UNCLASSIFIED

AD NUMBER
ADB015779
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; NOV 1976. Other requests shall be referred to Ballistic Research Laboratories, Attn: DRXBR-TS, Aberdeen Proving Ground, MD 21005.**
AUTHORITY
BRL ltr, 8 Mar 1978

THIS PAGE IS UNCLASSIFIED

BRL R 1945

BRL

REPORT NO. 1945

MUZZLE BLAST AMPLIFICATION

Edward M. Schmidt

November 1976

Distribution limited to US Government agencies only; Test and Evaluation; Nov 76. Other requests for this document must be referred to Director, USA Ballistic Research Laboratories, ATTN: DRXBR-TS, Aberdeen Proving Ground, Maryland 21005.

USA BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND, MARYLAND

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER BRL Report No. 1945	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) MUZZLE BLAST AMPLIFICATION		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Edward M. Schmidt		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS USA Ballistic Research Laboratory Aberdeen Proving Ground, MD 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS RDT&E 1W161102AH43
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Materiel Development & Readiness Command 5001 Eisenhower Avenue Alexandria, Virginia 22333		12. REPORT DATE NOVEMBER 1976
		13. NUMBER OF PAGES 33
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to US Government agencies only; Test and Evaluation; Nov 1976. Other requests for this document must be referred to Director, USA Ballistic Research Laboratories, ATTN: DRXBR-TS, Aberdeen Proving Ground, Maryland 21005.

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

18. SUPPLEMENTARY NOTES

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

Muzzle Blast
Dispersion
Fin-Stabilized Projectiles
Muzzle Devices
Launch Dynamics

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

An experimental program is conducted having the dual goals of verifying quasi-steady analyses of muzzle gasdynamics and investigating muzzle device effects on projectile accuracy. Firings are performed using a muzzle adaptor to increase blast loadings without altering the mechanical launch environment. The resulting data compare well with quasi-steady analysis and indicates that amplified muzzle gasdynamic loadings can significantly increase dispersion.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

Following separation from the gun tube and prior to entering undisturbed free flight, a projectile must traverse the muzzle blast field. Since this region is highly energetic, it is of interest to determine both the magnitude of gasdynamic forces acting on the round and their effect on the resultant trajectory. The development of the muzzle blast is obviously an unsteady phenomena; however, it has been demonstrated[1,2] that the flow between the gun muzzle and the inward facing shock or Mach disc of the propellant gas jet may be treated as being quasi-steady[1] in nature. Based on this postulate, muzzle blast loadings upon fin-stabilized projectiles have been calculated[3,4].

Gretler[3] assumes the quasi-steady core flow is adequately represented as a supersonic, spherical source. Fansler and Schmidt[4] improve on this solution by treating the core as an axi-symmetric, underexpanded jet. While this produces an estimate of the muzzle blast impulse which is nearly twice that predicted by Gretler, the resultant contribution of muzzle blast induced jump to the overall dispersion of typical weapons is shown to be negligible.

Both models assume that the flow may be treated as quasi-steady, that body loadings may be neglected in comparison to those on fins, and that fin loads may be calculated using thin airfoil theory. Evaluation of the validity of these approximations requires comparison with experiment; however, detailed information on muzzle blast flow fields

---

1. *K. Oswatitsch, "Intermediate Ballistics," Deutsche Luft und Raumfahrt FB 64-37, December 1964. AD 473249.*

2. *E. M. Schmidt and D. D. Shear, "The Flow Field About the Muzzle of an M-16 Rifle," BRL Report No. 1692, U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, January 1974. AD 916646L.*

3. *W. Gretler, "Intermediate Ballistics Investigations of Wing Stabilized Projectiles," Deutsche Luft und Raumfahrt Report 67-92, FSTC-HT-23-22-69-72, 1967.*

4. *K. S. Fansler and E. M. Schmidt, "The Influence of Muzzle Gasdynamics upon the Trajectory of Fin-Stabilized Projectiles," BRL Report No. 1793, U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1975. AD B005379L.*

and loadings on projectiles is difficult to obtain. This author[5] has reviewed some of the experimental techniques available and concludes that direct measurement of loadings transmitted to projectiles in transit of the muzzle region is not currently feasible. Rather, observations of the downrange dynamics of a round should be used to infer properties of the launch regime. Since the effects of gasdynamic loadings on downrange motion may not be separated from those due to mechanical loadings, it is necessary to introduce artificial constraints which hold one source of loadings constant while systematically varying the other.

This approach is taken in the present work. A muzzle device is designed to amplify the gasdynamic loadings experienced by a small caliber flechette round at launch. Two series of firings are conducted, one with and the other without the device attached. The resulting impact distributions are measured in each case. A calculation of the flow within the device and the loadings upon the round is performed using the approach of Fansler and Schmidt[4]. Comparison between the measured and predicted changes in impact distribution is used to establish the validity of the analysis.

II. EXPERIMENT

Tests are conducted using a 5.77mm smoothbore, Mann barrel firing the XM-645 single flechette round at a velocity of 1473 m/s. Pertinent physical properties of the gun and round are given in Table I. This system has been the subject of an intensive experimental survey[6] of the launch dynamics of flechette projectiles. Data from this study will be used as input to the present study. The flow at the muzzle of the gun is modified by the addition of a muzzle adaptor, Figure 1.

The device is a nozzle which prohibits free expansion of the propellant gases. When the projectile separates from the muzzle, the propellant gases expand into the adaptor channel where they form a high pressure, high velocity stream over the projectile. A comparison of the centerline density variation in the free muzzle jet with the density distribution in the adaptor (calculated using quasi-one-dimensional theory), Figure 2, verifies this point. While free expansion in the muzzle jet brings about a rapid decay in centerline density, the density along the adaptor remains fixed at a relatively high level.

