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Optimum Velocity Penetrators

William S. de Rosset
D. Andrew D'Amico

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Three different representations of impact data have been examined. The data were limited to tungsten projectiles impacting rolled homogeneous steel armor at 0° obliquity. The impact velocity range was from 900 to 4,800 m/s, and the range of length-to-diameter (L/D) ratios was from 1 to 32. The data representations were used to determine the dependence of the optimum impact velocity on the L/D ratio. For two of the functions, the optimum velocity decreased rapidly as the L/D ratio went from 1 to 5. In general, the optimum velocity did not change a great deal as the L/D ratio went from 15 to 30. The values of the optimum velocity for long rods found in the present study did not differ significantly from previously determined values.

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1. INTRODUCTION

One of the goals of the Weapons Technology Directorate of the U.S. Army Research Laboratory is to understand the penetration performance of penetrators under certain circumstances. The penetration depth of tungsten rods into rolled homogeneous armor (RHA) is one such performance measure. It was shown by Frank and Zook (1987) that there exists an impact velocity such that, for a constant energy, constant length-to-diameter (L/D) ratio rod, the penetration depth is a maximum. This optimum velocity can be obtained from the penetration-vs.-velocity curve in a simple manner (Frank and Zook 1987, 1991). This has been done for three different analytical representations of data for tungsten penetrators (de Rosset 1992). All three data representations result in an optimum velocity of about 2.1 km/s. However, none of the three representations is well documented with respect to the data used or the method by which the constants for the analytical expressions were derived. In addition, only one of the analytical expressions contains dependence of penetration on length and diameter. The purpose of this work is to examine several functions which might be used to fit penetration-velocity data for tungsten penetrators impacting RHA. Each of the functions will have an explicit dependence on L/D ratio. The database will be screened for acceptable data (primarily low-yaw tests) and will feature a range of L/D ratios. These functions will then be used to determine an optimum velocity, based on the fitting parameters for each function. The dependence of the optimum velocity on L/D ratio will then be apparent.

The approach used was first to gather and screen data. One of the primary data sources used for this work was a recently published compendium of terminal ballistics data (Anderson, Morris, and Littlefield 1992). Other reports containing tungsten-vs.-RHA data were also examined (Magness and Leonard 1993; Frank and Zook 1987, 1990, 1991, 1992). Next, a suitable statistical analysis program was selected. The work started out using RS/1, which was soon discarded in favor of the more user-friendly SigmaPlot. Finally, several functions were considered to represent the data. The results from the fits to the data are compared in the discussion section.

Section 2 describes the general features of SigmaPlot, gives the criterion by which data were accepted, and documents the data used for this study. The following section describes the different fitting functions considered in this study. After the results section, the findings of this study are discussed. A concluding section summarizes the report.

2. APPROACH

SigmaPlot (Norby et al. 1986) is a program that uses a wide variety of graphing techniques to fit data in a statistical manner. The data worksheet in SigmaPlot consists of over 64,000 rows and 16,000 columns. The following parameters are used as input to fit the prescribed curve: the ratio of penetration depth to initial rod length (P/L), penetrator material density, rod L/D ratio, and rod striking velocity (v). The target density was taken to be 7.85 g/cm^3 in all cases. The prescribed function is then entered into the program. In all cases, the function is limited to two fitting parameters, which are labeled A and B. The Marquardt-Levenberg algorithm is then used by the program to find the values of A and B, which minimize the difference between the data and the function in a least-squares manner. The program also calculates the standard error for A and B. This is used to determine the coefficient of variation (CV), defined by

$$CV = \text{standard error} \times 100/\text{parameter value}. \tag{1}$$

CV is a measure of how well the choice of the function and the fitting parameters represent the data and will be used to select the best fitting function of the ones examined.

All the data were screened to eliminate high-yaw impacts. This was done in order to reduce the amount of scatter and assure that the maximum penetration at each velocity was being entered into the database. The criterion used to exclude data was that the impact yaw could not exceed a critical yaw given by the following formula (Bjerke et al. 1992):

$$\text{critical yaw} = \sin^{-1}\left[(H-D)/2L\right]. \tag{2}$$

Here, H is the penetration channel entrance diameter, L is the penetrator length, and D is the penetrator diameter. The channel entrance diameter is also found in Bjerke et al. (1992) and given by

$$H = \left(1.524 + .3388v + .1286v^2\right)D, \tag{3}$$

where v is the impact velocity.

