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BRL-R-1982

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REPORT NO. 1982
(Supersedes IMR No. 245) NR

# ANALYSIS OF LONG ROD PENETRATION AT HYPERVELOCITY IMPACT

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April 1977

USA ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
USA BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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# REPORT DOCUMENTATION PAGE

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(14) 1. REPORT NUMBER
BRL ~~Report No.~~ 1982

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (*and Subtitle*)
(6) ANALYSIS OF LONG ROD PENETRATION AT HYPERVELOCITY IMPACT.

5. TYPE OF REPORT & PERIOD COVERED
(9) Final rept.,

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
(10) John J. Misey

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
USA Ballistic Research Laboratory
Aberdeen Proving Ground, Maryland 21005

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
(16) 1T161102A336

11. CONTROLLING OFFICE NAME AND ADDRESS
U.S. Army Materiel Development and Readiness Command
5001 Eisenhower Avenue
Alexandria, Virginia 22333

12. REPORT DATE
(11) APR~~IL~~ 1977

13. NUMBER OF PAGES
29

14. MONITORING AGENCY NAME & ADDRESS (*if different from Controlling Office*)
(12) 19p.

15. SECURITY CLASS. (*of this report*)
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15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

This report supersedes interim memorandum report 245, June 1974.

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Rod projectiles
Metal plate perforation
Hypervelocity impact
Computer codes

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*) (mba)

The hypervelocity impact of a long rod penetrator against targets of like material was studied analytically with the aid of the HELP code and the results were compared with experimental data. The computations of projectile residual speed deviated by no more than 3% from the experimental data; of residual mass by no more than 16%; of final rod length by no more than 5%; and of target exit diameter by no more than 8%. This agreement demonstrated that the HELP code can serve as a useful analytical tool for the study of kinetic energy projectile penetration at hypervelocity impact.

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# I. INTRODUCTION

The study of the dynamic response of materials to intense impulsive loading may be approached from three distinct points of view: experimental, analytical and numerical. In the experimental approach tests are conducted to deduce relationships between various parameters from the observed results. Generally many data points (therefore many tests) are required so that this approach becomes both time consuming and expensive, especially in the hypervelocity regime (striking velocities > 3km/sec). To obtain some knowledge of the physics of the deformation process and at the same time to reduce the number of tests, recourse is made to analytical methods. Simplifying assumptions are introduced into the governing equations of continuum physics and these are reduced to a set of partial differential equations which characterize the elastic-plastic hydrodynamic response of a material or structure. Very often the resulting differential equations are mathematically intractable and further approximations must be introduced to obtain an approximate analytical solution, at the expense of reducing the scope of the problem. With the present availability of large digital computers, however, there now exists the realization that systems of differential equations never attempted before can be solved. The main advantage of computer utilization is that parameters can be varied easily and quickly in any problem and their effects noted and compared. Furthermore, even if only a part of the problem can be formulated correctly, several methods of complete formulation can be assumed and a determination of which is the best or most sensible solution can be made.

The objectives of this study were threefold: to determine the applicability of the HELP code to the study of hypervelocity impact of long rod kinetic energy penetrators, to ascertain the effects of material strength on target and projectile deformations with varying target thickness, and to validate, if possible, the numerical results with experimental data.

# II. APPROACH

The modeling of the hypervelocity impact by a long rod kinetic energy penetrator was done with the aid of the HELP code[1], a two-dimensional multi-material Eulerian code for solving material flow problems in the hydro-dynamic and elastic-plastic regimes. Although the code is basically Eulerian, material interfaces and free surfaces are propagated in a Lagrangian manner through the calculational mesh as discrete interfaces across which material is not allowed to diffuse.

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[1] *Hageman, Laura J., Walsh, J. M., HELP, A Multi-Material Eulerian Program for Compressible Fluid and Elastic-Plastic Flows in Two Spaced Dimensions and Time, BRL Contract Report 39, Vol. 1, Aberdeen Proving Ground, Maryland, May 1971. (AD 726459)*

The material model employed in HELP includes the Tillotson[2] equation of state, modified to give a smooth transition between condensed and expanded states, a deviatoric constitutive relation, a yield criterion defined to account for the increase in strength at high pressures and decrease at elevated temperatures, and failure criteria. Failure in tension is based on relative volume. When the relative volume in a cell reaches a certain value greater than a specified maximum distension, that cell is said to fail and any computed tensions are zeroed out. Recently[3], a failure criterion based on a maximum allowable value of plastic work has been incorporated in order to model plugging failure. When the material ahead of the slip surface has been subjected to that value of plastic work, the slip surface is advanced to the next row of cells and the material in those cells through which the slip surface passes is said to have failed. For this problem the plugging failure model was not used.

The problem selected for study was that of a blunt 2024-T3 aluminum cylinder with a length to diameter ratio (L/D) of 9.2 impacting a target of like material at normal incidence with a velocity of approximately 4.7 km/sec. The ratio of target thickness-to-projectile diameter (t/d) was varied in steps of 1, 2, 4, 6 and 8. The input parameters of the problem were the following:

PROJECTILE

| | |
|---|---|
| Material | Al. 2024-T3 |
| Length | 29.19mm. |
| Diameter | 3.175mm. |
| Mass | 0.647g. |
| Striking Velocity | 4.718 km/s. |
| L/D Ratio | 9.2 |

TARGET

| t/d | thickness, mm |
|---|---|
| 1 | 3.175 |
| 2 | 6.350 |
| 4 | 12.700 |
| 6 | 19.050 |
| 8 | 25.400 |

Material..............Al. 2024-T3

A computational mesh 30 cells wide by 90 cells long was used to model the problem. In the region of impact and perforation the cell dimensions were .4 x .4 mm to provide an aspect ratio of 1 but to

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[2] *Tillotson, J. H., Metallic Equations of State for Hypervelocity Impact, General Atomic Report GA-3216, July 1962. (AD 486711)*

[3] *Hageman, Laura J., Sedgwick, Robert T., Modification to the HELP Code for Modeling Plugging Failure, AFA Contract Report 3SR-1009, Eglin Air Force Base, Florida, May 1972.*

incorporate the entire projectile-target configuration the aspect ratio was varied up to 3 for the 25.4mm target. Elsewhere the cell dimensions were increased at the ratio of 10% for the same reason. The computational mesh is shown in Figure 1 where the cell dimensions are in centimeters and the projectile-target configuration for t/d = 4 is superimposed. Variable zoning in both directions is indicated with the finest zoning being restricted to the region where the greatest deformation occurs. This region has an aspect ratio of 1.5. The problems were run on a UNIVAC 1108, EXEC 8 computer. Computer run time was dependent on the target thickness, varying from 5 minutes per microsecond of real-time for the 3.175mm target to more than 20 minutes per microsecond for the 25.4mm target. The run times were shorter when the strength phase of the code was turned off.

