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GENERAL MOTORS CORPORATION

TECHNICAL REPORT

ON

IMPACT OF ROD PROJECTILES AGAINST MULTIPLE-SHEET TARGETS

By

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ABSTRACT

A series of experiments was carried out to study the influence of projectile L/D (aspect ratio) and velocity on impact damage to multiple-sheet structures. Projectiles with L/D of 1/6 to 10 were launched at 4.8 km/sec, and projectiles with L/D = 2 were launched at velocities of 2.9 to 6.1 km/sec. Results are presented in terms of thin-sheet hole area, projectile residual velocity, rod length used, backup plate penetration, and backup plate momentum loading. Empirical equations are presented for predicting thin-sheet hole area and rod length used.

CONTENTS

ILLUSTRATIONS

LIST OF SYMBOLS

B_{Max}	Brinell Hardness Number (kg/mm^2)
D	Projectile Diameter (inches)
d	Hole Diameter (inches)
f_p	Projectile Shape Factor
L	Projectile Length (inches)
L_u	Projectile Length Used (inches)
m	Projectile Mass (gms)
M	Backup Plate Momentum (gram-km/sec)
P_2	Backup Plate Penetration (inches)
t_s	Front Sheet Thickness (inches)
V_I	Impact Velocity (km/sec)
V_R	Residual Velocity (km/sec)
ρ_P	Projectile Density (g/cc)
ρ_T	Target Density (g/cc)

INTRODUCTION

Recent studies at GM DRL on the impact of rods against semi-infinite targets,[1,2] and spheres and cylinders against multiple-sheet targets[3] have raised some specific questions regarding the impact of rods against multiple-sheet targets. Of particular interest is the influence of projectile L/D and impact velocity on projectile breakup and subsequent backup plate damage (penetration and/or impulsive loading). Accordingly, a brief research program was planned and carried out to provide preliminary answers to some of these questions.

Three areas of interest were studied: (1) Front sheet or bumper damage, i.e., hole size; (2) Residual projectile parameters, i.e., length of projectile used in perforating a thin sheet, and residual velocity; (3) Backup plate damage, i.e., penetration and impulsive loading. The impact tests were carried out with a 0.30-caliber accelerated-reservoir light-gas gun. Spark shadowgraph pictures of a disc and a rod in flight are shown in Figure 1. Dynamic impact data were obtained with a dual-channel flash radiography system, and a ballistic pendulum.*

FRONT SHEET

Front sheet damage is commonly expressed in terms of hole diameter d. Hole diameter data (normalized with respect to projectile diameter D) are presented in Figure 2 as a function of projectile diameter for constant velocity, and as a function of velocity for constant projectile size. Maiden

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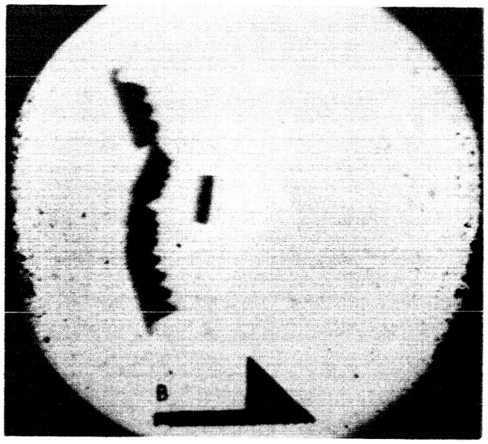
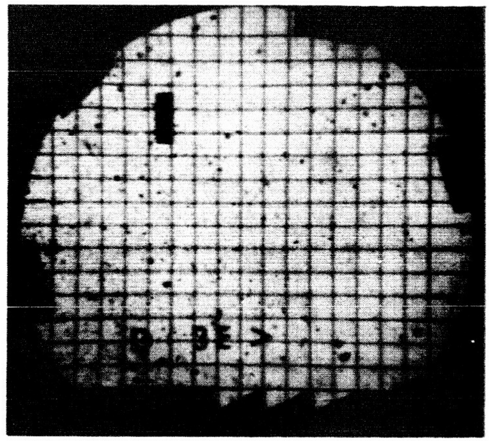
*For a detailed description of test facilities, see "Aerospace Research Capabilities," GM DRL Report TR63-223 (Rev.), April 1964

2024-T3 Al DISC, L/D = 1/3

4.8 km/sec



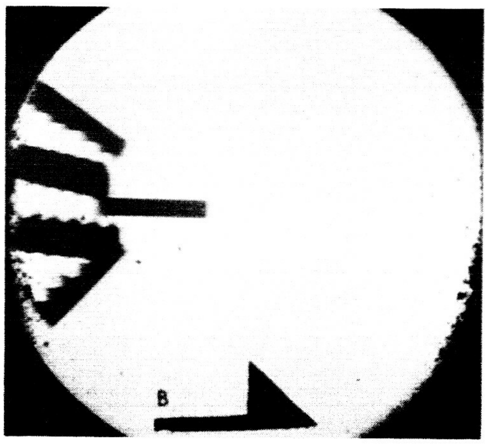
6-ft. FROM
GUN MUZZLE



26-ft. FROM
GUN MUZZLE

2024-T3 Al ROD, L/D = 6

4.8 km/sec



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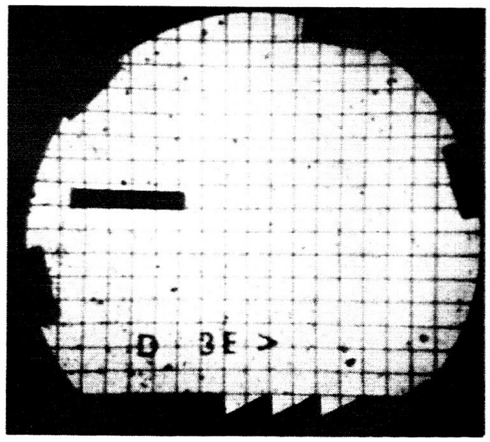

