ARMY RESEARCH LABORATORY

Penetration of Multiple, Axially Offset, Disk-Shaped Penetrators

by Kent Kimsey and Stephen J. Schraml

ARL-TR-2507

June 2001

Approved for public release; distribution is unlimited.

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

ARL-TR-2507 **June 2001**

Penetration of Multiple, Axially Offset, Disk-Shaped Penetrators

Kent Kimsey and Stephen J. Schraml
Weapons and Materials Research Directorate, ARL

Abstract

The terminal ballistic performance of high-velocity, low length-to-diameter (L/D) ratio projectiles impacting steel targets has been a topic of considerable interest in penetration mechanics to evaluate the efficacy of segmented projectiles. A computational study has been conducted to examine the penetration performance of multiple (i.e., three), axially offset, disk-shaped projectiles impacting semi-infinite rolled homogeneous armor (RHA). A constant 3.25 projectile diameter separation distance between each disk-shaped projectile was maintained for the impact conditions modeled in this study. The three-dimensional (3-D) simulations suggest that the total depth of penetration into steel is not degraded for disk offsets less than 0.5 projectile diameters based on the range of disk offsets modeled in the study.

Contents

INTENTIONALLY LEFT BLANK.

List of Figures

INTENTIONALLY LEFT BLANK.

List of Tables

INTENTIONALLY LEFT BLANK.

1. Introduction

The penetration performance of high-density, low length-to-diameter (L/D) ratio projectiles impacting steel targets has been a topic of considerable interest in penetration mechanics due to the speculated performance of a segmented rod projectile. This has been spurred by the observation that normalized penetration performance, i.e., penetration per unit length (P/L), increases as L/D decreases, provided that the impact velocity is relatively high. Computational and experimental research to date has focused on penetrators shaped as either spheres or right-circular cylinders, with an L/D of 1 or slightly greater [1–18]. De Rosset and Sherrick [19] modeled segmented rod performance at ordnance velocity for high-density tungsten alloy segments with an L/D of 1. They observed that multiple segment rod performance was less than that predicted by simply multiplying single segment performance by the total number of segments due to interactions with residual segment material in the penetration cavity.

Recently, computational and experimental studies have focused on characterizing and understanding the penetration mechanics of high-density metallic projectiles with an L/D ratio of less than 1 [20–22]. Herbette [23] noted a dramatic increase in P/L for steel disks with an L/D ratio of 1/30, impacting aluminum targets at 2 km/s when compared to penetrators with considerably greater L/D. Orphal and Franzen [24] also reported a significant increase in P/L as projectile L/D was reduced from 1 to 1/8 for tungsten, tungsten alloy, and tantalum alloy projectiles impacting steel targets at striking velocities between 1.5 km/s and 7.5 km/s. A thorough review of the fundamentals of penetration and perforation of solids and their application to practical problems has been prepared by Goldsmith [25], Johnson [26], Backman and Goldsmith [27], Zukas et al. [28], and Zukas [29].

This report summarizes a numerical study to examine the penetration performance of multiple (i.e., three) tungsten heavy alloy (WHA), axially offset, disk-shaped projectiles impacting semi-infinite rolled homogeneous armor (RHA) at a striking velocity of 2.6 km/s. The separation distance between each disk-shaped projectile is 3.25 projectile diameters. Segment offsets between 0 and 1 projectile diameters were modeled in the study. The impact dynamics of multiple, axially offset, disk-shaped projectiles impacting a steel target are discussed in the sections that follow.

2. Numerical Model

The numerical study was conducted with the Eulerian wave propagation code CTH [30]. A single program multiple data (SPMD) paradigm with explicit message passing between computational subdomains was used to map the global computational domain onto a scalable architecture [31]. CTH is a family of computer programs for modeling solid dynamics problems involving shock wave propagation, multiple materials, and large deformations in one, two, and three dimensions. CTH employs a two-step solution scheme: a Lagrangian step followed by a remap step. The conservation equations are replaced by explicit finite volume equations that are solved in the Lagrangian step. The remap step uses operating splitting techniques to replace multidimensional equations with a set of one-dimensional (1-D) equations. The remap or advection step is based on a second order accurate van Leer scheme. To minimize material dispersion, a high-resolution material interface tracker is available. Both analytical and tabular equations of state are available to model the hydrodynamic behavior of materials. Models for elastic-plastic behavior and high-explosive detonation are also available.

