	AMSRD ARL SL BW W BRUCHEY

INTENTIONALLY LEFT BLANK.