26-ft. FROM
GUN MUZZLE

Figure 1 Projectiles In Flight

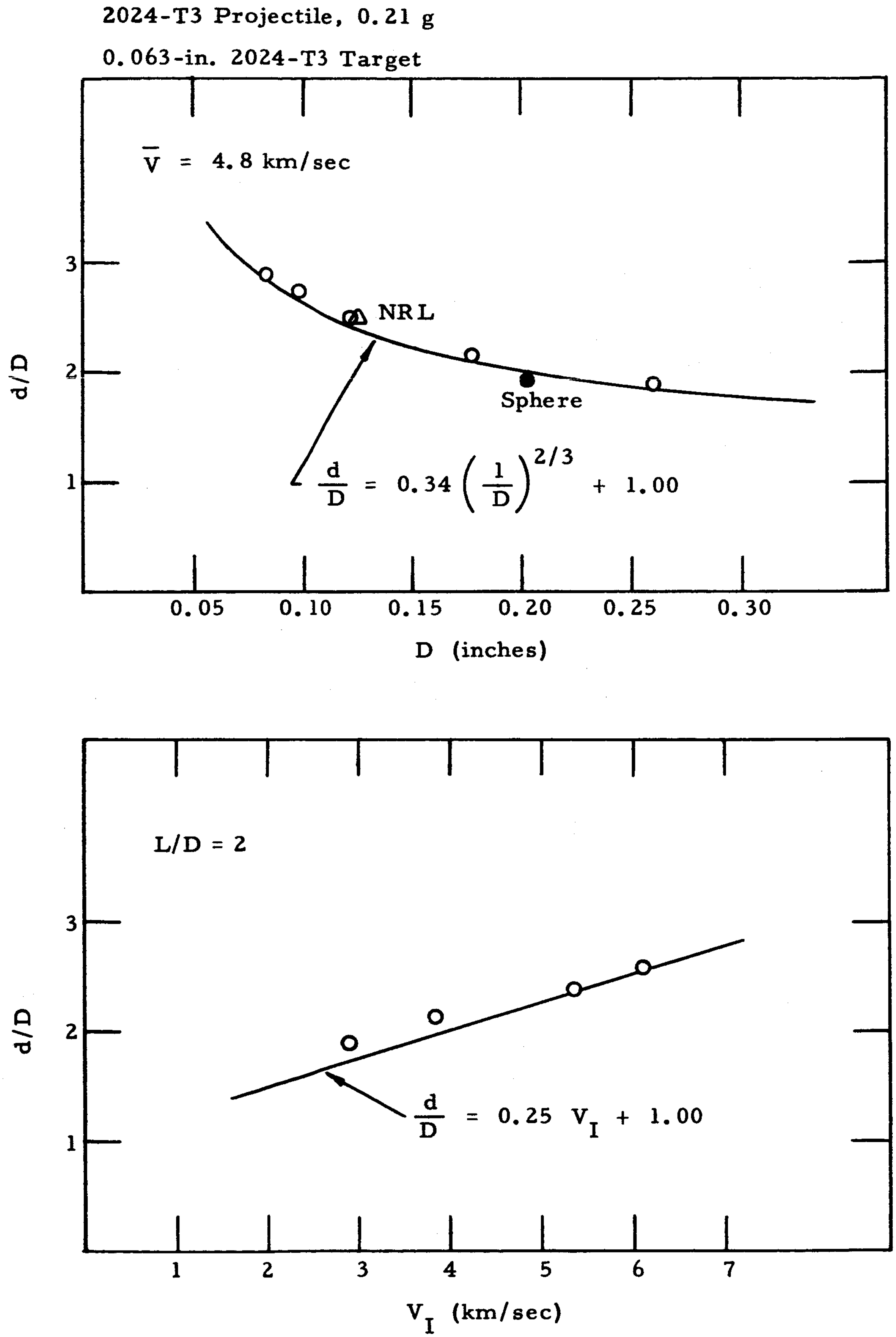

Figure 2 Front Sheet Hole Area

and McMillan[4] have published an expression for predicting thin sheet hole size,*

$$\frac{d}{D} = 0.45 \; V_I \left(\frac{t_s}{D} \right)^{2/3} + 1.00 \qquad (1)$$

This equation, with appropriate values substituted for V_I, t_s, and D, is compared with the experimental data in Figure 2. Good agreement is shown for all combinations of size and velocity.

RESIDUAL PROJECTILE

The two projectile parameters that are of primary interest after perforation of a thin sheet are residual velocity and amount of projectile used. Measured values of these parameters for various impact conditions are given in Figures 3 and 4. Also shown in Figure 3 is a plot of projectile shape factor f_p as a function of t_s/D. This shape factor takes into account the fact that penetration changes as projectile aspect ratio (L/D or t_s/D) changes, and is defined as,

$$f_p = \frac{\text{Penetration of Projectile with Aspect Ratio } t_s/D}{\text{Penetration of Sphere}}$$

The f_p vs t_s/D curve in Figure 3 is based on data from References 2 and 5. The factor is used in calculating the amount of rod used on impact with a thin sheet, as discussed below and shown by the solid curves in Figure 4. Flash X-ray pictures taken after impact of various projectiles against a thin sheet are given in Figures 5 and 6.

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*Reference 4 actually gave a value of 0.90 for the second term on the right-hand side of Eq. (1). However, Eq. (1) was originally intended to apply to spherical projectiles, and the fact that this second term was less than 1 was attributed to elastic recovery in the thin sheet. For cylindrical or rod projectiles, it appears that this elastic recovery may be significantly less and, therefore, a value of 1.00 has been selected.