An attempt was made to screen the targets according to their hardness. This was not always possible, since in some instances the target hardness was not reported. In those tests where the hardness was reported, the values ranged between BHN 255 and 290. Targets identified as mild steel were not included in the database.

The data points used in this study are provided in the Appendix in the event that others may wish to use them to fit different functions. Table 1 summarizes the sources, range of parameters, and amount of data from each of the sources. The data set is limited to 0° obliquity targets, and the range of penetrator masses was from 30 to 250 g. While this data set does not include every test that has been conducted, it does represent a large number of tests.

Table 1. Data Summary

Source	L/D	Velocity Range (m/s)	No. of Data Points
Hohler and Stilp (1991a)	1, 10, 16.3, 17.5, 20, 21.7, 22, 22.5, 32	951–3,663	55
Hohler and Stilp (1991b)	1, 3, 5, 7	2,281–3,652	18
de Rosset et al. (1989)	15, 20, 30	2,140–3,050	13
Magness and Leonard (1993)	20	1,167–1,680	8
Silsby (1984)	23	1,865–4,525	10
Frank and Zook (1990)	1.0	906–4,881	18

Figure 1 shows this data graphically.

3. DATA REPRESENTATION

In choosing a function to fit the penetration depth vs. velocity for tungsten impacting RHA at 0° obliquity, there were several criteria which had to be met. First, it was desirable that the function had some connection to physical reality. That is, a high-order polynomial was not considered. (See Bless et al. [1994] for an eight-parameter fit.) However, for this particular study the effect of target and

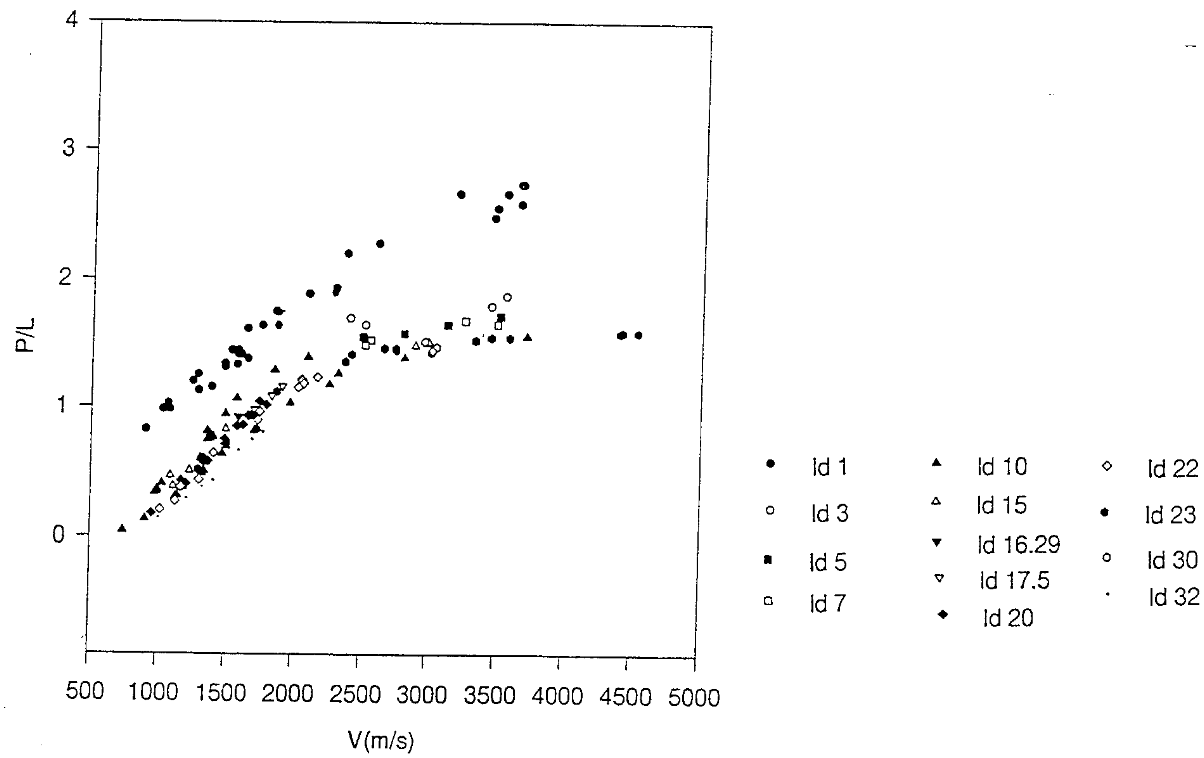

Figure 1. Graphical representation of penetration data.

penetrator hardnesses was ignored. This effect would have to be included in future refinements of the model, assuming that there is enough data in existence where the target hardness was measured (and the target, in fact, had a uniform through-thickness hardness). The function had to contain a dependence on L/D. The behavior of the function at input variable extremes (e.g., very high velocity, very high or low L/D ratio, etc.) had to produce the expected limiting conditions. The number of fitting parameters was limited to two. Finally, the function had to fit the data in a statistical sense.