The CTH simulations reported herein used a linear-Hugoniot shock-particle velocity equation of state to model the hydrodynamic behavior of the materials. An elastic perfectly plastic material model was used for WHA and RHA, with dynamic yield strengths of 19.3 kilobar (kbar) and 7.0 kbar, respectively [20]. The simulations used a three-dimensional (3-D) Cartesian coordinate system. The multiple material temperatures and pressures thermodynamic model was used to calculate separate temperatures and pressures for materials in multimaterial cells. The Sandia Modified Young's Reconstruction Algorithm (SMYRA) [32] was used to track material interfaces and minimize material dispersion in multimaterial cells. The March 1999 release of the CTH code was used to conduct the simulations discussed in this report. The computational mesh is composed of 0.4-mm cubic cells in the disk-target interaction region, with a geometric cell expansion to extend the mesh to the boundaries of the computational domain. The mesh is composed of a total of 6,346,800 cells. The 0.4-mm cubic cell subgrid region spanned from –6.4 to 2.4 cm in the X-coordinate direction, 0.0 to 3.2 cm in the Y-coordinate direction, and –3.2 to 2.04 cm in the Z-coordinate direction. The X-Z plane is modeled as a symmetry boundary to minimize the size of the computational mesh. To further reduce the number of required computational cells, the CTH data initialization and modification (DIATOM) input set was used to insert the second and third disk-shaped penetrators into the simulation at user-specified times, 17.692 μs and 35.385 μs, respectively, to accurately model the separation distance between individual disk-shaped penetrators. The DIATOM input set permits time-dependent insertion of material during the course of a calculation, i.e., virtual objects.

The geometry of each disk-shaped penetrator is constant, with a diameter of 16 mm and a thickness of 2 mm. The L/D of each disk is 1/8. Each disk-shaped penetrator was assigned an initial impact velocity of 2.6 km/s in the negative Z-coordinate direction. The separation distance between individual disks is 3.25 projectile diameters. This separation distance is sufficient to allow each disk to complete its contribution to the overall penetration before the next disk impacts the target. The target was modeled as a semi-infinite block of RHA. Figure 1 shows a schematic of the impact conditions examined in this study.

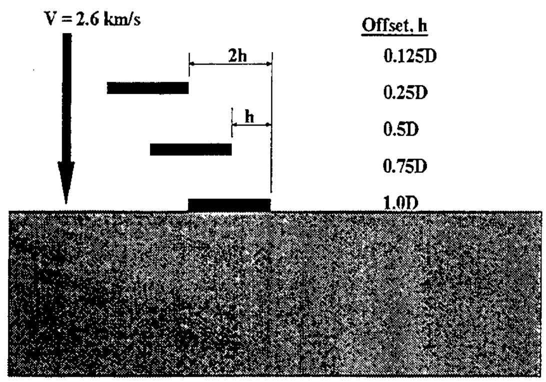

Figure 1. Multiple, axially offset, disk-shaped penetrator impact geometry.

3. Penetration of Single and Axially Aligned, Multiple Disks

Baseline simulations were conducted to assess the overall influence of axial offset on the penetration of multiple, disk-shaped penetrators. The first baseline simulation modeled the impact of a single disk-shaped penetrator. The single disk-shaped penetrator geometry was identical to the individual disk geometries modeled in the offset simulations, i.e., L/D = 1/8, and D = 16 mm. The single disk impact was modeled using the same 3-D computational domain and mesh resolution as established for the offset simulations. In addition, the same target and penetrator material properties were defined for the single disk impact simulation. The calculation was run for a simulated time of 50 μs. The predicted penetration channel for the single disk impact is shown in Figure 2.

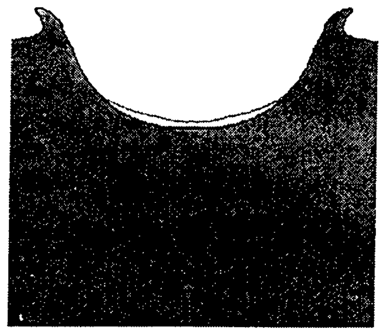

Figure 2. Penetration of 2.6-km/s single disk impact into semi-infinite RHA, at 50 μs.

Figure 3 shows the time history for two Lagrangian tracer particles initially located along the centerline of the disk, with Tracer 1 positioned on the impact face of the disk and Tracer 2 positioned on the rear surface of the disk. The predicted final depth of penetration at 50 μs is 10.8 mm or a predicted normalized penetration, P/L, ratio of 5.4. Figure 3 indicates that the single disk impact achieves a maximum penetration of 11.2 mm at about 25 μs.