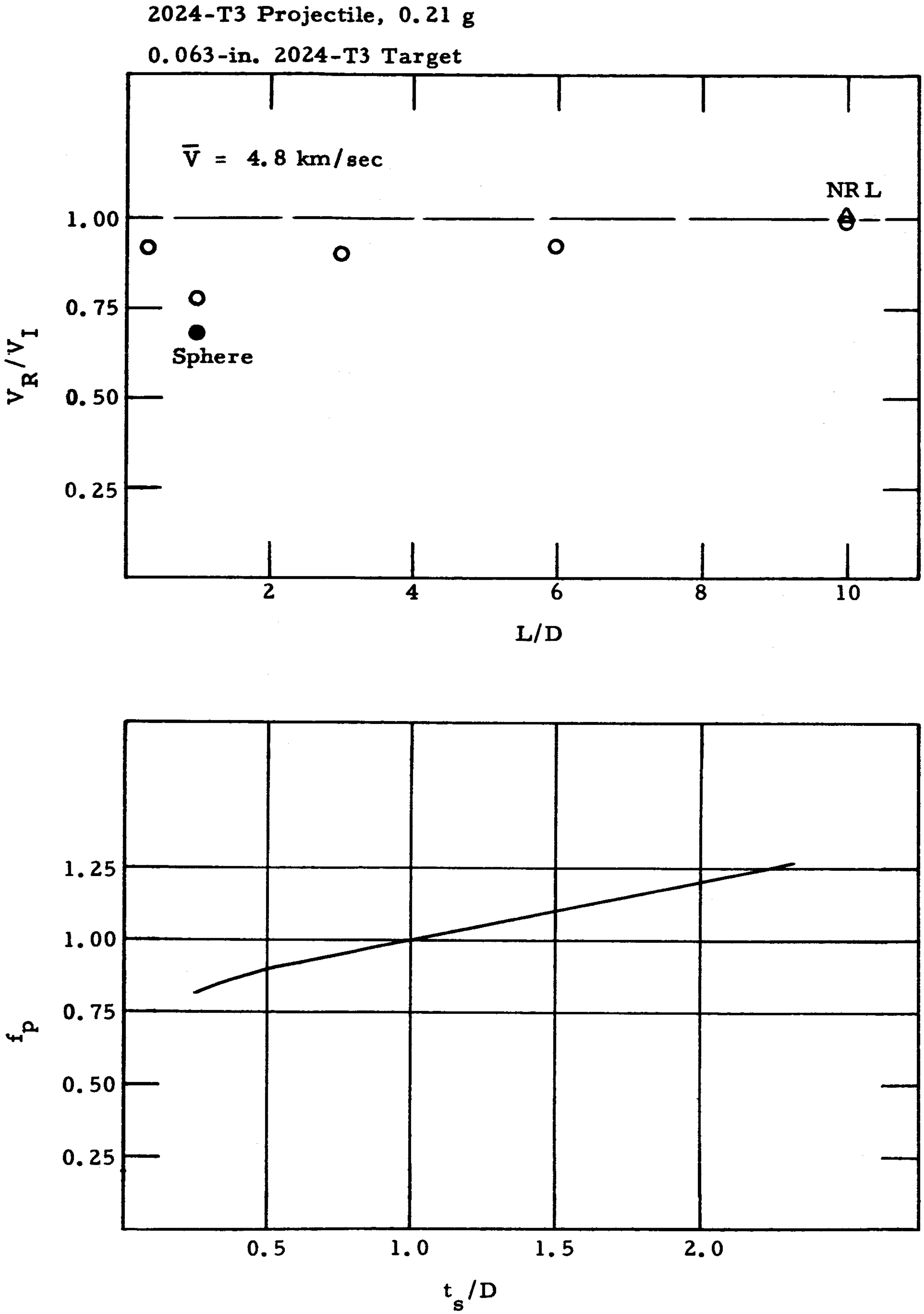


Figure 3 Projectile Residual Velocity and Projectile Shape Factor

2024-T3 Projectile, 0.21 g

0.063-in. 2024-T3 Target

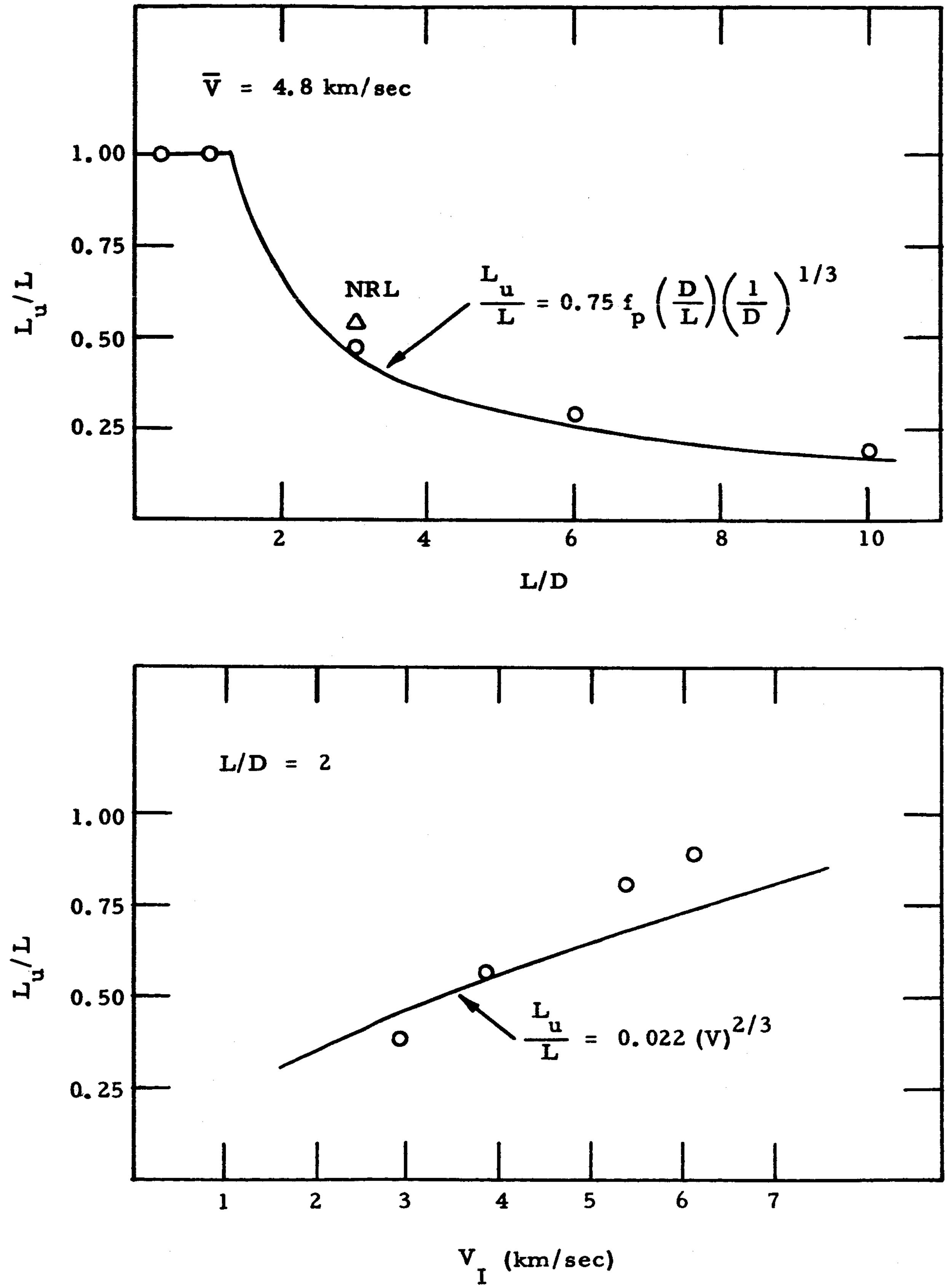
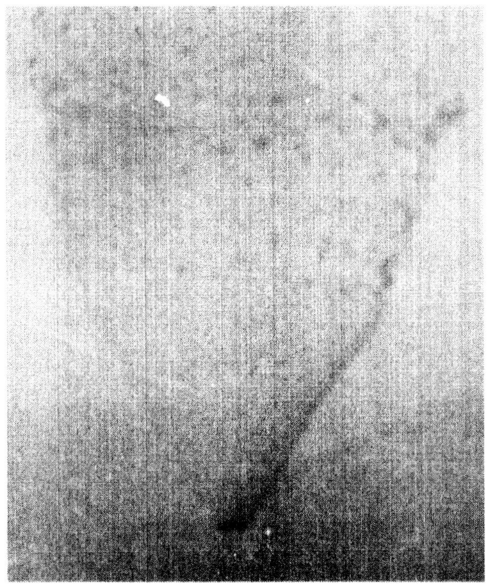