The first function which was examined was suggested by Frank (1994):

$$P/L = 1/\mu \cdot (v/A)^{[2/(1+2L/D)]} \exp\left[-(B/v)^2\right], \tag{4}$$

where μ is the square root of the ratio of target and penetrator densities. In this and the functions which follow, μ is present to account for small differences in various tungsten alloy densities. It also shows explicitly that the formulation approaches the density law for high L/D ratios and high velocity. This function produces the characteristic $v^{2/3}$ dependence for L/D = 1 penetrators at high velocity, and, the expected v^2 dependence for $L/D \rightarrow \emptyset$ (Orphal et al. 1993). The exponential is that used by Lanz and Odermatt (1992) to fit full-scale data. A more thorough discussion of the exponential function is given by Frank et al. (1992), who relate B to such parameters as target resistance and penetrator strength. Equation 4 will be referred to as Formula 1.

The special feature of this function is that a simple analytical expression for the optimum velocity of constant energy penetrators can be obtained. Assuming constant penetrator energy, constant penetrator geometry (L/D ratio), and penetration depth equal to penetrator length times a function of penetrator velocity and other relevent parameters (density, material strength, etc.), Frank and Zook (1991) give the condition for optimum penetrator velocity as

$$v(\partial P/\partial v) = 2/3 \ P. \tag{5}$$

For Formula 1, the optimum velocity is given by

$$v_{opt} = B \sqrt{3} \ / \sqrt{\left[1-\left(3/(1+2 \ L/D)\right)\right]} \ , \tag{6}$$

which, for $L/D \rightarrow \infty$, is identical to the optimum velocity derived by Frank et al. (1992).

Formula 1 was used to fit the data, and it was found that the fit at low to moderate velocities was fair. A second formulation was examined in an attempt to improve the fit. This formulation divided the penetration into two parts: a steady-state, long-rod contribution and a low L/D portion. The formulation follows the concept of Christman and Gehring (1966), who divided the penetration process into four parts. The two parts of the current formulation correspond to the primary and secondary penetration phases of Christman and Gehring. The formulation is given as

$$P/L = (1/\mu) \left((1-D/L) \exp\left[-(B/v)^2\right] + D/L \ (v/A)^{2/3}\right). \tag{7}$$

The idea here is that a length of rod equal to L – D contributes to and is eroded in the steady-state phase, while the remaining length D contributes to the final portion. For L = D, the usual dependence of P on

$v^{2/3}$ is recovered. The approach is similar to that used by Charters and Orphal (1988) and is denoted by Formula 2.

This representation results in an expression for the optimum velocity which is even simpler than that given by equation 6. In this particular case,

$$v_{opt} = B\sqrt{3}. \tag{8}$$

Thus, while P/L depends explicitly on L/D, the optimum velocity does not.

Charters (1992) has concluded that a function of the form $(v - vo)^{2/3}$ fits L/D = 1 penetration data better than a simple $v^{2/3}$ form. Frank and Zook (1990) have also derived an analytic expression for low L/D penetrators which fits the data well at all velocities. The general velocity dependence of their model was used to replace the $v^{2/3}$ in the previous model, now denoted as Formula 3:

$$P/L = 1/\mu \left((1 - D/L) \exp\left[-(B/V)^2\right] + D/L * \ln\left[1 + (v/A)^2\right]\right). \tag{9}$$

The expression for the optimum velocity using this formulation is not straightforward. While it may be possible to solve for v_{opt} in an analytical expression, the approach used here was simply to obtain v opt numerically for the desired L/D ratio.

4. RESULTS

The calculated values of A and B are shown in Table 2 along with the standard error and CV.

Table 2. Curve-Fitting Parameters

	A (m/s)	CV (%)	B (m/s)	CV (%)
Formula 1	1,098	3.2	1,068	2.7
Formula 2	1,471	2.2	1,215	2.4
Formula 3	1,365	1.6	1,198	2.7

The formulas and associated values of A and B were used to generate the optimum velocities. Table 3 compares the optimum velocities for each of the formulas at selected L/D ratios.