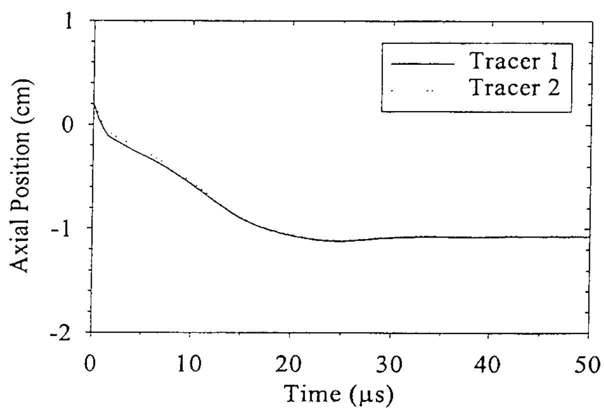

Figure 3. Tracer position history for single disk impact.

Figure 4 shows the axial velocity histories for tracer particles positioned on the front and rear surfaces of the disk. The axial velocity initially reaches 0 at about 25 μs, followed by a short duration of rebound until all of the impact kinetic energy has been absorbed. This suggests that for a multiple disk impact event, the second disk should be staged to impact the target at about 20–25 μs after the first disk impact in order to augment the axial momentum imparted to the target by the first disk. This corresponds to a disk-separation-to-projectile-diameter, S/D, ratio of 3.25–4.1 projectile diameters. Note that the time for an individual disk to traverse a separation distance of 5.2 cm is 20 μs. At 20 μs, the single disk

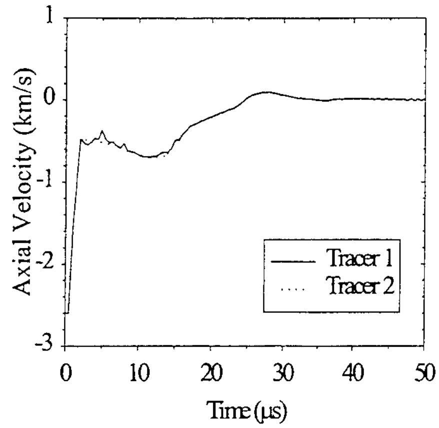

Figure 4. Tracer velocity history for single disk impact.

penetration is 10.7 mm, which corresponds to 95.5% of the predicted maximum depth of penetration and 99.1% of the predicted final depth of penetration. As a result, a normalized separation distance, S/D, of 3.25 projectile diameters was selected for the multiple disk impact simulations.

A second baseline simulation modeled perfectly aligned (no offset), multiple disk-shaped penetrators impacting a semi-infinite RHA target at 2.6 km/s. Figure 5 shows the predicted penetration channel at 100 μs. The penetration channel exhibits a scalloped penetration channel that corresponds to the impact of each disk-shaped penetrator. Some debris ejecta are noted along the centerline. Figure 6 shows the time history of a Lagrangian tracer particle initially located on the centerline, 0.2 mm below the target-impact face. The impact of each disk-shaped penetrator is clearly evident in Figure 6. The second disk impact occurs at about 25 μs, and the third disk impact occurs at about 50 μs.

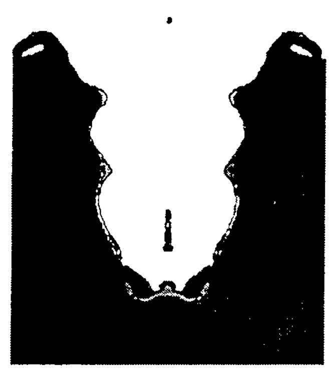

Figure 5. Penetration of perfectly aligned, multiple disk impact at 2.6 km/s.

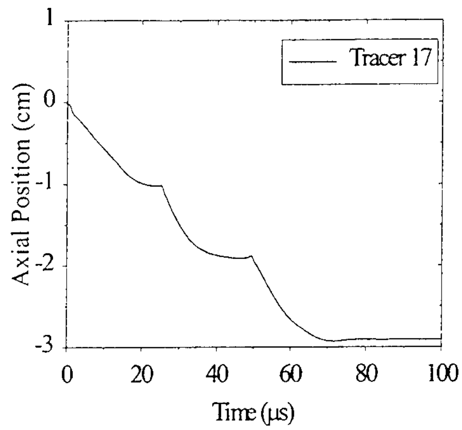

Figure 6. Tracer position history for perfectly aligned, multiple disk impact.