The computations for the five cases were divided into two groups. In the first group the problem of material response was treated as purely hydrodynamic in nature and the influence of deviation stresses not considered. In the second group the material response is considered to be strength dependent and the stress deviations were included. The termination of each computation was to be controlled by the average projectile velocity. When this velocity approached a constant minimum value the rod was considered to have perforated the target and the computation was stopped. In some cases the computations were stopped prior to this condition but the problems were sufficiently advanced to obtain reasonable results.

The experimental data used to validate the numerical results of the computations were taken from the work of J. R. Baker of the Naval Research Laboratory[4]. Slight variations in striking velocities, L/D ratios, and aluminum composition of the projectiles were noted.

## III. RESULTS

A comparison of the computational results for the two groups to determine the influence of strength effects at hypervelocity impact gave some interesting results as shown in Figure 2. In all five cases the penetration depth and the kinetic energy in the projectile, both as a function of time, remained relatively unchanged. If strength effects are significant, the projectile average velocity, the hole growth in the target and the target kinetic energy (a measure of the movement of target material away from the impact point) should decrease noticeably. When strength effects were included, however, the above quantities were only slightly lower than for the pure hydrodynamic case, indicating that for each of the cases studied the projectile greatly overmatched the target. The hole formed by the kinetic energy round is cylindrical in shape and therefore it is reasonable to estimate the hole diameter by measuring either the exit or entrance diameter of the target. For comparison with the experimental data the exit hole diameter was

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[4] *Baker, J. R., Rod Lethality Studies, NRL Report 6920, Naval Research Laboratory, Washington, D.C., July 1969. (AD 503920)*