Table 3. Optimum Velocities

	L/D 3 (m/s)	L/D 5 (m/s)	L/D 10 (m/s)	L/D 30 (m/s)
Formula 1	2,516	2,230	2,054	1,950
Formula 2	2,104	2,104	2,104	2,104
Formula 3	2,702	2,397	2,220	2,120

The dependence of the optimum velocity on L/D for each of the formulas is shown in Figure 2. For Formula 1 and Formula 3, there is a substantial change in the optimum velocities as the L/D ratio goes from 1 to 5. For values of L/D over 15, there is not a substantial change in the optimum velocity. The optimum velocity for Formula 2 is independent of the L/D, as previously stated. The value of the optimum velocity for Formula 2 is close to that obtained for high L/D ratios using Formula 3.

5. DISCUSSION

Each of the three functions chosen to represent the data provides a reasonable fit, considering that only two parameters were used. In addition, a wide range of velocities, L/D ratios, and data sources was used as input. This could also account for values of CV being higher than desired. The three functions give an explicit dependence of P/L on the L/D ratio, and this translates into a dependence of the optimum velocity on L/D ratio for two of the functions. From the results generated, it is clear that the optimum velocity does not change a great deal for rods with L/D greater than 15. In addition, the results indicate that the optimum velocity for long rods found during this study is not a great deal different from the values previously determined (de Rosset 1992; Frank and Zook 1987, 1991).

Conversely, the optimum velocity for short rods may be considerably higher than 2.1 km/s. This implies that segmented rods (with low aspect ratio segments) must be fired at much higher velocities than conventional long rods to achieve their optimum performance.

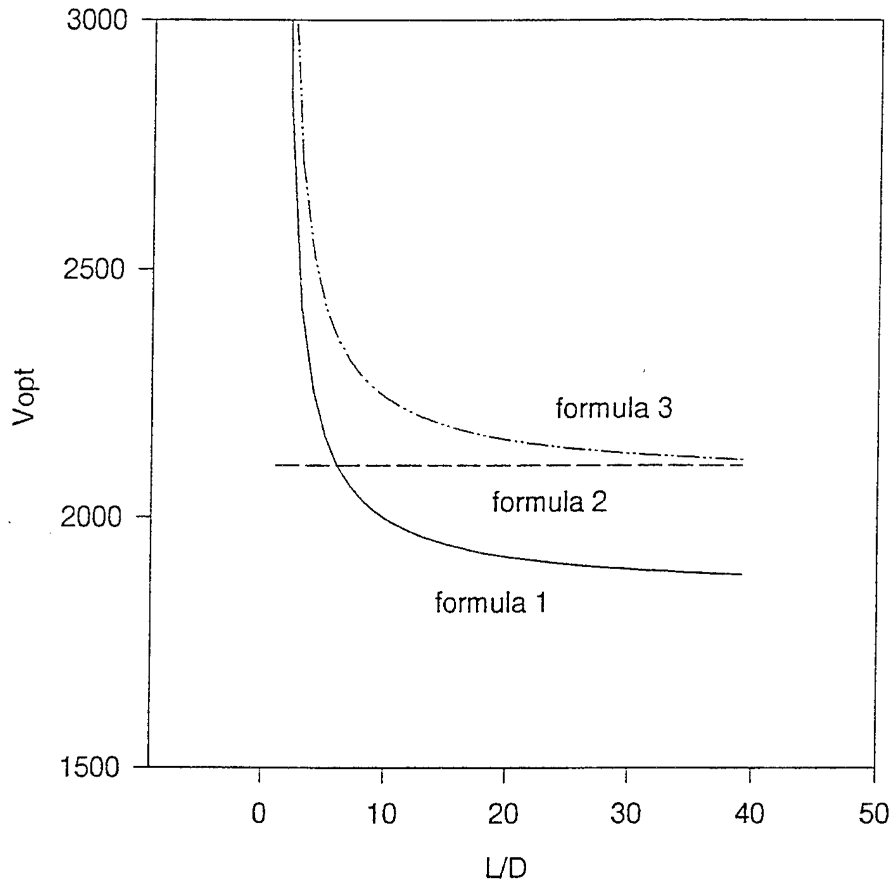

Figure 2. Optimum velocity vs. L/D ratio for three formulations.