The second disk impacts the target after the first disk has penetrated 10.2 mm into the target or approximately 94% of the predicted final depth of penetration for the baseline single disk impact previously discussed. Impact of the second disk increases the depth of penetration to 19.1 mm. At 48.5 μs, the third disk impacts the target, which contributes an additional 10 mm of penetration, resulting in a final predicted depth of penetration, along the centerline, of 29.1 mm. Material plots at intermediate times for this multiple disk impact event indicate that the third disk interacts with debris ejecta, generated during the second disk impact, along the centerline prior to impacting the target. The penetration channel produced as a result of this interaction is slightly deeper (29.8 mm) at the channel side wall when compared to depth of penetration (29.1 mm) at the centerline (see Figure 5). In addition, the interaction of the second and third disks, with residual penetrator material at the bottom of the channel, results in a predicted depth of penetration that is less than that suggested by simple multiplication of the baseline single disk penetration (10.8 mm) by a factor of 3.

4. Penetration of Axially Offset Disks

A set of 3-D CTH simulations was conducted to examine the penetration performance of multiple, axially offset, disk-shaped penetrators striking semi-infinite RHA targets. The study examined axial offsets between 0 (perfect alignment) and 1 projectile diameter. Each disk-shaped penetrator had an impact kinetic energy of 23.6 kJ, yielding a total impact energy of 70.8 kJ. The predicted maximum depth of penetration for each offset studied is presented in

Table 1. Figure 7 shows the predicted penetration channels at 100 μs for axial offsets of 0.25D, 0.5D, 0.75D, and 1.0D. All of the penetration channels are asymmetric. Distinct penetration channels for each disk impact are observed in the penetration channels, with axial offsets of 0.75D, and 1.0D. Review of the penetration channel for offsets of 0.5D and below, shown in Figure 7, as well as intermediate material plots during the development of the penetration channel, exhibits interactions between the side walls of the penetration channel and the trailing offset disks. This side wall interaction deflects each trailing disk towards the centerline of the penetration channel produced by the impact of the first disk. For axial offsets less than 0.5D, more of the impact energy is absorbed in producing a deeper penetration channel rather than increasing the diameter of the penetration channel.

Table 1. Penetration of multiple, axially offset, disk-shaped penetrators.

Simulation	Axial Offset (mm)	Penetration (mm)
Off 0	0	29.8
Off_125	2	32.0
Off_25	4	32.4
Off_5	8	33.2
Off_75	12	23.5
Off_1	16	22.0

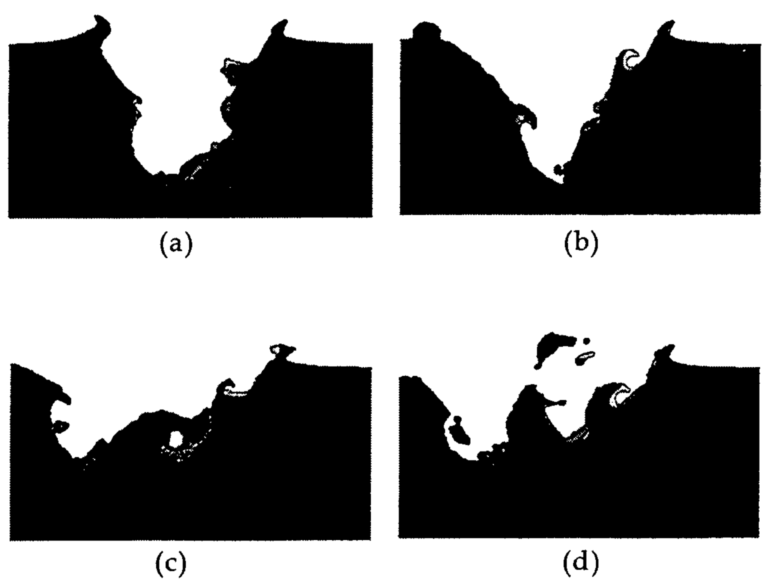

Figure 7. Penetration channels for axial offsets (a) 0.25D, (b) 0.5D, (c) 0.75D, and (d) 1.0D.

The larger axial offsets (0.75D and greater) produce discrete penetration channels for each disk impact. At these offsets, there is no coupling of the impact energy to increase the depth of penetration. Effectively, a large portion of the impact energy is absorbed in producing a larger diameter penetration channel. Comparison of the predicted depth of penetration of axial offsets of 0.5D and 0.75D (see Table 1) shows a 9.7 mm (29%) decrease in depth of penetration. Thus, axial offsets larger than 0.5D will significantly decrease penetration performance. This decrease in penetration performance can be seen in Figure 8, which summarizes the normalized depth of penetration as a function of axial offset.