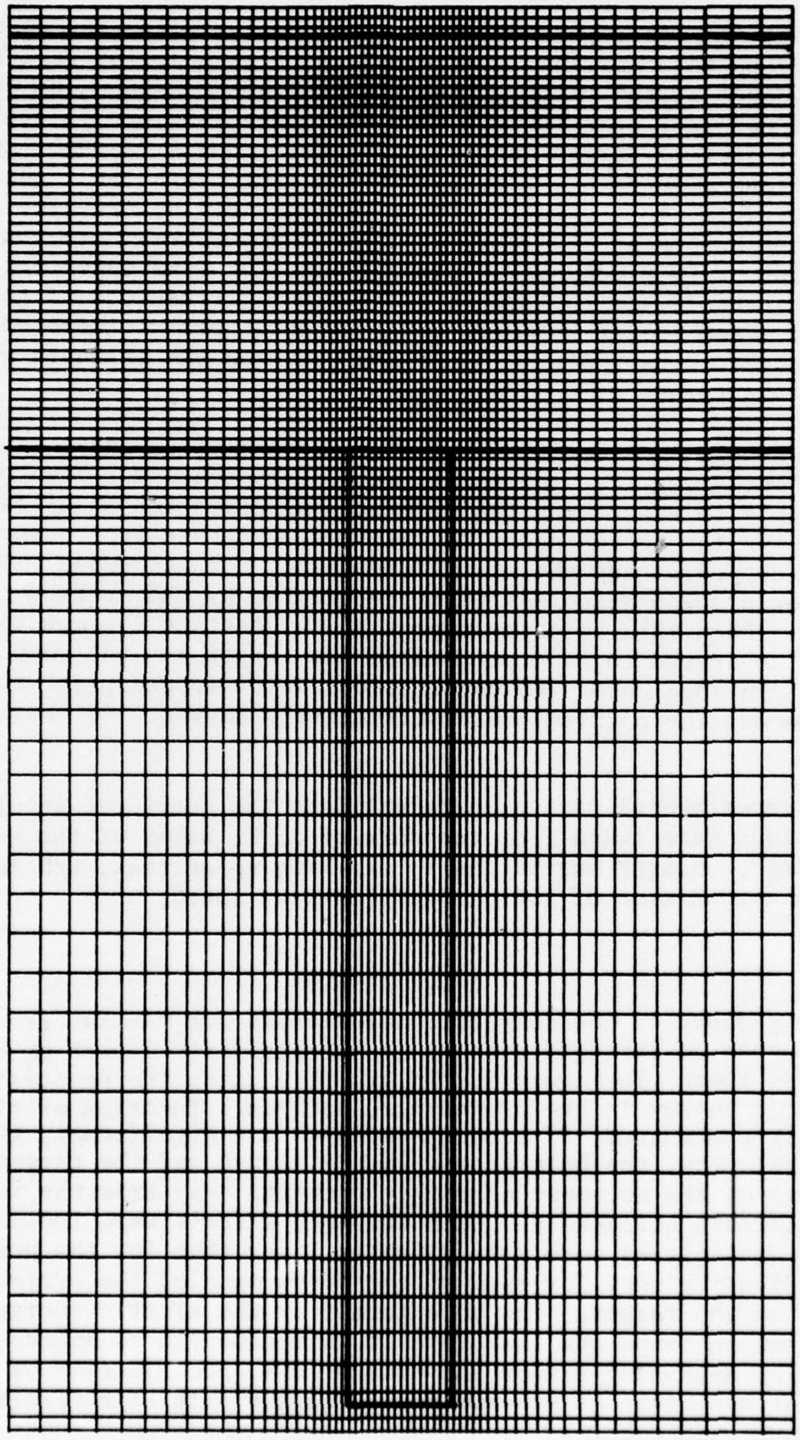

Figure 1. Computational Grid for Hypervelocity Impact Calculations, t/d = 4

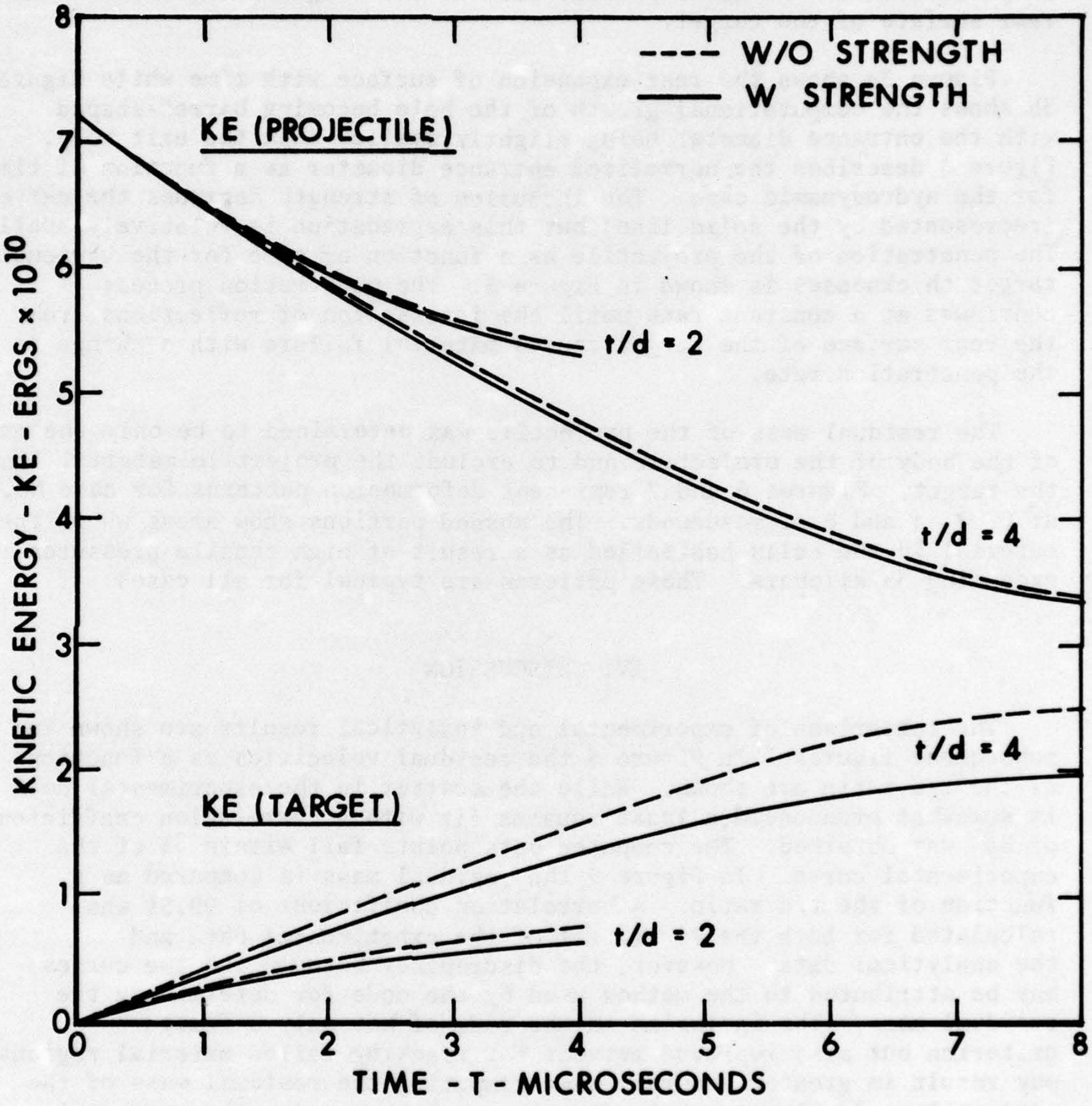

Figure 2. Influence of Strength Effects for a HV Impact at 4.72 KM/Sec (HELP Code)

computed from the material package plot at the original location of the rear surface of the target.

Figure 3a shows the rear expansion of surface with time while Figure 3b shows the computational growth of the hole becoming barrel-shaped with the entrance diameter being slightly smaller than the exit hole. Figure 4 describes the normalized entrance diameter as a function of time for the hydrodynamic case. The inclusion of strength degrades the curve (represented by the solid line) but this degradation is relatively small. The penetration of the projectile as a function of time for the various target thicknesses is shown in Figure 5. The penetration process continues at a constant rate until the interaction of reflections from the rear surface of the target causes material failure with a change in the penetration rate.

The residual mass of the projectile was determined to be only the mass of the body of the projectile and to exclude the projectile material lining the target. Figures 6 and 7 represent deformation patterns for case No. 2 at 0, 2, 4 and 6 microseconds. The shaded portions show areas where the material in the cells has failed as a result of high tensile pressures exceeding 35 kilobars. These patterns are typical for all cases.

## IV. DISCUSSION

The comparison of experimental and analytical results are shown in subsequent figures. In Figure 8 the residual velocities as a function of the t/d ratio are shown. While the scatter in the experimental data is somewhat pronounced a least squares fit with a correlation coefficient of 84% was obtained. The computed data points fall within 3% of the experimental curve. In Figure 9 the residual mass is compared as a function of the t/d ratio. A correlation coefficient of 99.5% was calculated for both the linear fit of the experimental data and the analytical data. However, the discrepancy between the two curves may be attributed to the method used by the code for determining the residual mass. The inclusion in the code of not only a fracture criterion but also improved methods for tracking failed material regions may result in greater accuracy when computing the residual mass of the projectile. In Figure 10 hole diameters are compared. The scatter in the experimental data is attributed to variations in the test conditions, but a least squares fit gave reasonable correlation. A similar curve was generated for the analytical data. However, the analytical data points for t/d = 6 and 8 are not the final exit diameters because the code was stopped prior to complete penetration. Finally the analytical loss in rod length for t/d = 1, 2, and 4 is in good agreement with the experimental data.