Several different subsets of the data presented in the Appendix were examined with SigmaPlot to see if inclusion of certain data was producing abnormal results. The L/D = 1 data points were removed, with little effect on the results. In fact, the value of CV for the functions increased, since the standard error for these points was lower than average. In another instance, only the L/D = 20 points were considered. While the value of A and B for Formula 3 changed somewhat, the value of CV did not decrease. A plot of the curve fit to these data points is shown in Figure 3. Data points at 1,500 m/s and below fall below the fitted curve. This may be due to the incorrect assumption that an amount equal to L-D of the rod length is entirely eroded during the steady-state process at all velocities. In fact, at low velocities, only a portion of the rod is eroded. Thus, the contribution to the penetration depth at low velocity would be lower than the formula predicts. If the formula were fit only to the high velocity data, the discrepancy would be even more obvious.

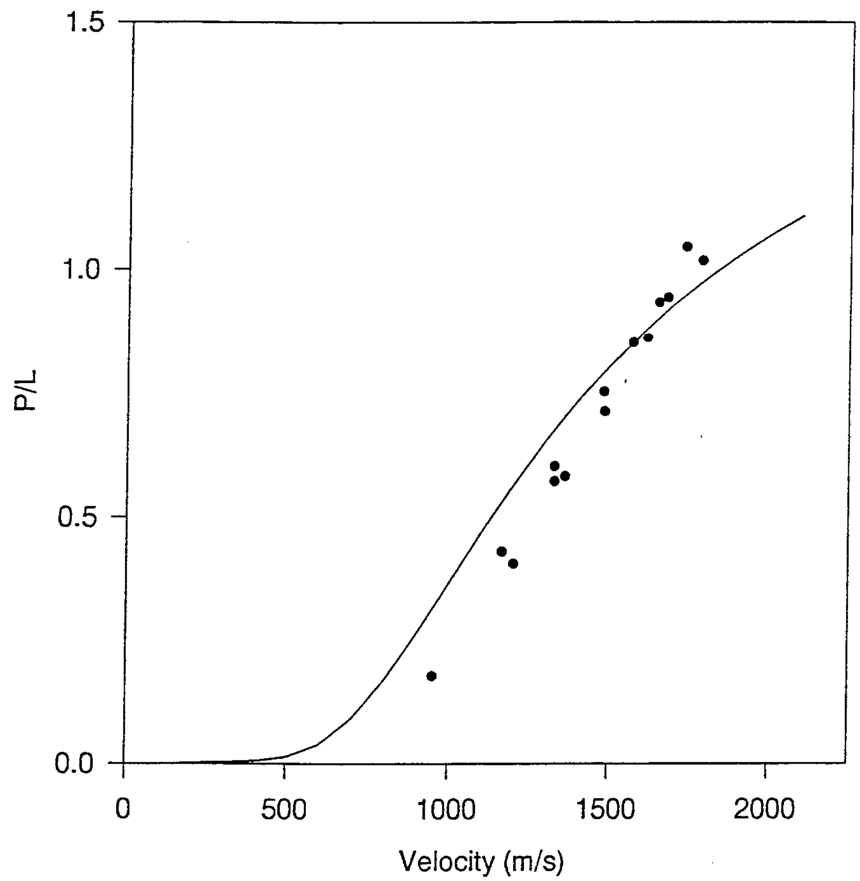

Figure 3. Comparison of L/D 20 data with Formula 3 representation.

In Formula 2, the dependence of penetration depth on $v^{2/3}$ for L/D = 1 penetrators also has the same problem. The relationship can be derived by setting the penetrator's kinetic energy (KE) proportional to the crater volume and assuming a hemispherical crater shape. This may have some validity at high velocity, but at low velocity the relationship breaks down. Note that using this proportionality leads to a constant penetration depth for a constant energy L/D = 1 penetrator at any velocity. Thus, using the $v^{2/3}$ dependency for the L/D = 1 rods in Formula 2 will not influence the determination of the optimum velocity.

An obvious point to make about this curve-fitting exercise is that it is valid only for the range of data employed. Thus, for L/D less than 1, there may be important features that are not captured by the formulas used here. In fact, Bjerke et. al (1991) have shown that P/L increases with decreasing L/D, but only to the point where L/D is approximately 1/8. For smaller values of L/D, P/L actually decreases.

Consequently, the extemely high values of the optimum velocity derived from Formulas 1 and 3 for penetrators with L/D near 1 are suspect.

6. SUMMARY

The effect of the L/D ratio on the optimum penetration velocity has been examined for tungsten penetrators impacting rolled homogeneous armor at 0° obliquity. Three different formulas were used to represent about 125 data points obtained from the open literature, spanning a large range of velocities and L/D ratios. The formulas were chosen based on some rudimentary physical considerations and simplicity. Only two adjustable parameters were used.