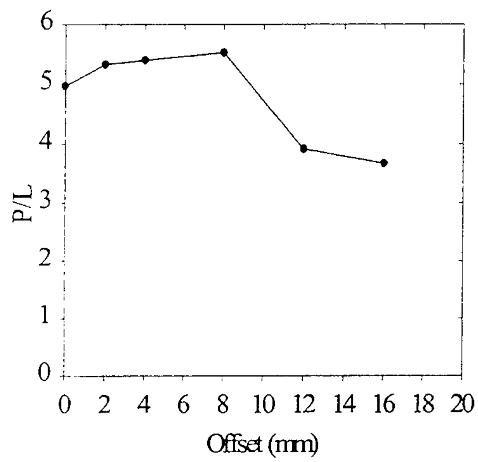

Figure 8. Penetration of multiple, axially offset, disk-shaped penetrators into RHA at 2.6 km/s.

5. Conclusion

The terminal ballistic performance of multiple, axially offset, high-velocity, low L/D ratio projectiles impacting semi-infinite RHA has been studied using 3-D continuum mechanics simulations. This numerical study investigated axial offsets between 0 (perfect alignment) and 1 projectile diameter. The impact scenarios modeled in this study suggest that the depth of penetration into steel is not degraded for axial offsets less than 0.5 projectile diameters. For the zero offset case, it was observed that as a result of interactions between the trailing disks and residual penetrator material at the bottom of the penetration channel, the predicted depth of penetration is less than that suggested by simple multiplication of the baseline single disk penetration by the number of disks impacting the target.

6. References

1. Brissenden, C. "Performance of Novel KE Penetrator Designs Over the Velocity Range 1600 to 2000 m/s." *Proceedings of the Thirteenth International Symposium on Ballistics*, pp. 183–190, American Defense Preparedness Association, Stockholm, Sweden, 1992.

2. Charters, A. C., T. L. Menna, and A. J. Piekutowski. "Penetration Dynamics of Rods From Direct Ballistic Tests of Advanced Armor Components at 2–3 km/s." *International Journal of Impact Engineering*, vol. 10, pp. 93–106, 1990.

3. Charters, A. C. "The Penetration of Rolled Homogeneous Armor by Continuous and Segmented Rods at High Velocity: Theory and Experiment." CR-87-1008, General Research Corporation, Santa Barbara, CA, 1987.

4. Cline, C. F., R. P. Gogolewski, and J. E. Reaugh. "Low Fineness Ratio Kinetic Energy Projectiles." *Proceedings of the Eleventh International Symposium on Ballistics, Vol. II*, pp. 277–283, American Defense Preparedness Association, Brussels, Belgium, 1989.

5. Cuadros, J. H. "Monolithic and Segmented Projectile Penetration Experiments in the 2 to 4 Kilometers per Second Impact Velocity Regime." *International Journal of Impact Engineering*, vol. 10, pp. 147–157, 1990.

6. Frank, K., and J. Zook. "Chunky Metal Penetrators Act Like Constant Mass Penetrators." *Proceedings of the Twelfth International Symposium on Ballistics—Volume I*, pp. 441–449, American Defense Preparedness Association, San Antonio, TX, 1990.

7. Hauver, G. E., and A. Melani. "Behavior of Segmented Rods During Penetration." BRL-TR-3129, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1990.

8. Hohler, V., and A. J. Stilp. "Penetration Performance of Segmented Rods at Different Spacing—Comparison With Homogeneous Rods at 2.5–3.5 km/s." *Proceedings of the Twelfth International Symposium on Ballistics, Vol. III*, pp. 178–187, American Defense Preparedness Association, San Antonio, TX, 1990.

9. Holland, P. M., J. T. Gordon, and A. C. Charters. "Hydrocode Results for the Penetration of Continuous, Segmented, and Hybrid Rods Compared With Ballistic Experiments." *International Journal of Impact Engineering*, vol. 10, pp. 241–250, 1990.

10. Hunkler, R. "Numerical Simulation of Segmented Rods." Proceedings of the Eleventh International Symposium on Ballistics, American Defense Preparedness Association, Brussels, Belgium, 1987.

11. Kivity, Y., E. Yitzhak, and E. Hirsh. "Penetration of Segmented Rods Into Homogeneous Targets." *Proceedings of the Eleventh International Symposium on Ballistics, Vol. II*, pp. 473–480, American Defense Preparedness Association, Brussels, Belgium, 1989.

12. Naz, P., and H. F. Lehr. "The Crater Formation Due to Segmented Rod Penetrators." *International Journal of Impact Engineering*, vol. 10, pp. 413–425, 1990.