---

5. *E. M. Schmidt, "The Effect of Muzzle Jet Asymmetry on Projectile Motion," BRL Report No. 1756, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, January 1975. AD B002159L.*

6. *E. M. Schmidt and D. D. Shear, "Launch Dynamics of a Single Flechette Round," BRL Report 1810, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1975. AD B006781L.*

To examine the effect of this variation in the launch environment on projectile trajectory, two groups of ten rounds were fired, respectively, with and without the muzzle adaptor in place. Impact distributions into a witness card placed 25 meters from the weapon muzzle were obtained, Figure 3. The measured dispersions in the horizontal and vertical directions are summarized below:

	σ_y (mils)	σ_z (mils)
Without Adaptor	1.27	1.30
With Adaptor	2.41	2.28

The increase in dispersion due to the presence of the adaptor is substantial. Since the adaptor is fabricated from aluminum and is installed on a stiff, rigidly mounted Mann barrel, the mechanical loadings are assumed to be invariant between configurations, and the observed increase in dispersion is interpreted as arising due to amplification of muzzle gasdynamic loadings. In the following section, the flow within the adaptor, gasdynamic loadings, and resultant trajectory perturbations will be calculated and compared with these results.

III. ANALYSIS

A. Flow Properties Within the Muzzle Adaptor

The conditions at the muzzle of the gun at shot ejection were calculated by B. Grollman[7] of BRL. His predictions are tabulated below:

$$\gamma = 1.25$$

$$R = 399.2\ m^2/s^{2\,o}K$$

$$V_e = 1473\ m/s$$

$$T_e = 1540^oK$$

$$a_e = 877\ m/s$$

$$M_e = 1.68$$

$$p_e = 428.6\ p_\infty$$

7. *B. Grollman, Private Communication, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1976.*

To simplify the analysis, variation in the exit properties during projectile residence in the adaptor will be neglected.

Using steady, quasi-one-dimensional theory[8], the computed exit conditions, and the area ratio of the device, $A/A_e = 4.0$, the flow properties within the adaptor may be calculated:

$$M = 2.95 \ , \tag{1a}$$

$$p/p_e = 0.114 \ , \tag{1b}$$

$$a/a_e = 0.805 \ . \tag{1c}$$

The relative Mach number with respect to the projectile is

$$M_r = \frac{u-V_p}{a} = M - \frac{V_p}{a}$$

$$= 0.863; \tag{1d}$$

thus, flow over the projectile is transonic.

B. Projectile Loadings and Dynamics

Following Fansler and Schmidt[4], transverse gasdynamic loadings upon the projectile are assumed to originate solely at the fins. Further, two-dimensional, thin airfoil theory will be used to compute the fin loadings under the assumptions that flow inclination, wing tip, and wing-body interference effects may be neglected. As a result, the following expression describes the transverse loadings on the round:

$$L = \frac{1}{2} \rho V_r^2 A_T C_{L_\alpha} \alpha, \tag{2}$$

where C_{L_α} is the lift coefficient on the fins in the reverse flow within the muzzle adaptor, Figure (4). For the relative Mach number in the adaptor, $M_r = 0.863$,

$$C_{L_\alpha} = 8.8.$$

---

8. *H. W. Liepmann and A. Roshko, Elements of Gasdynamics, pp. 125-126, John Wiley & Sons, New York, 1957.*

The gasdynamic moment about the projectile center of gravity is

$$M_t = \frac{1}{2} \rho V_r^2 A_T \ell C_{M_\alpha} \alpha \quad . \tag{3}$$

Where the moment coefficient is related[4] to the lift coefficient by:

$$C_{M_\alpha} = C_{L_\alpha} \frac{\Delta}{\ell} \quad , \tag{4}$$

Δ/ℓ being the separation between the projectile c.g. and the fin c.p. in calibers.

Based on these loadings, the equations of motion for the projectile flight through the muzzle adaptor may be written:

$$m_p \, [dv/dt] = \frac{1}{2} \rho V_r^2 A_T C_{L_\alpha} \alpha \, , \tag{5}$$

$$I_t \, [d^2\alpha/dt^2] = \frac{1}{2} \rho V_r^2 A_T \Delta C_{L_\alpha} \alpha \quad . \tag{6}$$

The independent variable in these equations may be transformed by noting

$$\frac{d}{dt} = \frac{d}{d\bar{x}} \frac{d\bar{x}}{dt}$$

$$= \frac{V_p}{\ell} \frac{d}{d\bar{x}} \quad ,$$

where $\bar{x} = x/\ell$,

V_p = projectile velocity.

Thus,

$$m_p \, [dv/d\bar{x}] = \frac{1}{2} \rho V_r^2 A_T C_{L_\alpha} \frac{\ell}{V_p} \alpha \quad , \tag{5a}$$

$$I_t \, [d^2\alpha/d\bar{x}^2] = \frac{1}{2} \rho V_r^2 A_T \Delta C_{L_\alpha} \frac{\ell^2}{V_p^2} \alpha \, . \tag{6a}$$

Since the flow properties in the adaptor are dependent only upon muzzle exit conditions (taken as constant) and assuming that the projectile axial velocity through the adaptor remains constant, Equations (5a) and (6a) may be rewritten as

$$v'/V_p = n\,\alpha \ , \tag{7}$$

$$\alpha'' - m^2\,\alpha = 0, \tag{8}$$

where

$$n = \rho\, V_r^2\, A_T\, C_{L_\alpha}\, \ell/2\, m_p\, V_p^2 \ , \tag{9}$$

$$m^2 = \rho\, V_r^2\, A_T\, \Delta\, C_{L_\alpha}\, \ell^2/2\, I_t\, V_p^2 \ . \tag{10}$$