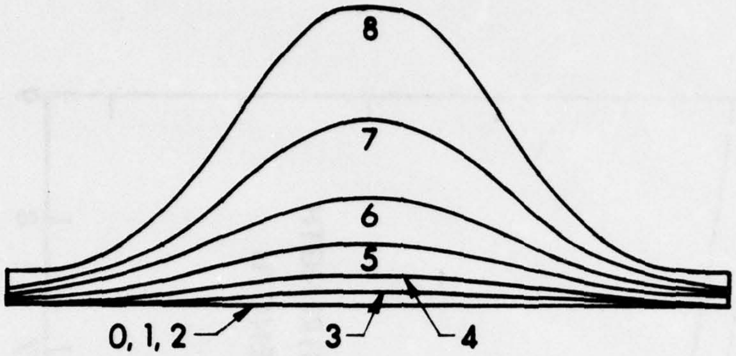

Figure 3a. Target Rear Surface Expansion History for t/d = 4

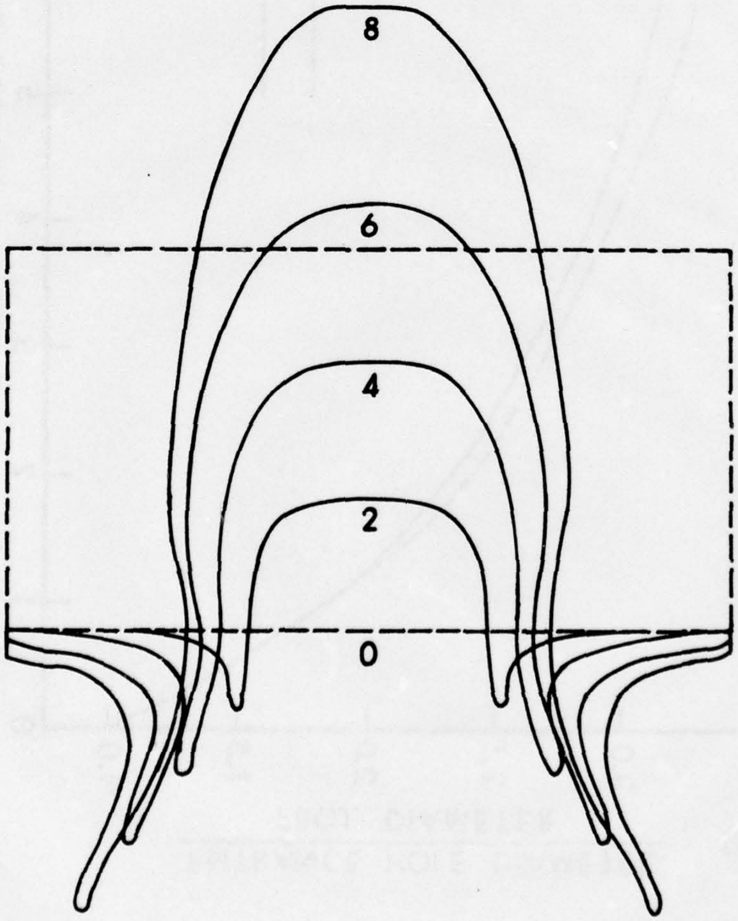

Figure 3b. Target Hole Growth Expansion History for t/d = 4