13. Raatschen, H. J., W. Pavel, S. Fuchs, H. Senf, and H. Rothenhausler. "Penetration Efficiency of Segmented Rods." *Proceedings of the Eleventh International Symposium on Ballistics, Vol. II*, pp. 493–500, American Defense Preparedness Association, Brussels, Belgium, 1989.

14. Scheffler, D. R., and J. A. Zukas. "Numerical Simulation of Segmented Penetrator Impact." *International Journal of Impact Engineering*, vol. 10, pp. 487–498, 1990.

15. Scheffler, D. R. "2-D Computer Simulations of Segmented Penetrators Impacting Semi-Infinite Steel Targets." *International Journal of Impact Engineering*, vol. 9, pp. 35–43, 1990.

16. Sorensen, B. R., K. D. Kimsey, G. F. Silsby, D. R. Scheffler, T. M. Sherrick, and W. S. de Rosset. "High Velocity Penetration of Steel Targets." *International Journal of Impact Engineering*, vol. 11, pp. 107–119, 1991.

17. Tate, A. "Engineering Modeling of Some Aspects of Segmented Rod Penetration." *International Journal of Impact Engineering*, vol. 9, pp. 327–341, 1990.

18. Zukas, J. A. "Numerical Simulation of Semi-Infinite Target Penetration by Continuous and Segmented Rods." BRL-TR-3081, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1990.

19. De Rosset, W. S., and T. Sherrick. "Segmented Rod Performance at Ordnance Velocity." ARL-MR-291, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 1996.

20. Bjerke, T. W., J. A. Zukas, and K. D. Kimsey. "Penetration Performance of Disk Shaped Penetrators." *International Journal of Impact Engineering*, vol. 12, pp. 263–280, 1992.

21. Orphal, D. L., C. E. Anderson, and R. R. Franzen. "Impact Calculations of $L/D < 1$ Penetrator." *Proceedings of the Twelfth International Symposium on Ballistics*, pp. 458–464, American Defense Preparedness Association, San Antonio, TX, 1990.

22. Orphal, D. L., C. E. Anderson, R. R. Franzen, J. D. Walker, and P. N. Schneidewind. "Penetration by L/D < 1 Projectiles." *Proceedings of the Thirteenth International Symposium on Ballistics, Vol. III*, pp. 235–242, American Defense Preparedness Association, Stockholm, Sweden, 1992.

23. Herbette, G. "The Influence of Projectile Shape on Penetration Power." *Proceedings of the Eleventh International Symposium on Ballistics, Vol. II*, pp. 561–567, American Defense Preparedness Association, Brussels, Belgium, 1989.

24. Orphal, D. L., and R. R. Franzen. "Penetration Mechanics and Performance of Segmented Rods Against Metal Targets." *International Journal of Impact Engineering*, vol. 10, pp. 427–438, 1990.

25. Goldsmith, W. *Impact*. London: Edward Arnold, 1960.

26. Johnson, W. *Impact Strength of Materials*. New York: Crane Russak, 1972.

27. Backman, M. E., and W. Goldsmith. "The Mechanics of Penetration of Projectiles Into Targets." *International Journal of Engineering Sciences*, vol. 16, pp. 1–99, 1978.

28. Zukas, J. A., T. Nicholas, H. F. Swift, L. B. Greszczuk, and D. R. Curran. *Impact Dynamics*. New York: Wiley-Interscience, 1982.

29. Zukas, J. A. *High Velocity Impact Dynamics*. New York: Wiley-Interscience, 1990.

30. McGlaun, J. M., and S. L. Thompson. "CTH: A Three-Dimensional Shock Wave Physics Code." *International Journal of Impact Engineering*, vol. 10, pp. 351–360, 1990.

31. Kimsey, K. D., S. J. Schraml, and E. S. Hertel. "Scalable Computations in Penetration Mechanics." *Advances in Engineering Software*, vol. 29, pp. 209–216, 1998.

32. Bell, R. L., and E. S. Hertel. "An Improved Material Interface Reconstruction Algorithm for Eulerian Codes." SAND92-1716, Sandia National Laboratories, Albuquerque, NM, 1992.

INTENTIONALLY LEFT BLANK.