For constant m^2, Equation (8) may be solved directly:

$$\alpha = c_1\, e^{m\bar{x}} + c_2\, e^{-m\bar{x}} \ , \tag{11}$$

with boundary conditions at $\bar{x} = 0$

$$\alpha = \alpha_e \ ,$$

$$\alpha' = \alpha'_e \ ,$$

yielding

$$c_1 = \frac{1}{2}\,(\alpha_e + \frac{\alpha'_e}{m}) \ , \tag{12}$$

$$c_2 = \frac{1}{2}\,(\alpha_e - \frac{\alpha'_e}{m}) \ . \tag{13}$$

Substitution of Equation (11) into Equation (7) permits direct integration over the length of the muzzle adaptor, $\bar{x}_L$, giving

$$(v_L - v_e)/V_p = (n/m^2)\,(c_1\, me^{m\bar{x}_L} - c_2\, me^{-m\bar{x}_L} - \alpha'_e]. \tag{14}$$

The projectile angular velocity at exit from the adaptor is obtained by differentiating Equation (11):

$$\alpha'_L - \alpha'_e = c_1\, me^{m\bar{x}_L} - c_2\, me^{-m\bar{x}_L} - \alpha'_e \ . \tag{15}$$

To specify the projectile dynamics upon entry into free flight, it is also necessary to consider the effect of transit of the adaptor muzzle blast, Figure 5. The flow properties along the centerline of the propellant gas jet are calculated using the method of characteristics[9], Figure 6. The change in projectile dynamics is computed using the method of Fansler and Schmidt[4], who show:

$$\delta\,(v/V_p) = (\gamma+1)\; P^*\, A_T\, \alpha_L \frac{D'}{m_p\, V_p^2}\, \bar{P} \;, \qquad (16)$$

$$\delta\,(\alpha') = (\gamma+1)\; P^*\, A_T\, \alpha_L \frac{\Delta\, D'\, \ell}{I_t V_p^2}\, \bar{P} \;, \qquad (17)$$

where α_L is given by Equation (11),

$\delta(\;)$ refers to an incremental increase in the bracketted property due to muzzle blast loadings,

$$\bar{P} = \int \bar{L}\, d\frac{x}{D'} \;,$$

$$\bar{L} = \frac{\gamma}{2(\gamma+1)}\, C_{L_\alpha} \frac{\rho}{\rho^*}\, M_r^{*2} \;,$$

$D' = 2D$ = diameter of muzzle adaptor.

For the jet properties given in Figure 5,

$$\bar{P} = 0.24 \;. \qquad (18)$$

Using the tabulated projectile and gun muzzle properties, Equations (11) and (14) through (18) may be used to determine the

---

9. *A. R. Vick, et al, "Comparison of Experimental Free-Jet Boundaries with Theoretical Results Obtained with the Method of Characteristics," NASA TN D-2327, June 1964. NTIS N64-23032.*

amplification of the projectile dynamics due to transit of the adaptor and its muzzle blast:

$$\frac{v_f - v_e}{V_p} = 0.056\ \alpha_e + 2.31\ \alpha_e' \tag{19}$$

$$\alpha_f' - \alpha_e' = 0.018\ \alpha_e + 0.71\ \alpha_e' \tag{20}$$

C. Dispersion Increase Due to Muzzle Adaptor

To compute the effect of the amplified muzzle gasdynamic loadings upon the projectile trajectory, it is necessary to know the distribution in initial projectile dynamics and the impact of this upon the resultant flight path. For the XM-645 round, the distribution of projectile dynamics at the muzzle was measured by Schmidt and Shear[6], Table II. The amplification of this dynamic state due to transit of the adaptor may be calculated using Equations (19) and (20). Finally, the resultant trajectory perturbation is obtained by summing the aerodynamic[10] and transverse linear momentum jumps:

$$\theta_T = \frac{\bar{C}_{L_\alpha}}{\bar{C}_{M_\alpha}} \frac{I_t}{m_p \ell^2} (\alpha_f' - \alpha_e') + \frac{v_f - v_e}{V_p} , \tag{21}$$

where $\bar{C}_{L_\alpha}$, $\bar{C}_{M_\alpha}$ are the lift and static moment coefficients of the projectile in forward flight.

Substitution of known projectile properties and Equations (19) and (20) into Equation (21) gives

$$\theta_T = - 0.114\ \alpha_e - 4.52\ \alpha_e' , \tag{22}$$

where θ_T is in milliradians for α_e expressed in milliradians and α_e' expressed in milliradians per caliber. Using Equation (22) and the distribution in α_e and α_e', Table II, the increase in dispersion

10. *C. H. Murphy, "Free Flight Motion of Symmetric Missiles," BRL Report 1216, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1963. AD 442757.*

due to presence of the muzzle adaptor is computed to be

$$\Delta\sigma_y = 0.4,$$

$$\Delta\sigma_z = 0.9.$$

A comparison of the predicted and measured results is given in Figure 7.

Considering the simplistic nature of the theoretical analysis and the crude nature of the experimental data, the comparison in Figure 7 is reasonably good. It demonstrates that the interpretation of the physical gasdynamics and the resultant loadings upon the projectile are within a better than order of magnitude agreement with the actual phenomena. Possible sources of error include data sample size, difficulties in predicting the flow properties both at the weapon muzzle[11] and within the adaptor (especially with transonic relative flow over the projectile), and the lack of treatment of sabot discard interactions.

IV. CONCLUSIONS

An experimental program was conducted which clearly demonstrates the possibility of amplification of muzzle gasdynamic loadings due to the presence of muzzle devices. By installing a muzzle adaptor with a length of 25 calibers and an inside diameter of two calibers (a geometry quite similar to that of a number of small arms muzzle devices, e.g., silencers), the round-to-round dispersion pattern of a 5.8mm flechette was increased from 1.25 milliradians to 2.25 milliradians. This one milliradian increase in dispersion is interpreted as arising solely due to increased propellant gasdynamic loadings upon the projectile during transit of the muzzle adaptor.

A theoretical analysis of these loadings is conducted using the approach of Fansler and Schmidt[4]. The predicted values of dispersion amplification are shown to agree reasonably well with the data. This is taken as a validation of the general correctness of the analytical approach.