For two of the formulas, the optimum velocity decreased rapidly as the L/D ratio went from 1 to 5. The other formula did not show any dependence of the optimum velocity on L/D ratio. All formulas indicated that for L/D greater than 15, there was very little change in the optimum velocity, which was calculated to be between 1,900 and 2,200 m/s. This range of values is consistent with other values that have been calculated previously for long-rod tungsten penetrators.

If the optimum velocity dependence on L/D is derived from either Formula 1 or Formula 3, then the optimum velocity for a segmented rod with L/D 1 segments will be in excess of 3,000 m/s for the conditions examined, assuming no segment interactions.

7. REFERENCES

Anderson, Jr., C. E., B. L. Morris, and D. L. Littlefield. "A Penetration Mechanics Database." SwRI Report 3593/001, Southwest Research Institute, San Antonio, TX, January 1992.

Bjerke, T. W., G. F. Silsby, D. R. Scheffler, and R. M. Mudd. "Yawed Long-Rod Armor Penetration." International Journal of Impact Engineering, vol. 12, no. 2, pp. 281–292, 1992.

Bjerke, T. W., J. A. Zukas, and K. D. Kimsey. "Penetration Performance of Tunsten Alloy Penetrators With L/D Ratios of 1 to 1/32." BRL-TR-3246, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1991.

Bless, Stephan, Ravi Subramanian, and Thomas Kiehne. "Performance of L/D = 30 Tungsten Rods Against RHA at 1.8 and 2.6 km/s." IAT.R0026, Institute for Advanced Technology, Austin, TX, May 1994.

Charters, A. C. "A New Look at the Penetration of Heavy Armor by Constant Energy Segmented Rods at Velocities from 1.5 to 5.0 km/s." Paper No. 12861, Classified Session of the Hypervelocity Impact Symposium, Institute for Advanced Technology, University of Texas, Austin, TX, November 1992.

Charters, A. C., and D. L. Orphal. "Penetration of Homogeneous Armor by Continuous and Segmented Rods at High Velocity." Briefing given to the Defense Advanced Research Projects Agency, Arlington, VA, March 1988.

Christman, D. R., and J. W. Gehring. "Analysis of High-Velocity Projectile Mechanics." Journal of Applied Physics, vol. 37, no. 4, pp. 1579–1587, March 1966.

de Rosset, W. S. "Optimum Velocity for High-Velocity Penetrators." BRL-TR-3377, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1992.

de Rosset, W., G. Silsby, K. Kimsey, and D. Scheffler. "Effects of Increased Penetrator Velocity, Part I." BRL-MR-3799, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, November 1989.

Frank, K. Private communication. U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, January 1994.

Frank, K., M. J. Keele, E. J. Rapacki, J. A. Zook, and R. E. Joinson. "Uranium and Tungsten Heavy Alloy, Constant Geometry Kinetic Energy Penetrators: Full-Scale Terminal Ballistic Results and Analysis." Proceedings of the Second Ballistics Symposium on Classified Topics, Johns Hopkins Applied Physics Laboratory, 26–29 October 1992.

Frank, K., and J. Zook. "Energy Efficient Penetration and Perforation of Targets in the Hypervelocity Resume." International Journal of Impact Engineering, vol. 5, pp. 277–284, 1987.

Frank, K., and J. Zook. "Energy Efficient Perforation of Targets." BRL-MR-3885, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, February 1991.

Frank, K., and J. Zook. "Chunky Metal Penetrators Act Like Constant Mass Penetrators." Proceedings of the 12th International Symposium on Ballistics, San Antonio, TX, November 1990.

Hohler, V., and A. Stilp. Tabulated data in letter of 21 June 1991a.

Hohler, V., and A. Stilp. Tabulated data from a letter of 6 August 1991b.

Magness, L., and W. Leonard. "Scaling Issues for Kinetic Energy Penetrators." Proceedings of the 14th International Symposium on Ballistics, Quebec, Canada, September 1993.

Norby, J., S. Rubenstein, T. Tuerke, C. S. Farmer, R. Forood, and J. Bennington. "SigmaPlot." Jandel Software, 1986–1992.

Lanz, W., and W. Odermatt. "Penetration Limits of Conventional Large Caliber Anti Tank Guns/Kinetic Energy Projectiles." Proceedings of the 13th International Ballistics Symposium (vol. 3: Terminal Ballistics Vulnerability Modeling), Stockholm, Sweden, 1–3 June 1992.