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC OCA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	HQDA DAMO FDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460
1	OSD OUSD(A&T)/ODDR&E(R) DR R J TREW 3800 DEFENSE PENTAGON WASHINGTON DC 20301-3800
1	COMMANDING GENERAL US ARMY MATERIEL CMD AMCRDA TF 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN 3925 W BRAKER LN STE 400 AUSTIN TX 78759-5316
1	DARPA SPECIAL PROJECTS OFFICE J CARLINI 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	US MILITARY ACADEMY MATH SCI CTR EXCELLENCE MADN MATH MAJ HUBER THAYER HALL WEST POINT NY 10996-1786
1	DIRECTOR US ARMY RESEARCH LAB AMSRL D DR D SMITH 2800 POWDER MILL RD ADELPHI MD 20783-1197

NO. OF COPIES	ORGANIZATION
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CI AI R 2800 POWDER MILL RD ADELPHI MD 20783-1197
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1197
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI IS T 2800 POWDER MILL RD ADELPHI MD 20783-1197
	<u>ABERDEEN PROVING GROUND</u>
2	DIR USARL AMSRL CI LP (BLDG 305)

NO. OF COPIES	ORGANIZATION
1	CECOM PM GPS COL S YOUNG FT MONMOUTH NJ 07703
1	CECOM SP & TERRESTRIAL COMM DIV AMSEL RD ST MC M H SOICHER FT MONMOUTH NJ 07703-5203
1	US MILITARY ACADEMY MATH SCI CTR OF EXCELLENCE DEPT OF MATH SCIENCES MADN A MAJ DON ENGEN THAYER HALL WEST POINT NY 10996-1786
5	COMMANDER US ARMY ARDEC AMSTA AR AEE WW E BAKER C CHIN R FONG J WALSH TECH LIBRARY PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR AET M TECH LIBRARY PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR FS E ANDRICOPOULOS PICATINNY ARSENAL NJ 07806-5000
3	COMMANDER US ARMY MERDEC AMSME RD ST WF L CRAFT D LOVELACE M SCHEXNAYDER REDSTONE ARSENAL AL 35898-5250

NO. OF COPIES	ORGANIZATION
1	DIRECTOR US ARO WASH AMXRO W K A BANNISTER ROOM 8N31 5001 EISENHOWER AVENUE ALEXANDRIA VA 22333-0001
3	COMMANDER US ARMY RESEARCH OFFICE J CHANDRA K IYER TECH LIBRARY PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211
1	COMMANDER US ARMY CORPS OF ENGINEERS T BLEVINS 3909 HALLS FERRY ROAD VICKSBURG MS 39180-6199
3	DARPA J RICHARDSON B WILCOX TECH LIBRARY 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
2	COMMANDER US ARMY TACOM AMSTA RSK J THOMPSON S GOODMAN WARREN MI 48397-5000
2	DIR NRL J A NEMES A E WILLIAMS CODE 6684 4555 OVERLOOK AVE SW WASHINGTON DC 20375
3	CDR NSWC W H HOLT W MOCK CODE G22 TECH LIBRARY 17320 DAHLGREN ROAD DAHLGREN VA 22448-5000

NO. OF COPIES	ORGANIZATION
1	CDR NWC CODE 3261 T GILL CHINA LAKE CA 93555-6001
1	NAVAL POSTGRADUATE SCHOOL CODE 73 J STERNBERG MONTEREY CA 93943
1	USAF PHILLIPS LAB PL WSCD F ALLAHDADI KIRTLAND AFB NM 87185
3	USAF WL MNMW W COOK M NIXON TECH LIBRARY EGLIN AFB FL 32542-5434
1	CDR FC DSWA FCTTS P RANDLES KIRTLAND AFB NM 87115
11	DIRECTOR LOS ALAMOS NATL LAB J BOLSTAD CIC ACL T CARNEY EES 5 MS C305 E FERM DX 3 MS P940 G T GRAY MST 8 MS G755 K HOLIAN CIC 12 MS D413 L HULL DX 3 MS P940 J JOHNSON F663 L LIBERSKY X HM MS D413 D A MANDELL X CI MS F663 L SCHWALBE X HM MS D413 TECH LIBRARY PO BOX 1663 LOS ALAMOS NM 87545
6	DIR LLNL C HOOVER L125 D LASSILA L170 P RABOIN L125 J E REAUGH L282 R E TIPTON L170 TECH LIBRARY PO BOX 1663 LIVERMORE CA 94550