---

11. *E. M. Schmidt, E. J. Gion, and D. D. Shear, "Acoustic Thermometric Measurements of Propellant Gas Temperatures in Guns," BRL Report 1919, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1976.* (AD #A030359)

Projectile Properties:

$$m_p = 6.8 \times 10^{-4} \text{ kg}$$

$$I_a = 3.2 \times 10^{-10} \text{ kg-m}^2$$

$$I_t = 7.1 \times 10^{-8} \text{ kg-m}^2$$

$$\ell = 1.8 \times 10^{-3} \text{ m}$$

$$\Delta = 1.78 \times 10^{-2} \text{ m}$$

$$n = 4$$

$$A = 1.0 \times 10^{-5} \text{ m}^2$$

$$A_T = nA/2 = 2.0 \times 10^{-5} \text{ m}^2$$

$$\bar{C}_{L_\alpha} = 15$$

$$\bar{C}_{M_\alpha} = -50$$

Weapon Properties:

Smoothbore

$$D = 5.77 \times 10^{-3} \text{ m}$$

$$L = 0.495 \text{ m} \quad \text{(overall)}$$

$$m_c = 1.361 \times 10^{-3} \text{ kg} \quad \text{(ball powder)}$$

$$V_c = 1.089 \times 10^{-6} \text{ m}^3$$

$$V_p = 1473 \text{ m/s}$$

TABLE I: PROPERTIES OF PROJECTILE AND WEAPON

ROUND	ANGLE OF ATTACK $\tilde{\alpha}_e$ (mr)	$\tilde{\alpha}'_e$ (mr/cal)	ANGLE OF SIDESLIP $\tilde{\beta}_e$ (mr)	$\tilde{\beta}'_e$ (mr/cal)
1	-7.42	-0.121	+2.46	-0.156
2	-0.56	-0.005	+1.95	-0.138
3	-1.84	-0.089	-3.74	+0.041
4	-0.40	+0.015	-0.44	+0.114
5	-1.30	-0.133	-0.03	-0.076
6	+3.99	+0.151	+1.90	-0.034
7	-0.68	-0.125	+3.72	-0.276
8	+3.64	+0.109	-4.50	+0.098

TABLE II: DISTRIBUTION IN LAUNCH ANGLE AND ANGULAR VELOCITY[6]