Figure 4 Rod Used Against Thin Sheet

2024-T3 PROJECTILES, 0.21 g

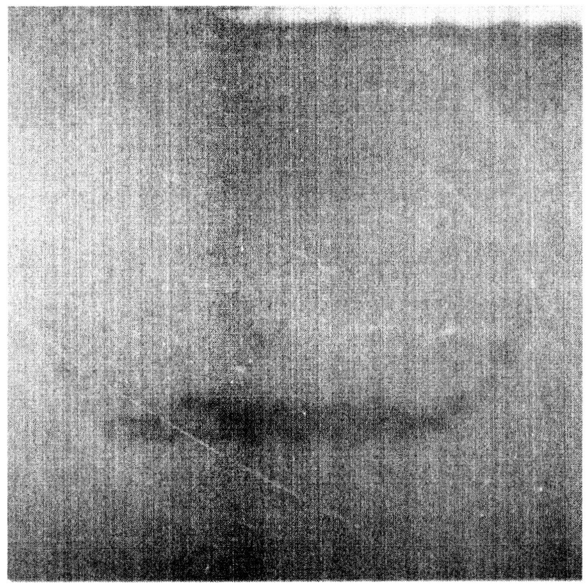
0.063-inch 2024-T3 TARGETS

$\overline{V}$ = 4.8 km/sec



DISC, L/D = 1/3

+ 15 μs



CYLINDER, L/D = 1

+ 15 μs

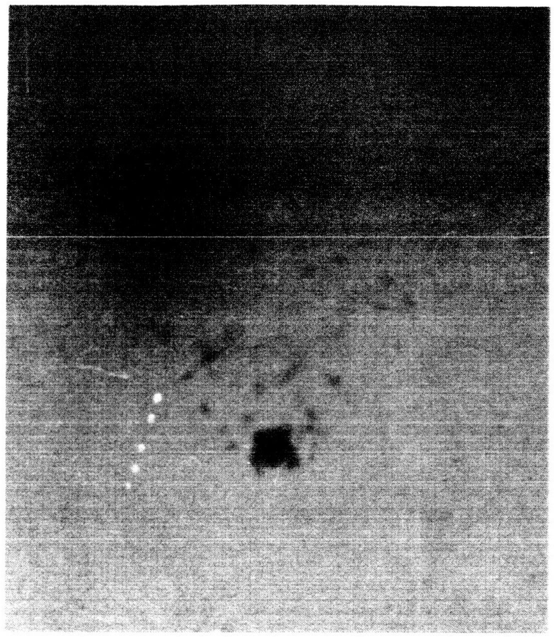
SPHERE

+ 16 μs

Figure 5 X-Ray Pictures

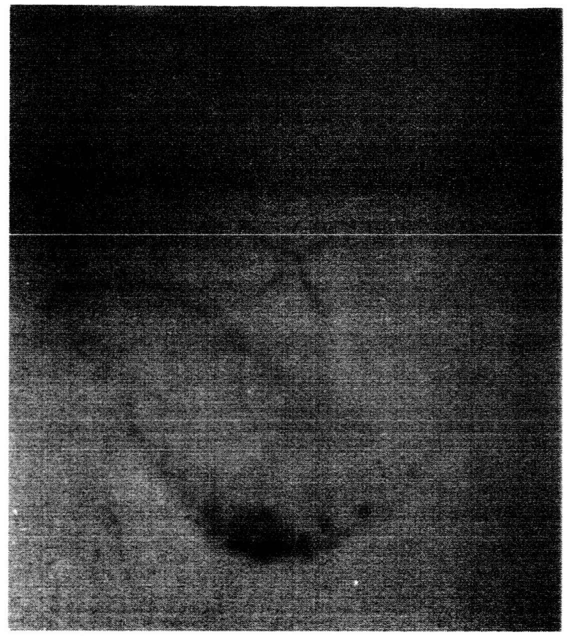
2024-T3 RODS, 0.21 g

0.063-inch 2024-T3 TARGETS



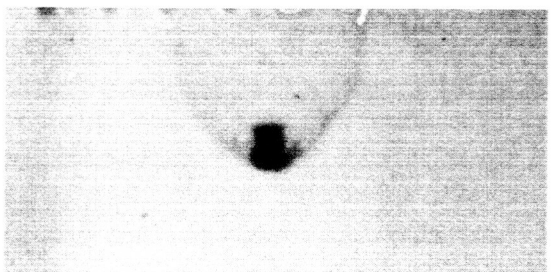
2.9 km/sec, L/D = 2

+ 25 μ s



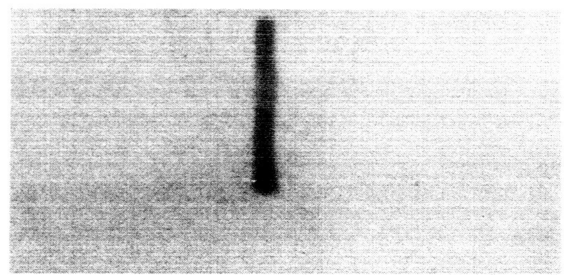
5.4 km/sec, L/D = 2

+ 14 μ s



L/D = 3, 4.6 km/sec

+ 5 μ s



L/D = 10, 4.6 km/sec

+ 7 μ s

Figure 6 X-Ray Pictures

Figure 3 shows residual velocity gradually decreases as L/D decreases down to 1, but then there is an anomalous increase as L/D decreases further to 1/3. Because of the limited data available, this behavior is not completely understood. However, it appears that flat-ended projectiles with a sufficiently high value of D/t_s generate a plane, one-dimensional shock wave into the thin sheet, which reaches the rear surface of the sheet without appreciable attenuation due to side rarefactions. Upon reaching the rear surface, the plane shock drives the free surface forward with a velocity equal to twice the particle velocity behind the shock wave.[6] Since, for like materials, the initial particle velocity is equal to one-half the impact velocity, the free surface velocity (or residual velocity V_R) would be expected to approach the impact velocity V_I, thereby giving a value of V_R/V_I close to 1. The L/D = 1 cylinder might have had a value of D/t_s sufficient to give a similar effect, except that the projectile had a yaw angle of about 10^o at impact, thereby preventing generation of a plane shock wave.

The data obtained on V_R/V_I as a function of V_I for L/D = 2 rods was not entirely satisfactory and, therefore, is not presented in a graph. However, the data did indicate that V_R/V_I increases as V_I increases. (It should be noted that the value of V_R measured in all cases was actually the average velocity of the leading edge of the debris behind the thin sheet, measured over a distance from 1 to 3 inches behind the sheet.)

Reference 2 proposed a method for estimating the amount of rod used in perforating a thin sheet. This method is based on reversing the impact, i. e., by considering the rod as the target and the thin sheet as the projectile (or more precisely, a disc or rod with L equal to sheet thickness t_s, and D equal to rod diameter D). The general equation for L_u is,*

*This equation is based on an analysis of impact test data gathered at GM DRL over the past three years. Strictly speaking, the equation applies only to semi-infinite targets, a condition which is obviously not satisfied by a rod; however, the equation should give an approximate value of rod used.