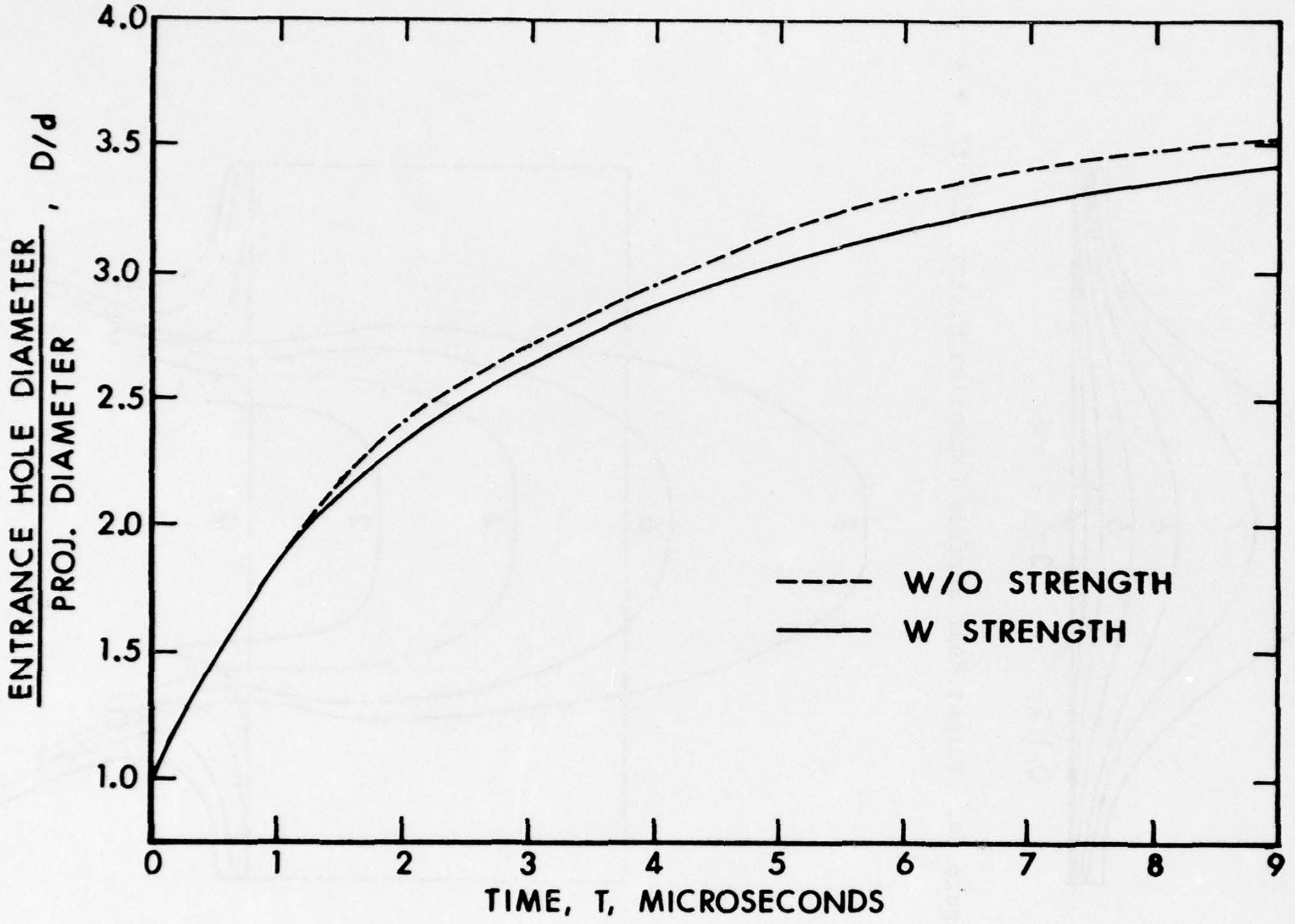

Figure 4. Normalized Entrance Diameter Growth for HV Impacts

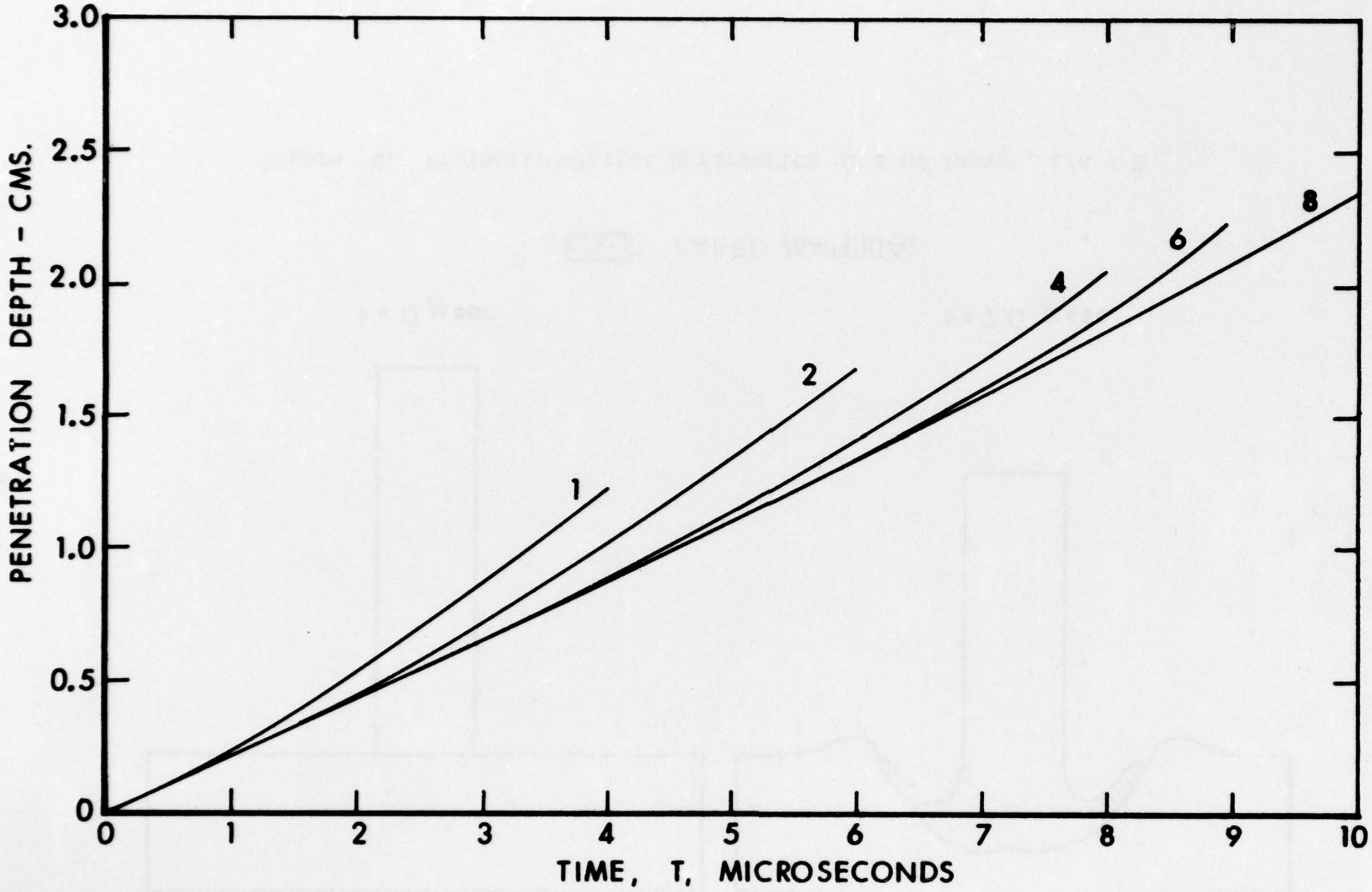

Figure 5. Penetration of Various Target Thicknesses by HV Impact; t/d = 1, 2, 4, 6, and 8