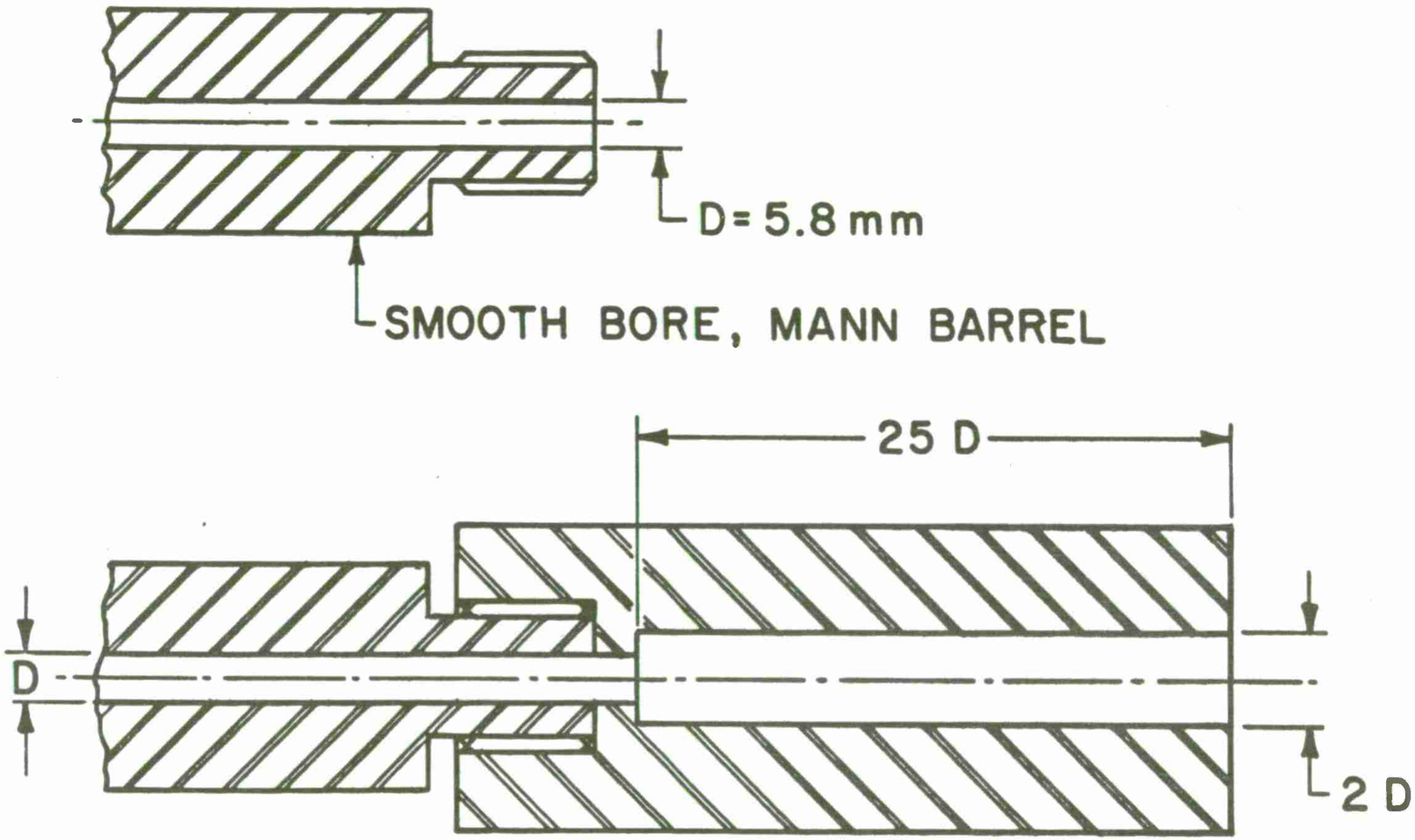

Figure 1. Schematic of Muzzle Adaptor

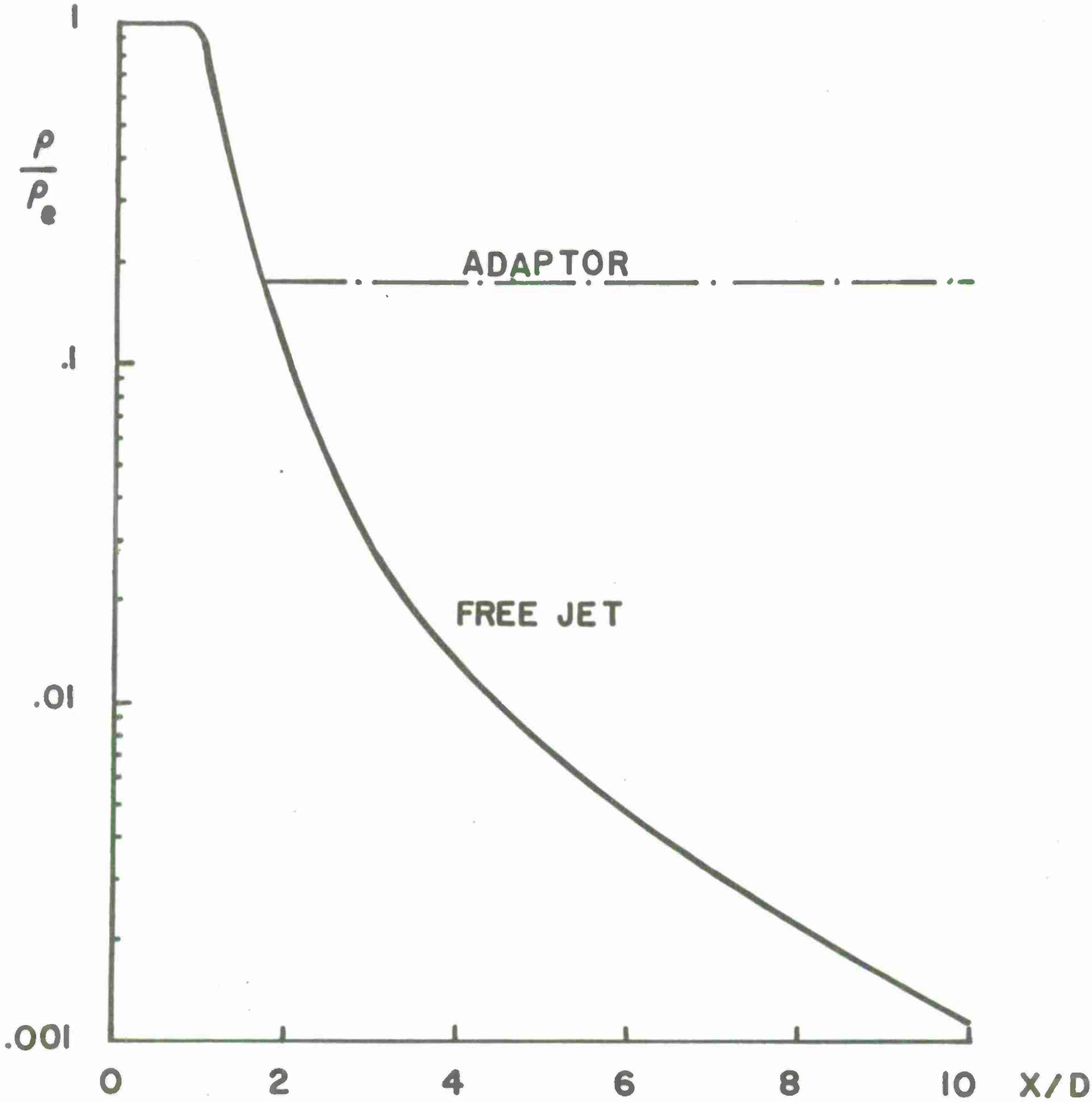

Figure 2. Comparison of Density Distribution Along Centerline of Adaptor and Free Jet, Both Expanding from Identical Exit Conditions.