NO. OF COPIES	ORGANIZATION
2	DIRECTOR SANDIA NATIONAL LABS D BAMMANN MS 9405 M CHIESA MS 9042 PO BOX 969 LIVERMORE CA 94550
15	DIRECTOR SANDIA NATIONAL LABS R L BELL MS 0820 R M BRANNON MS 0820 D E CARROL MS 0819 L C CHABILDAS MS 1181 M G ELRICK MS 0819 M FORRESTAL MS 0315 E S HERTEL JR MS 0819 M KIPP MS 0820 J M MCCLAUN MS 1202 J S PEERY MS 0819 S A SILLING MS 0820 R M SUMMERS MS 0819 P A TAYLOR MS 0820 T TRUCANO MS 0819 P YARRINGTON MS 0820 PO BOX 5800 ALBUQUERQUE NM 87185-0307
1	ALLIANT TECHSYSTEMS INC R STRYK 600 SECOND ST NE HOPKINS MN 55343
1	APPLIED RSRCH ASSOC INC J D YATTEAU 5941 S MIDDLEFIELD RD STE 100 LITTLETON CO 80123
4	APPLIED RSRCH ASSOC INC J CREPEAU S HIKIDA C NEEDHAM R NEWELL 4300 SAN MATEO BLVD SE STE A220 ALBUQUERQUE NM 87110
1	COMPUTATIONAL MECH ASSN J A ZUKAS PO BOX 11314 BALTIMORE MD 21239-0314

NO. OF COPIES	ORGANIZATION
1	IAT UNIV OF TEXAS AT AUSTIN D LITTLEFIELD 4030 2 W BRAKER LN AUSTIN TX 78759-5329
2	MAXWELL TECHNOLOGIES J BARTHEL S ROGERS 8888 BALBOA AVE SAN DIEGO CA 92123
1	NETWORK COMPUTING SERVICES INC T HOLMQUIST 1200 WASHINGTON AVE S MINNEAPOLIS MN 55415
1	ORLANDO TECH INC D A MATUSKA PO BOX 855 SHALIMAR FL 32579
2	SOUTHWEST RSCH INST C ANDERSON J WALKER 8500 CULEBRA ROAD PO DRAWER 28510 SAN ANTONIO TX 78284

NO. OF COPIES	ORGANIZATION
	ABERDEEN PROVING GROUND
30	DIR USARL AMSRL CI H T KENDALL R NAMBURU AMSRL WM T B BURNS AMSRL WM TA W BRUCHEY JR Y HAUNG P KINGMAN D KLEPONIS H MEYER JR A MIHALCIN AMSRL WM TB R FREY J STARKENBERG R LOTTERO AMSRL WM TC R COATES T FARRAND K KIMSEY (5 CYS) D SCHEFFLER S SCHRAML B SORENSEN AMSRL WM TD R L BITTING A M DIETRICH JR K FRANK N GNIAZDOWSKI F GREGORY M RAFTENBERG S SCHOENFELD S SEGLETES

NO. OF COPIES	ORGANIZATION
	ABSTRACT ONLY
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CS EA TP TECH PUB BRANCH 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	PRIN DPTY FOR TECHGY HDQ US ARMY MATL CMND AMCDCG T M FISETTE 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	PRIN DPTY FOR ACQTN HDQ US ARMY MATL CMND AMCDCG A D ADAMS 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	DPTY CG FOR RDE HDQ US ARMY MATL CMND AMCRD BG BEAUCHAMP 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001

INTENTIONALLY LEFT BLANK.

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 2001	Final, October 1997 – September 2000

4. TITLE AND SUBTITLE
Penetration of Multiple, Axially Offset, Disk-Shaped Penetrators

5. FUNDING NUMBERS
1L162618AH80

6. AUTHOR(S)
Kent Kimsey and Stephen J. Schraml

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-WM-TC
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-2507

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The terminal ballistic performance of high-velocity, low length-to-diameter (L/D) ratio projectiles impacting steel targets has been a topic of considerable interest in penetration mechanics to evaluate the efficacy of segmented projectiles. A computational study has been conducted to examine the penetration performance of multiple (i.e., three), axially offset, disk-shaped projectiles impacting semi-infinite rolled homogeneous armor (RHA). A constant 3.25 projectile diameter separation distance between each disk-shaped projectile was maintained for the impact conditions modeled in this study. The three-dimensional (3-D) simulations suggest that the total depth of penetration into steel is not degraded for disk offsets less than 0.5 projectile diameters based on the range of disk offsets modeled in the study.

14. SUBJECT TERMS
impact, penetration, segmented projectile

15. NUMBER OF PAGES
22

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-2507 (Kimsey) Date of Report June 2001

2. Date Report Received ____________________

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ____________________

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) ____________________

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ____________________

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ____________________

CURRENT ADDRESS

Organization

Name E-mail Name

Street or P.O. Box No.

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)

(DO NOT STAPLE)