$$L_u = 2.5 \times f_p \; (D^2 \, t_s)^{1/3} \left(\frac{\rho_P^{\,2} \, V_I^{\,2}}{\rho_T \, B_{Max}} \right)^{1/3} \tag{2}$$

where f_p is a shape factor to account for the influence of t_s/D on penetration,[2,5] ρ_P is thin sheet material density, ρ_T is rod material density, and B_{Max} is maximum hardness of rod material[2].

For the specific conditions given in the two graphs in Figure 4, Eq. (2) reduces to,

$$\frac{L_u}{L} = 0.75 \times f_p \left(\frac{D}{L}\right) \left(\frac{1}{D}\right)^{1/3} \tag{3}$$

and,

$$\frac{L_u}{L} = 0.022 \; (V_I)^{2/3} \tag{4}$$

There is good agreement at constant velocity for all values of L/D covered. For constant rod size, the measured L_u/L begins to deviate markedly from the predicted at high (>0.75) values of L_u/L. This is probably analogous to the behavior observed in finite thickness targets where penetration increases as target thickness is reduced, finally resulting in perforation of targets with thicknesses in the range of 1.4 to 2.0 times the penetration in a semi-infinite target.

This technique of reversing the impact has also been applied to other experiments carried out at GM DRL and at the Naval Research Laboratory[7] on rod impact against thin sheets. For steel, aluminum, and lexan rods impacting 2024 and copper sheets (with t_s/D ranging from 0.09 to 2.0, and velocity ranging from 3.3 to 4.8 km/sec), the empirical approach outlined above gave predicted values of rod used that ranged from 75 to 118% of that determined experimentally.

It was reported in Reference 8 that, at a given velocity and rod diameter, the amount of rod shattered by the shock propagating back into the rod would be independent of target thickness. This conclusion was based on the fact that "the peak pressure on the rod axis as a function of rod length traversed is independent of target thickness". However, the shape of the pressure pulse will be influenced by target thickness and, therefore, so should the amount of rod shattered. Analysis of the GM DRL and NRL[7] data does not reveal a region or "plateau" of constant amount of rod used. Reference 8 further states that this plateau ends when "rod erosion", or interaction of the remaining rod with debris behind the thin sheet, begins to act to shorten the rod. Existence of such an erosion phase does not appear to be substantiated by the available data. Instead, what is taken to be erosion may be simply the transition from the transient penetration phase to the primary penetration phase. For very thin sheets, the transition may never be reached, while for very thick targets the primary phase acts to use up the entire rod.[2]

Reference 8 also noted that L_u might change as D is changed, and that L_u would increase markedly as V_I increases. Both of these comments are supported by the data in Figure 4. Multiplying the ordinate (L_u/L) by L/D would show that L_u/D increases as L/D increases (or, in this case, as D decreases).