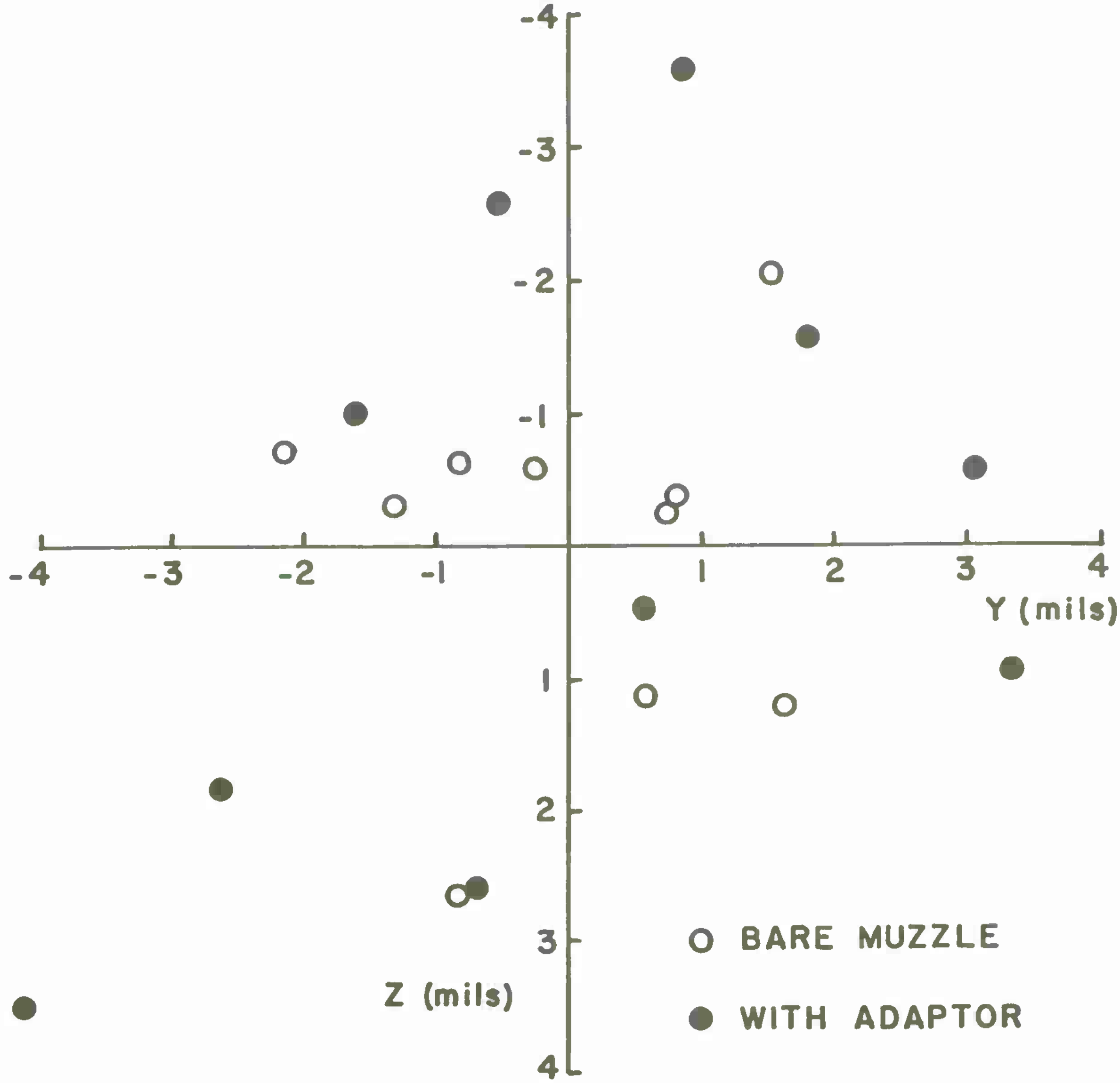

Figure 3. Measured Impact Patterns with and without Muzzle Adaptor.

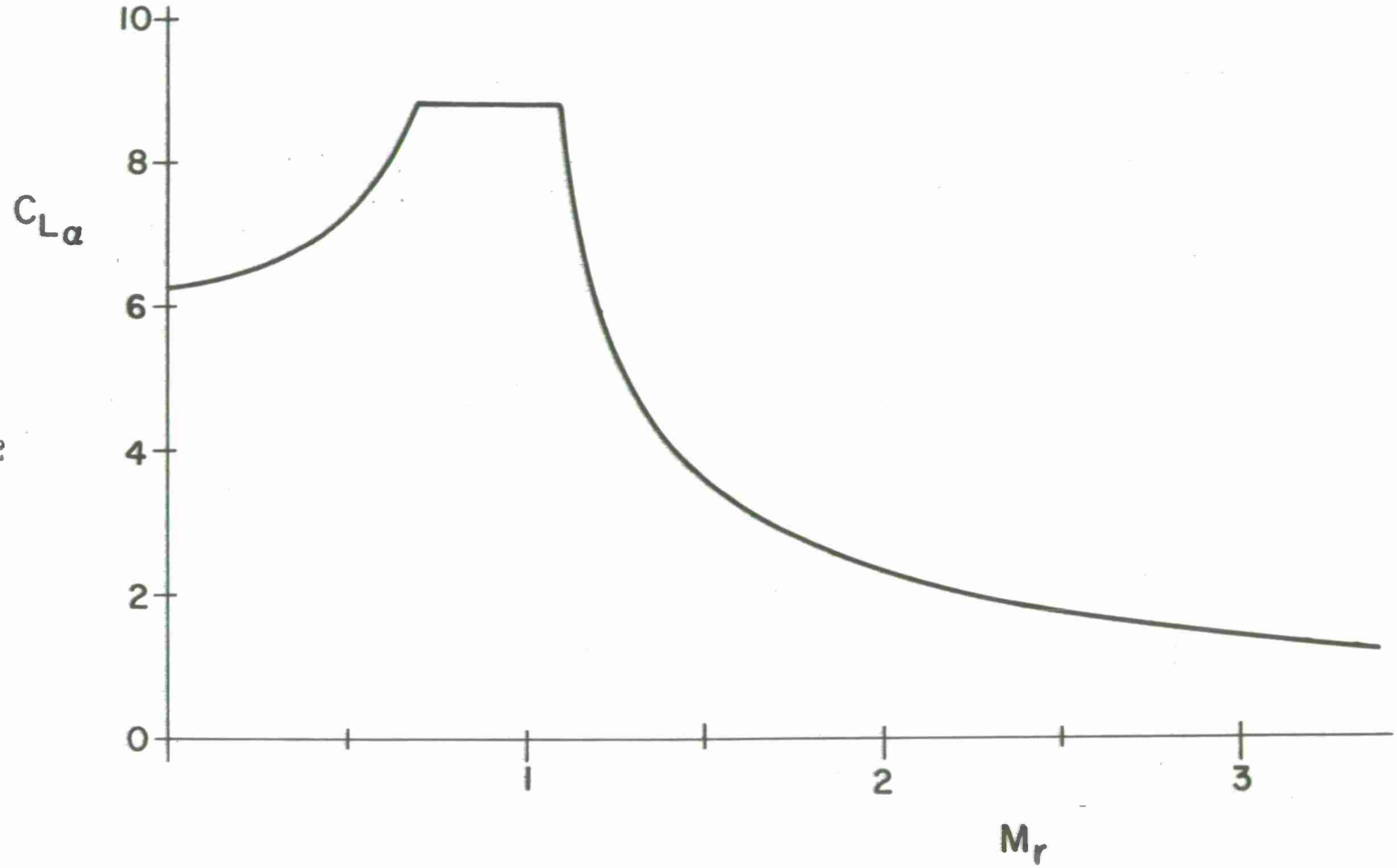

Figure 4. Fin Lift Coefficient Versus Relative Mach Number.