Orphal, D. L., C. E. Anders, Jr., R. R. Franzen, J. D. Walker, P. N. Schneidewind, and M. E. Majerus. "Impact and Penetration by L/D < 1 Projectiles." International Journal of Impact Engineering, vol. 14, pp. 551–560, 1993.

Silsby, G. F. "Penetration of Semi-Infinite Steel Targets by Tungsten Long Rods at 1.3 to 4.5 km/s." Proceedings of the Eighth International Symposium on Ballistics, Orlando, FL, October 1984.

APPENDIX: BALLISTIC DATA

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Table A-1. Data from Hohler and Stilp (1991a)

Test No.	ρ (g/cm²)	L (mm)	L/D	P (mm)	P/L	v (m/s)
3140	17	87	10	74	0.851	1,475
2789	17	116	20	20.6	0.178	951
2791	17	116	20	47.2	0.407	1,203
2810	17	116	20	67.3	0.58	1,363
2440	19.3	60	10	21.6	0.36	992
2787	19.3	60	10	24.4	0.407	1,025
2917	19.3	60	10	48.8	0.813	1,354
2433	19.3	60	10	47.5	0.792	1,373
2796	19.3	60	10	56.7	0.945	1,487
2925	19.3	60	10	64	1.067	1,570
2593	19.3	60	10	77.4	1.290	1,846
2821	19.3	60	10	83.5	1.392	2,089
2439	18	60	10	20.7	0.345	990
2431	18	60	10	46.1	0.768	1,399
2441	18.5	60	10	20.4	0.34	976
2435	18.5	60	10	44.8	0.747	1,357
2432	18.5	60	10	45.2	0.753	1,377
4845	17.6	9	1	9.2	1.022	1,067
4846	17.6	9	1	10.8	1.200	1,244
4847	17.6	9	1	10.4	1.156	1,385
4844	17.6	9	1	12.4	1.378	1,648
4843	17.6	9	1	17	1.889	2,093
4841	17.6	9	1	19.8	2.200	2,368
4849	17.6	9	1	24	2.667	3,203
4851	17.6	9	1	24	2.667	3,650
4852	17.6	9	1	24.6	2.733	3,663
4888	17.6	9	1	24.6	2.733	3,845
4098	17.6	101.5	17.5	99.2	0.977	1,700
4104	17.6	101.5	17.5	110.5	1.089	1,828
4103	17.6	101.5	17.5	118	1.163	1,906
4342	17.6	94.5	16.29	92.5	0.979	1,700
4458	17.6	102.14	16.29	94	0.920	1,582

Table A-1. Data From Hohler and Stilp (1991a) (continued)

Test No.	ρ (g/cm²)	L (mm)	L/D	P (mm)	P/L	v (m/s)
4099	17.6	116	20	108	0.931	1,653
4102	17.6	116	20	118	1.017	1,790
4919	17.6	124	20	129.6	1.045	1,737
4136	17.6	125.86	21.7	113.3	0.900	1,725
4138	17.6	125.86	21.7	121.3	0.964	1,740
4172	17.6	107.8	22	124.4	1.154	2,023
4163	17.6	107.8	22	131.1	1.216	2,048
4164	17.6	107.8	22	130.2	1.208	2,049
4157	17.6	107.8	22	127.8	1.186	2,063
4171	17.6	107.8	22	133.4	1.237	2,162
5131	17.6	110.25	22.5	22.9	0.208	1,015
5135	17.6	110.25	22.5	48.5	0.440	1,299
5154	17.6	110.25	22.5	42	0.381	1,164
5155	17.6	110.25	22.5	70.8	0.642	1,403
5133	17.6	110.25	22.5	30	0.272	1,126
5136	17.6	156.8	32	22.4	0.143	1,007
5149	17.6	156.8	32	46	0.293	1,213
5150	17.6	156.8	32	60.1	0.383	1,325
5156	17.6	156.8	32	67.9	0.433	1,407
4402	17.6	163.2	32	108.1	0.662	1,590
4459	17.6	163.2	32	122	0.748	1,690
4460	17.6	163.2	32	131.6	0.806	1,771
4461	17.6	163.2	32	175.5	1.075	1,903

Table A-2. Data From Hohler and Stilp (1991b)