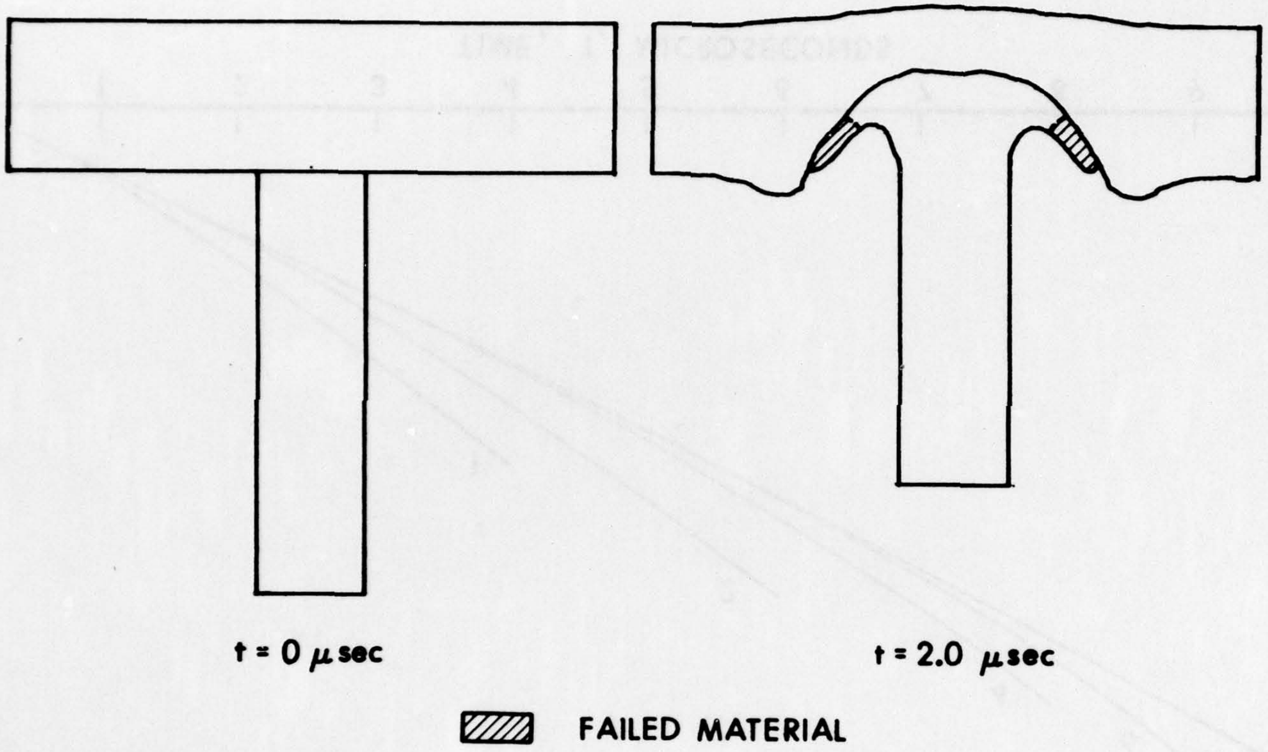

Figure 6. Projectile-Target Deformation of a HV Impact, t/d = 2

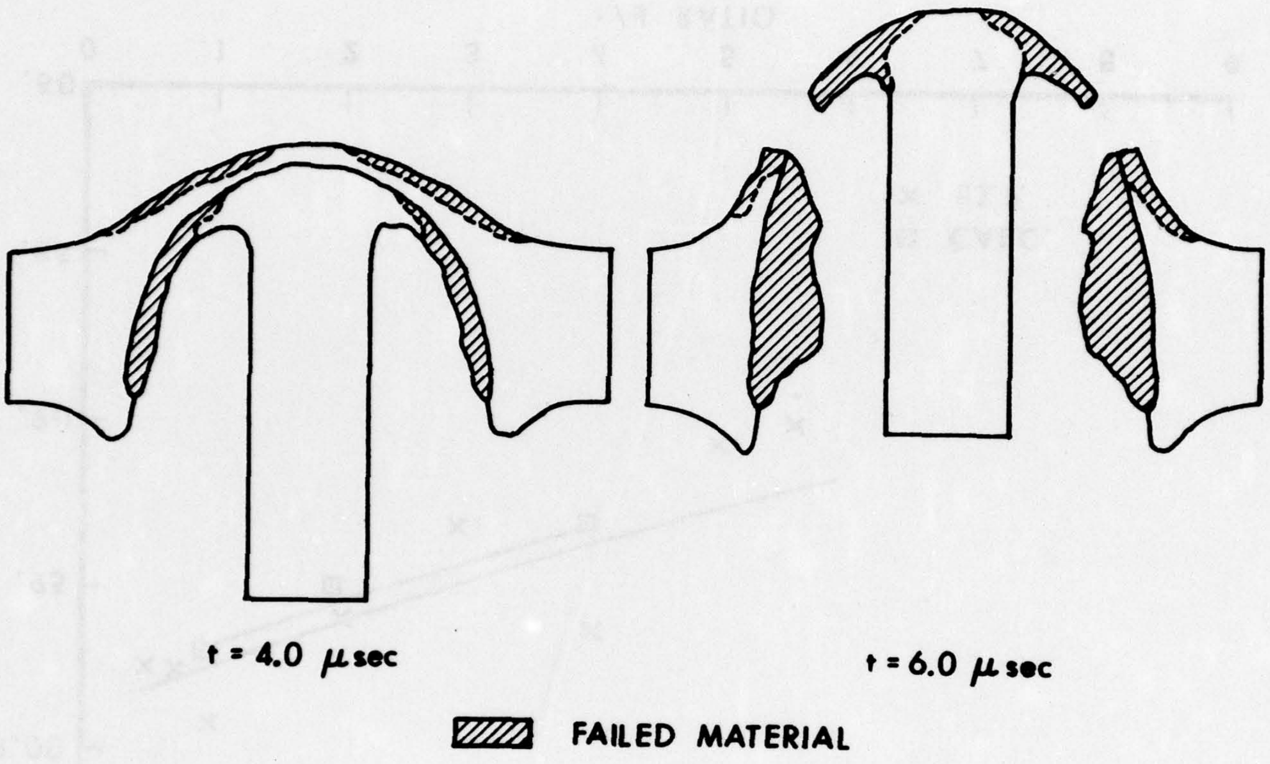

Figure 7. Projectile-Target Deformation of a HV Impact, t/d = 2

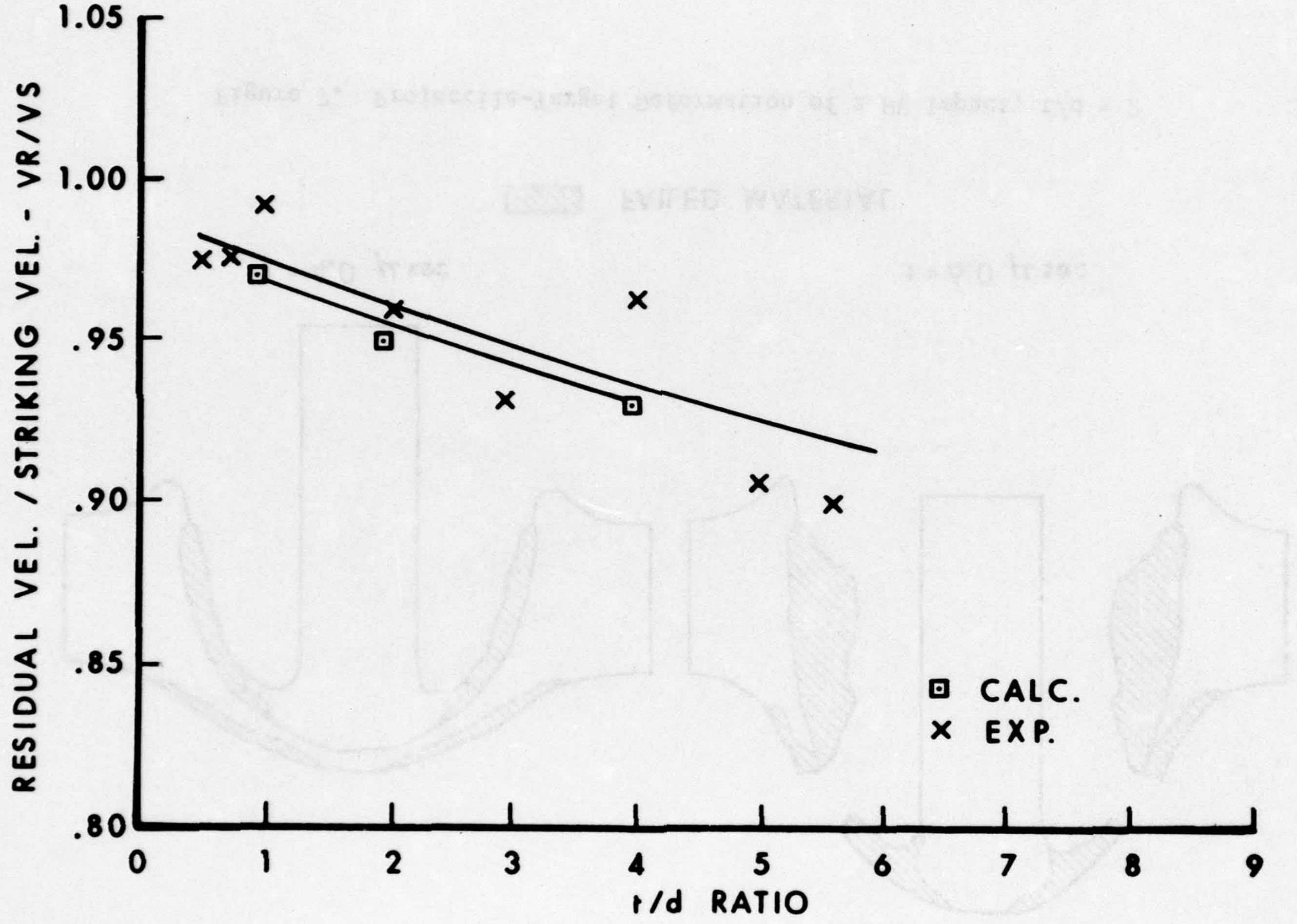

Figure 8. Residual Velocity vs. t/d Ratio for Aluminum-Aluminum HV Impact

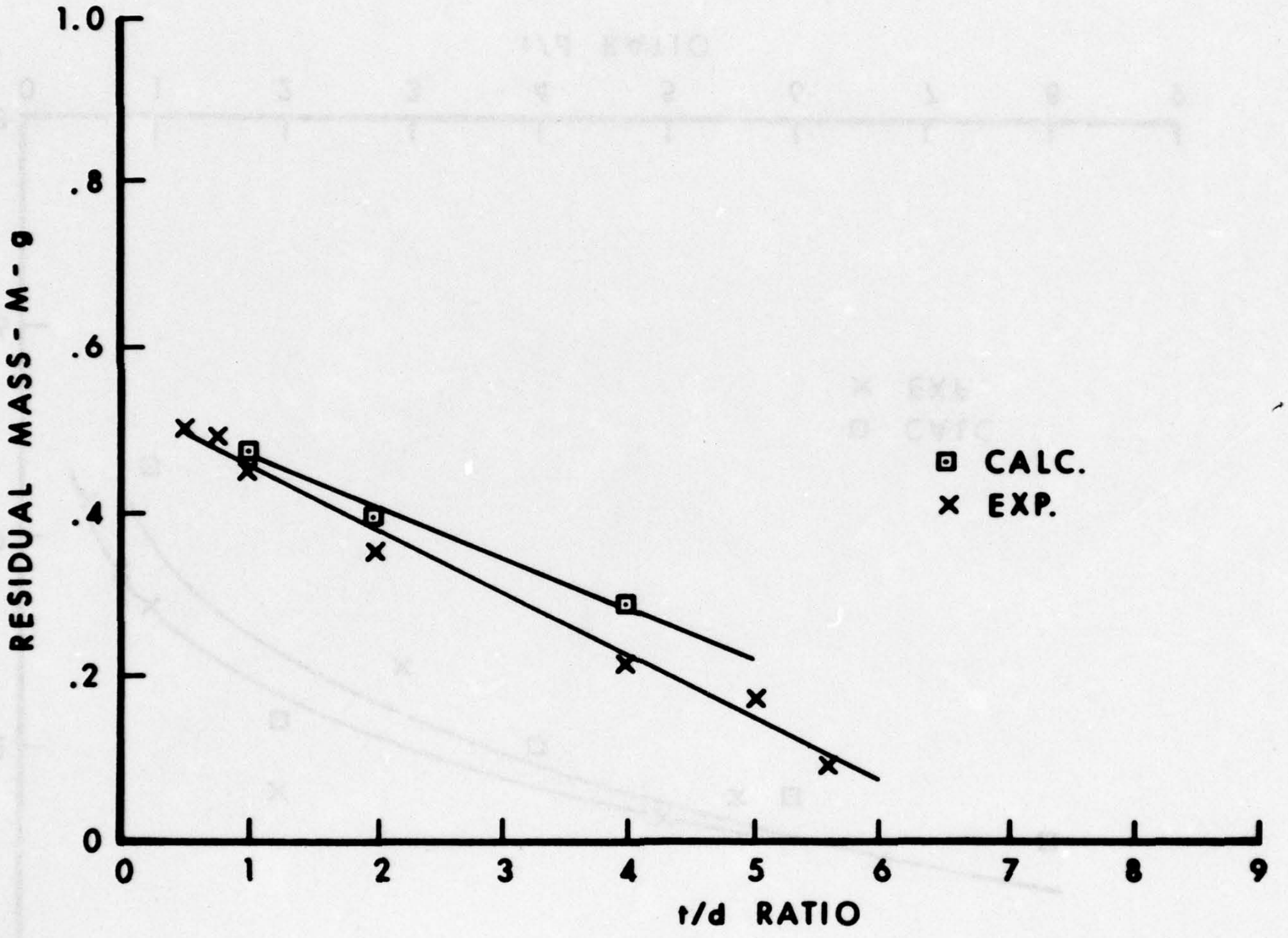

Figure 9. Residual Mass vs. t/d Ratio for Aluminum-Aluminum HV Impact

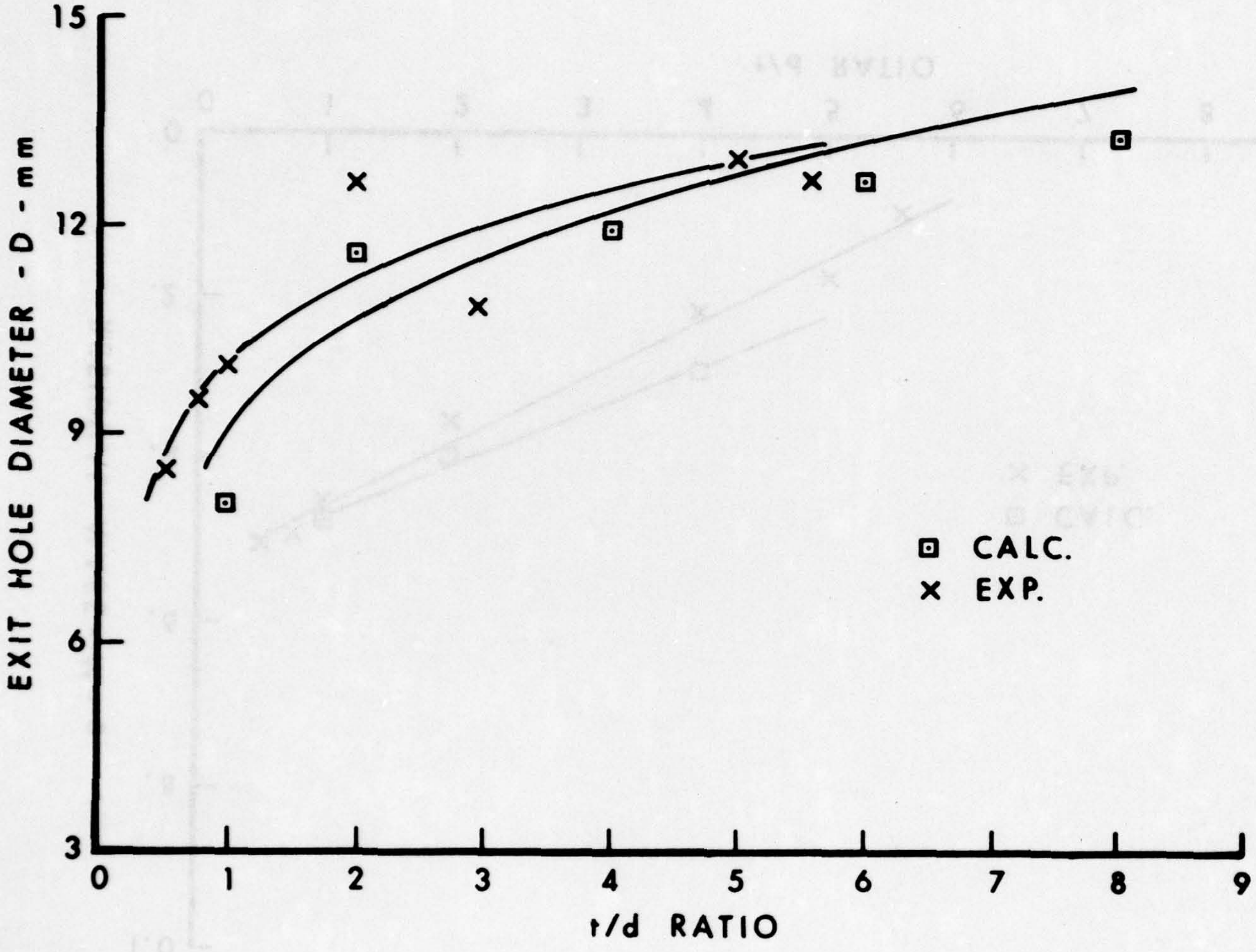

Figure 10. Hole Diameter vs. t/d Ratio for Aluminum-Aluminum HV Impact

# V. CONCLUSIONS

For the cases studied, material strength effects proved to be negligible. Continued studies are planned to vary such parameters as target thickness, striking velocity and projectile geometry. Because of the overall good agreement between the experimental and analytical results, it can be concluded that for the solution of hypervelocity impact problems where the material response is considered purely hydrodynamic, computer codes such as HELP can provide an efficient tool for both supplementing and reducing the number of experimental investigations.

# LIST OF SYMBOLS

| | |
|---|---|
| d | diameter of projectile |
| t | thickness of target |
| w | with |
| w/o | without |
| D | diameter of entrance hole in target |
| $KE_p$ | kinetic energy in projectile |
| $KE_t$ | kinetic energy in target |
| L | length of projectile |
| M | mass |
| T | time in microseconds |
| VR | residual velocity |
| VS | striking velocity |

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