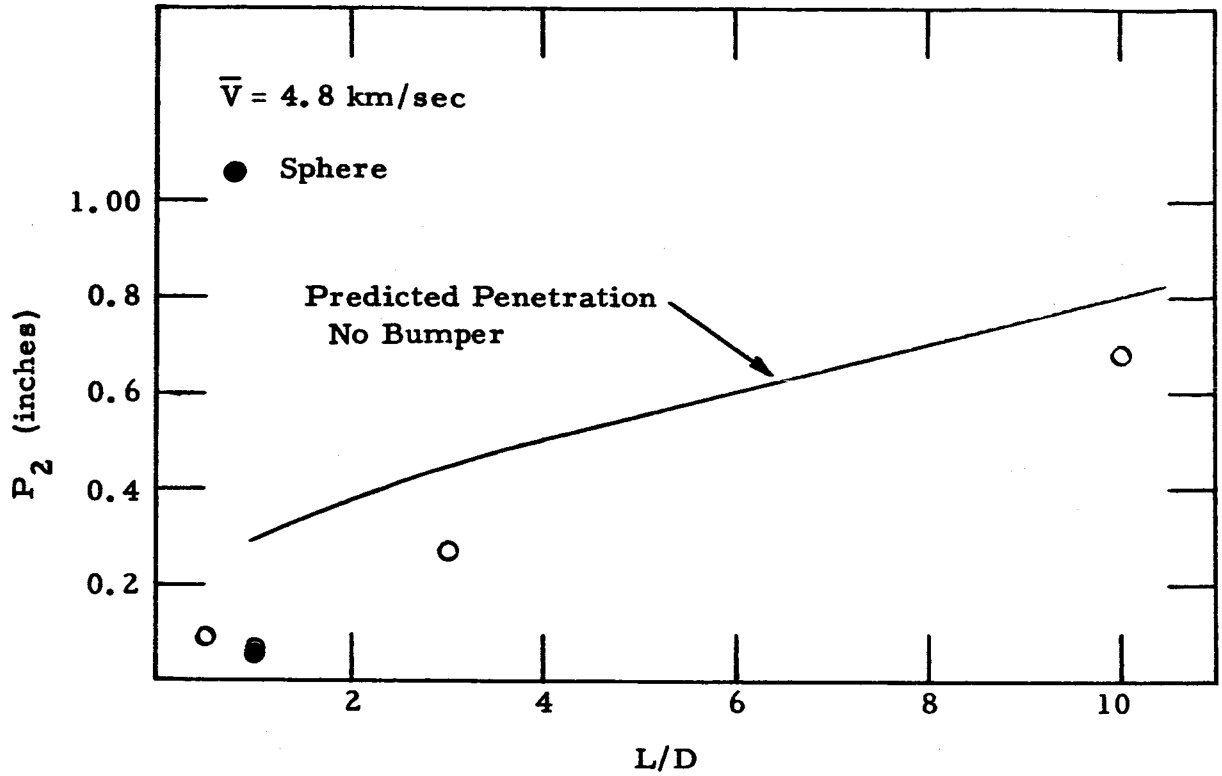
BACKUP PLATE

Damage to the backup plate or primary target behind a thin sheet will generally be due to discrete particle penetration and to impulsive or shock loading. For the case where there is a significant portion of the projectile remaining after impact with a shield, backup plate penetration will probably be the primary mode of damage. For the case where the projectile is essentially "used up," impulsive loading of the backup plate by projectile and bumper debris (and the subsequent deformation, spalling, and/or petalling), may become the primary mode of damage. Quantitative data on these two damage modes are given in Figures 7 and 8.

The backup plate penetration results are shown in Figure 7 for constant impact velocity and for constant projectile size. Penetration increases as L/D increases, and at L/D = 10 begins to approach the penetration achieved with no bumper. This is consistent with the results shown in Figure 4, where the percentage of rod used in perforating a thin plate decreases with increasing L/D. As was the case with residual velocity (see Figure 3), the disc (L/D = 1/3) shows an anomalous behavior with regard to backup plate penetration. The X-ray picture of the disc shown in Figure 5 reveals that there is a discrete projectile of significant size leading the debris behind the thin sheet, and it is this particle that results in the relatively high penetration. This particle may be the rear portion of the bumper that was ejected due to interaction of the shock wave with the rear surface of the sheet.

For a constant projectile size, Figure 7 shows that backup plate penetration, although reaching a maximum at about 5 km/sec, is always

2024-T3 Projectile, 0.21 g
0.063-in. 2024-T3 Sheet (Bumper)
4.0-in. Spacing
1.00-in. 2024-T3 Plate