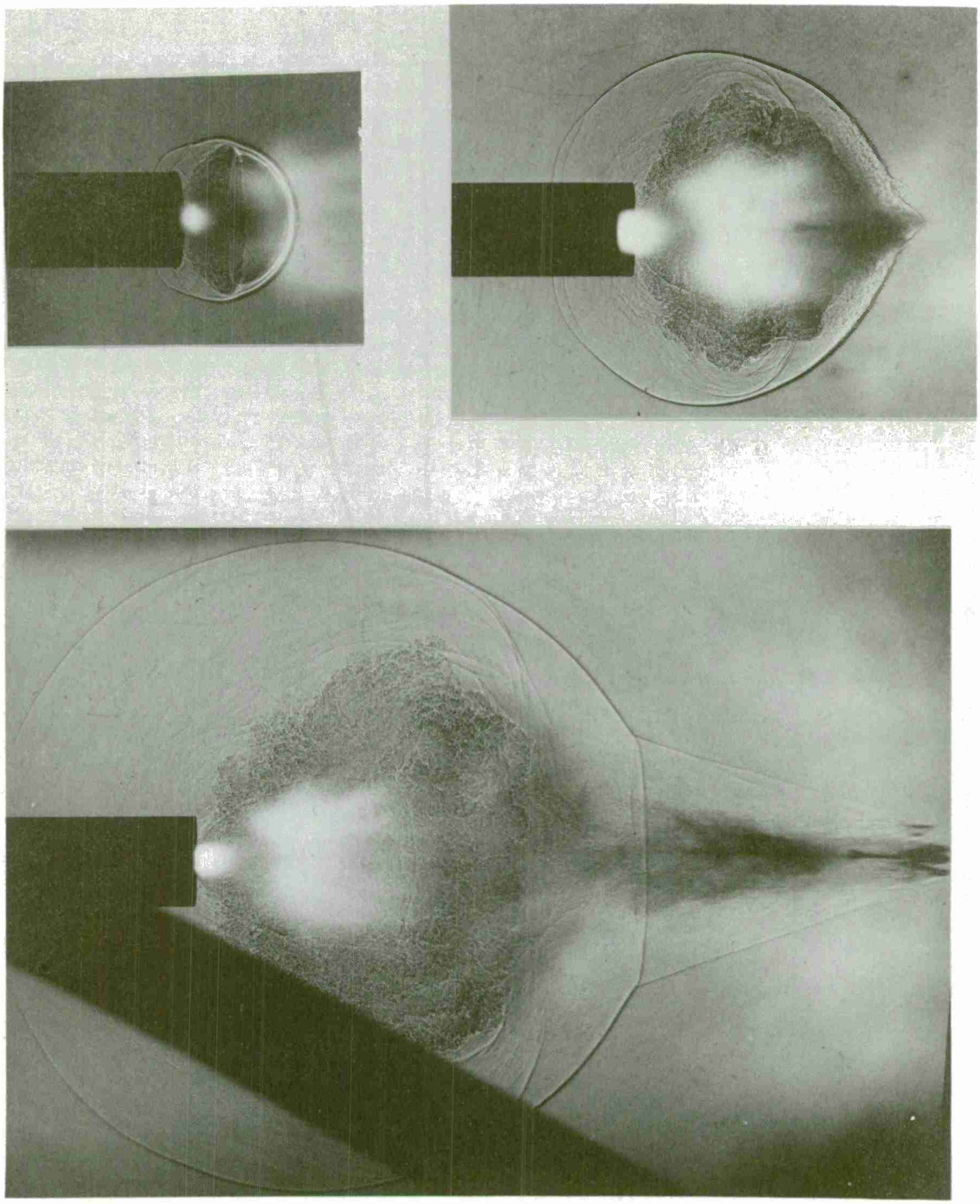

Figure 5. Spark Shadowgraphs of Muzzle Blast from Weapon Equipped with Muzzle Adaptor.