Test No.	ρ (G/cm^2)	L (mm)	L/D	P (mm)	P/L	v (m/s)
6536	17.6	5.8	1	11.0	1.897	2,281
6537	17.6	5.8	1	11.2	1.931	2,291
6545	17.6	5.8	1	13.2	2.276	2,602
6524	17.6	5.8	1	14.4	2.483	3,459
6517	17.6	5.8	1	14.8	2.552	3,480
6516	17.6	5.8	1	15.0	2.586	3,652
6539	17.6	17.4	3	29.5	1.695	2,400
6559	17.6	17.4	3	28.6	1.644	2,513
6576	17.6	17.4	3	31.2	1.793	3,448
6569	17.6	17.4	3	32.6	1.874	3,555
6543	17.6	29.0	5	45.0	1.552	2,494
6540	17.6	29.0	5	45.8	1.579	2,803
6573	17.6	29.0	5	47.8	1.648	3,128
6575	17.6	29.0	5	49.8	1.717	3,513
6577	17.6	40.6	7	62.0	1.527	2,553
6556	17.6	40.6	7	60.4	1.488	2,511
6508	17.6	29.4	7	49.4	1.680	3,257
6621	17.6	29.4	7	48.6	1.653	3,494

Table A-3. Data From de Rosset et al. (1989)

Test No.	ρ (G/cm²)	L (mm)	L/D	P (mm)	P/L	v (m/s)
6289	17.2	125	15	186	1,488	2,890
6296	17.2	125	15	188	1,504	2,980
6297	17.2	125	15	189	1.512	2,990
6290	17.2	152	20	220	1.447	2,900
6298	17.2	152	20	229	1.507	2,980
6299	17.2	152	20	230	1.513	3,020
6313	17.2	152	20	220	1.447	2,420
6317	17.2	152	20	210	1.381	2,330
6291	17.2	198	30	287	1,449	3,020
6315	17.2	198	30	292	1,475	3,050
6331	17.2	198	30	284	1,434	3,010
6314	17.2	191	20	250	1.309	2,180
6328	17.2	191	20	244	1.277	2,140

Table A-4. Data From Magness and Leonard (1993)

Test No.	ρ (G/cm²)	L (mm)	L/D	P (mm)	P/L	v (m/s)
—	17.6	—	20	—	0.86	1,619
—	17.6	—	20	—	0.94	1,680
—	17.6	—	20	—	0.71	1,486
—	17.6	—	20	—	0.60	1,329
—	17.6	—	20	—	0.43	1,167
—	17.6	—	20	—	0.57	1,331
—	17.6	—	20	—	0.75	1,484
—	17.6	—	20	—	0.85	1,573

Table A-5. Data From Silsby (1984)

Test No.	ρ (G/cm^2)	L (mm)	L/D	P (mm)	P/L	v (m/s)
5833	17.3	155.83	22.8	174.5	1.119	1,865
5841	17.3	121.79	23.1	165.2	1.356	2,365
5840	17.3	121.79	22.8	172.3	1.415	2,409
5835	17.3	155.83	23.1	228.5	1.466	2,653
5834	17.3	155.83	23.2	228.0	1.463	2,742
5843	17.3	121.79	23.5	176.3	1.448	2,746
5838	17.3	155.83	22.9	237.9	1.524	3,335
5842	17.3	121.79	23.1	188.6	1.549	3,580
5836	17.3	155.83	22.7	248.1	1.592	4,415
5844	17.3	121.69	23.2	193.7	1.591	4,525

Table A-6. Data From Frank and Zook (1990)

Test No.	ρ (G/cm^2)	L (mm)	L/D	P (mm)	P/L	v (m/s)
—	17.16	15.24	1	12.5	0.82	906
—	17.16	15.24	1	15.0	0.98	1,027
—	17.16	15.24	1	15.0	0.98	1,078
—	17.16	15.24	1	19.0	1.25	1,283
—	17.16	15.24	1	17.2	1.13	1,286
—	17.16	15.24	1	20.5	1.34	1,480
—	17.16	15.24	1	20.0	1.31	1,481
—	17.16	15.24	1	22.0	1.44	1,527
—	17.16	15.24	1	20.3	1.33	1,572
—	17.16	15.24	1	21.5	1.41	1,573
—	17.16	15.24	1	22.0	1.44	1,578
—	17.16	15.24	1	21.5	1.41	1,600
—	17.16	15.24	1	24.5	1.61	1,642
—	17.16	15.24	1	25.0	1.64	1,748
—	17.16	15.24	1	26.7	1.75	1,853
—	17.16	15.24	1	26.5	1.74	1,864
—	17.16	15.24	1	25.0	1.64	1,867
—	17.3	25.4	1	99.3	3.90	4,881

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