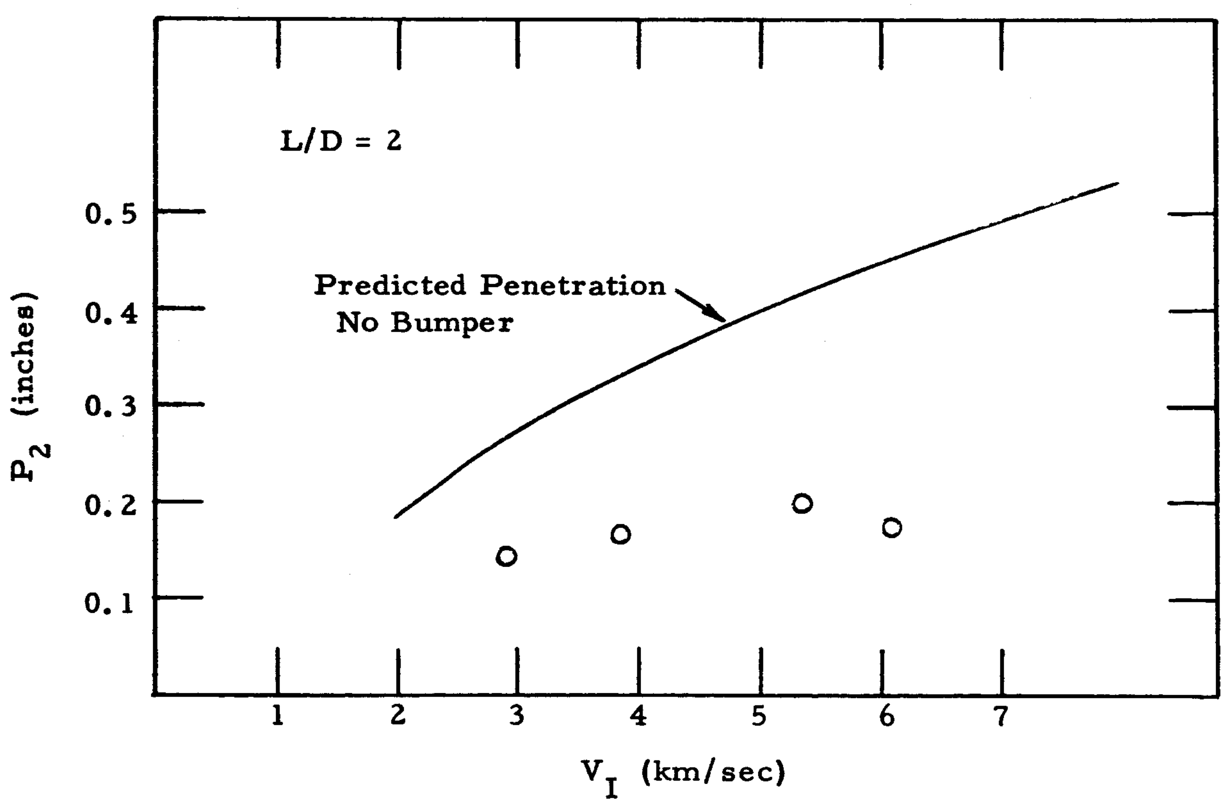
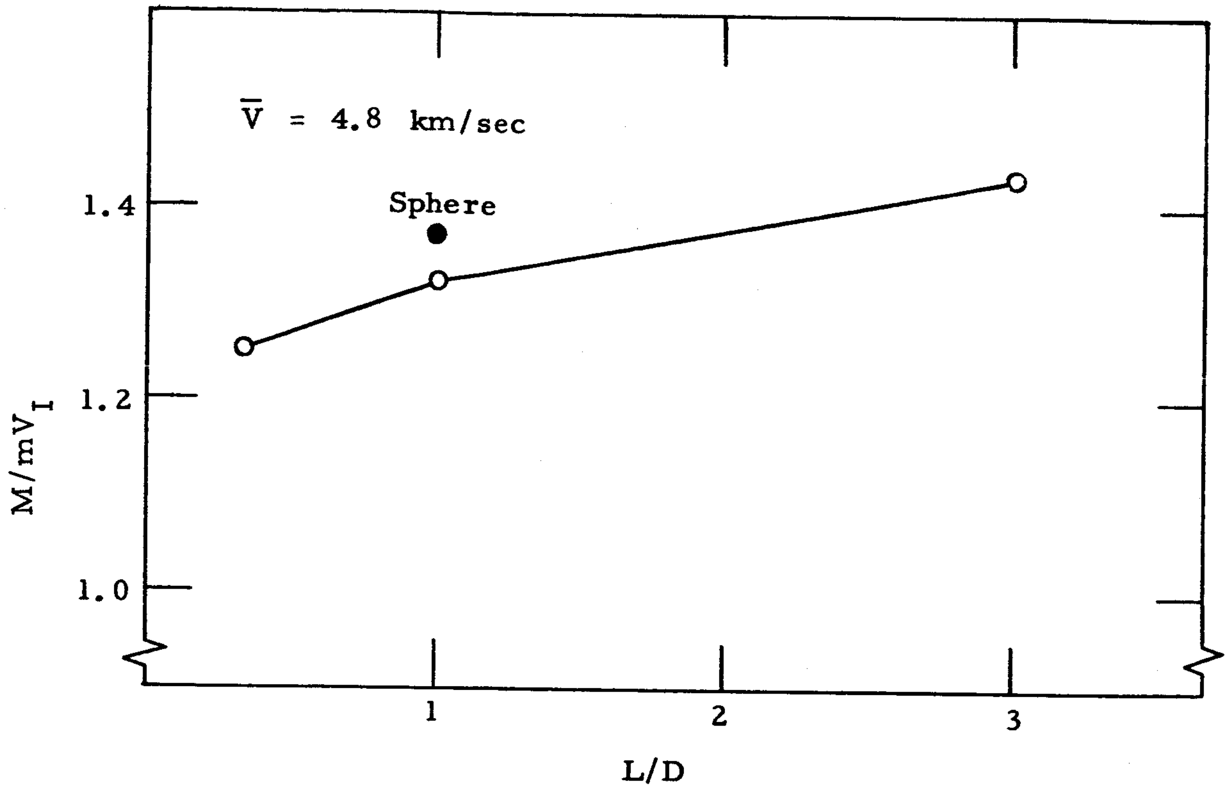


Figure 7 Penetration into Second Plate

2024-T3 Projectile, 0.21 g
0.063-in. 2024-T3 Sheet
4.0-in. Spacing
1.00-in. 2024-T3 Plate



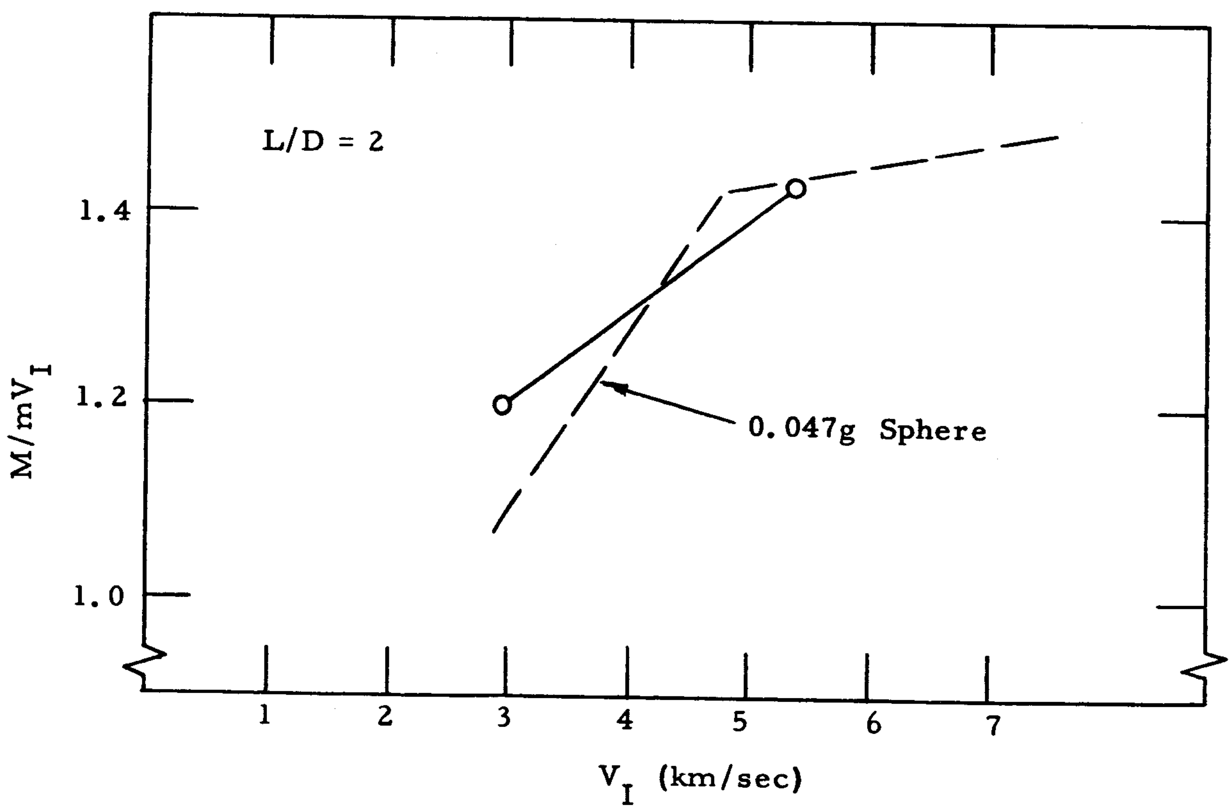


Figure 8 Backup Plate Momentum

substantially less than penetration with no bumper. (It should be noted that, as L/D changes, the relative positions of the predicted penetration curves (no bumper) and the P_2 data points will change; however, there will always be some velocity at which the data points will reach a maximum and then begin to decrease.) It was shown in Reference 3 that at sufficiently high velocities, where the entire projectile is melted or even vaporized, the backup plate penetration will actually become negligible, and be limited to just a scouring or abrasion of the surface.

Impulsive loading data are presented in Figure 8 in terms of total momentum imparted to the backup plate divided by original projectile momentum. At constant velocity, momentum multiplication increases with increasing L/D, which appears to be due to the fact that more total material is ejected from the backup plate as L/D increases, thereby increasing the total momentum felt by the plate. Momentum multiplication also increases as velocity increases, although the dotted curve shown in Figure 8 for the sphere indicates that the rate of increase will become less at higher velocities, particularly after the projectile has been vaporized. It has been estimated that the upper limit for momentum multiplication on the second sheet in multiple-sheet impact is 2, which would be achieved when perfectly elastic collisions occur between each gas atom and the second sheet (assuming that the momentum of the vaporized debris impacting the second sheet is equal to the original projectile momentum mV_I).[9]

CONCLUSIONS AND RECOMMENDATIONS

The principal conclusions reached in this brief study of the penetration of multiple-sheet targets by rod projectiles are:

(1) Front sheet hole area can be expressed as:

$$\frac{d}{D} = 0.45 \ V_I \left(\frac{t_s}{D}\right)^{2/3} + 1.00$$

(2) Maximum residual particle velocity (after perforation of a thin sheet) has been found to be very sensitive to impact velocity, projectile L/D, and thin sheet thickness.

(3) Reasonable predictions of the amount of rod used in perforating thin sheets can be made by reversing the impact conditions, i.e., by analyzing the impact of a disc into a rod projectile.

(4) Backup plate penetration increases as projectile L/D increases, for $L/D > 1$ and at a given velocity.

(5) Impulsive loading or momentum multiplication on the backup plate increases as both L/D and velocity increase, although it may tend to level off at very high velocity.

REFERENCES

1. D. R. Christman and J. W. Gehring, "Penetration Mechanisms of High Velocity Projectiles," Semi-Annual Report, Contract DA-04-495-AMC-534(X), GM Defense Research Laboratories Report TR65-04, January 1965 (see also, Proc. Seventh Hypervelocity Impact Symposium Vol. VI, Martin Co., February 1965)

2. D. R. Christman and J. W. Gehring, "Penetration Mechanisms of High Velocity Projectiles," Final Report, Contract DA-04-495-AMC-534(X), GM Defense Research Laboratories Report TR65-50, July 1965

3. C. J. Maiden, A. R. McMillan, and R. E. Sennett, "Thin Sheet Impact," Proc. Seventh Hypervelocity Impact Symposium, Vol. IV, Martin Co., February 1965

4. C. J. Maiden and A. R. McMillan, "An Investigation of the Protection Afforded a Spacecraft by a Thin Shield," AIAA J., Vol. 2, No. 11, November 1964, pp. 1992-98; and, "Investigation of Fundamental Mechanism of Damage to Thin Targets by Hypervelocity Projectiles," Final Report, Contract ARPA Nonr-3890(00)(X), GM Defense Research Laboratories Report TR63-225, September 1963

5. A. C. Charters, "A Critique of Accelerator Techniques for Hypervelocity Impact," Proc. Sixth Hypervelocity Impact Symposium, Vol. I, DA-31-124-ARO(D)-16, Firestone Tire and Rubber Co., August 1963

6. J. A. Charest, "Measurements of Shock Wave Pressures Generated by Hypervelocity Impacts in Aluminum," GM Defense Research Laboratories Report TR64-58, November 1964

7. J. J. Condon, "Rod Lethality Studies (U)," RTD Technical Report No. ATL-TR-65-18, March 1965 (Confidential)

8. R. L. Bjork and M. Rosenblatt, "Hypervelocity Impact of End-Oriented Rods," Proc. Seventh Hypervelocity Impact Symposium, Vol. IV, Martin Co., February 1965

9. C.J. Maiden, A.R. McMillan, R.E. Sennett and J.W. Gehring, "Experimental Investigations of Simulated Meteoroid Damage to Various Spacecraft Structures," Summary Report, Contract NAS 9-3081, GM Defense Research Laboratories Report TR65-48, July 1965

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13 ABSTRACT

A series of experiments was carried out to study the influence of projectile L/D (aspect ratio) and velocity on impact damage to multiple-sheet structures. Projectiles with L/D of 1/6 to 10 were launched at 4.8 km/sec, and projectiles with L/D = 2 were launched at velocities of 2.9 to 6.1 km/sec. Results are presented in terms of thin-sheet hole area, projectile residual velocity, rod length used, backup plate penetration, and backup plate momentum loading. Empirical equations are presented for predicting thin-sheet hole area and rod length used.

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