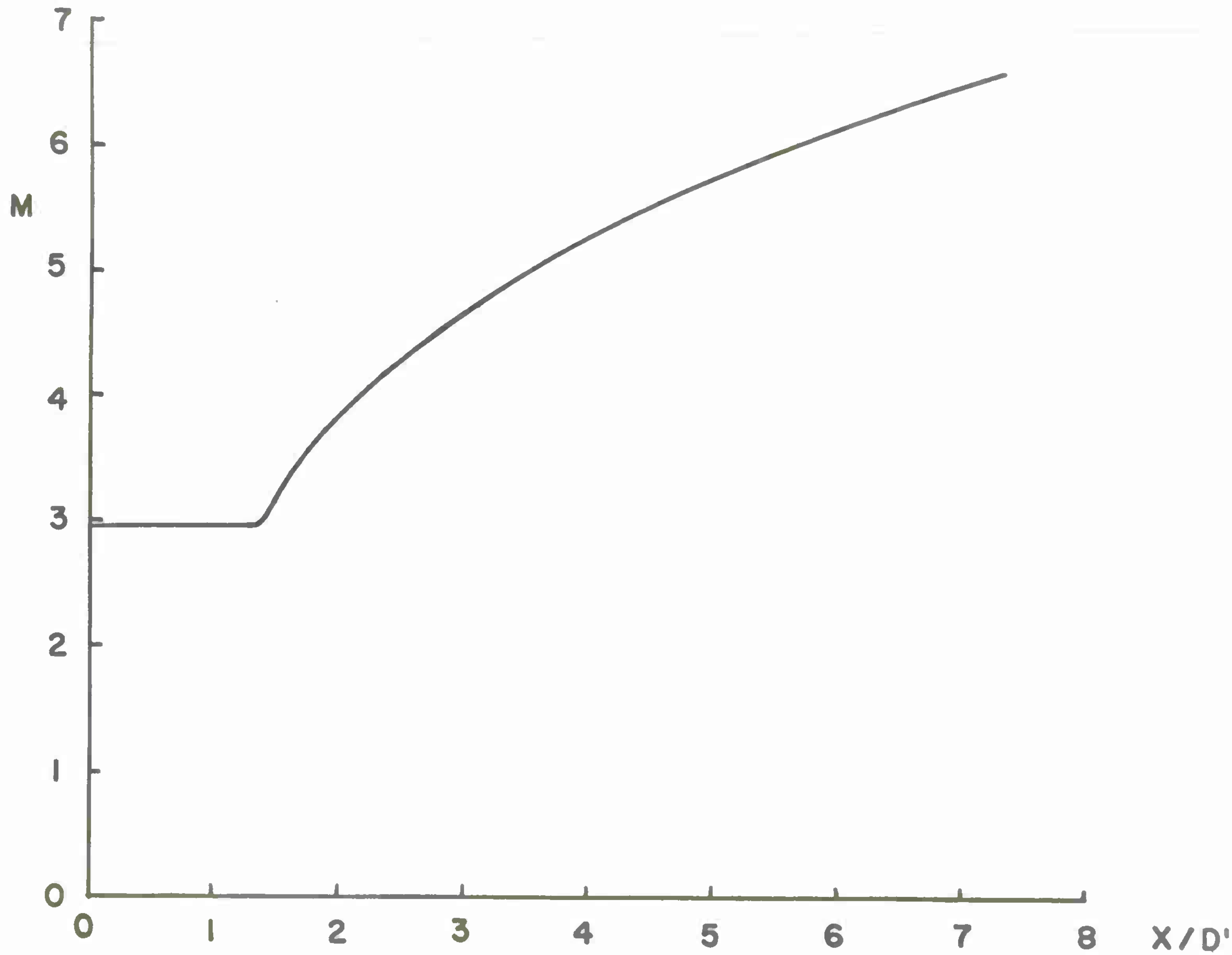

Figure 6. Mach Number Distribution Along Centerline of Underexpanded Jet where $M_e = 2.95$.

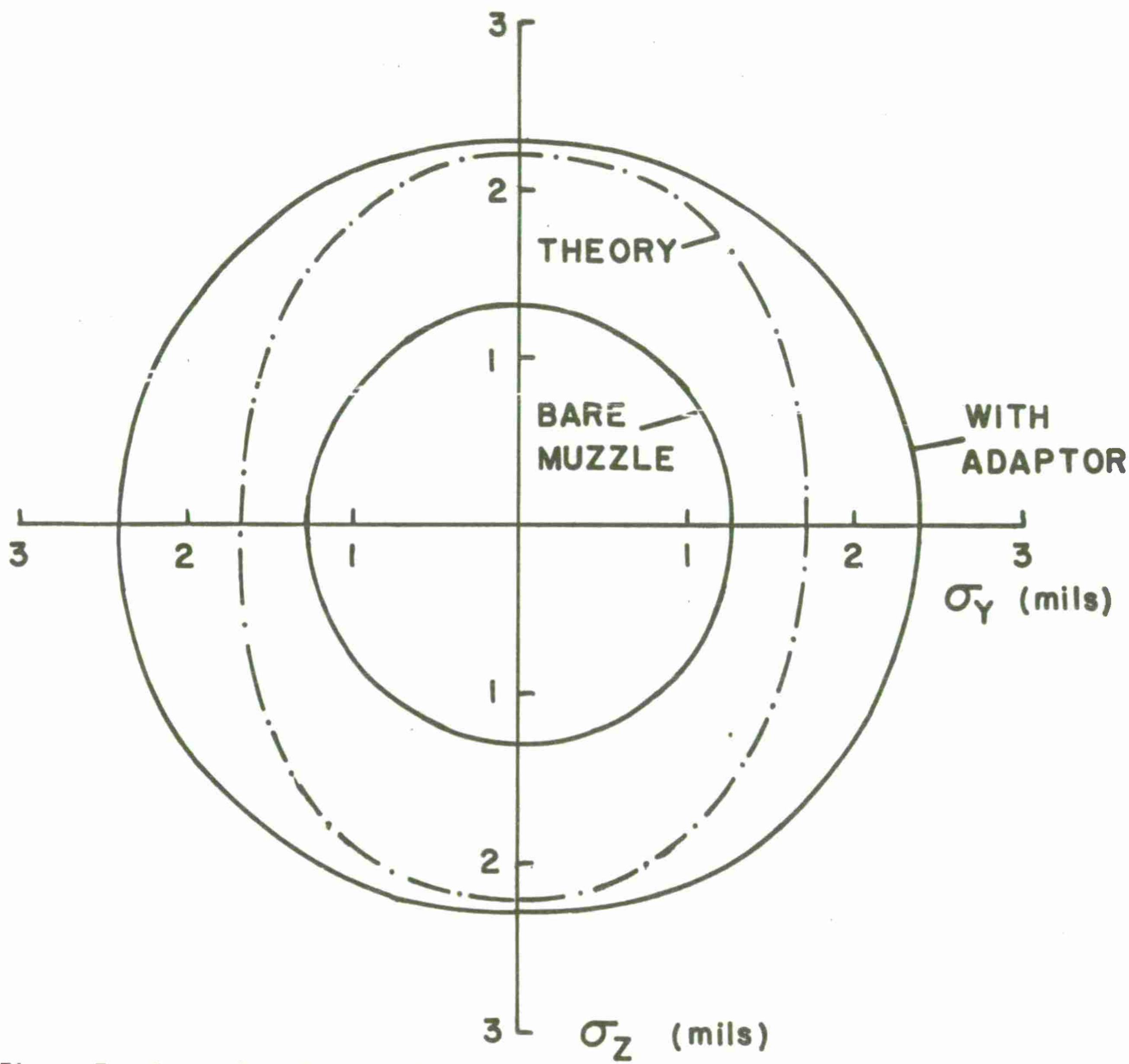

Figure 7. Comparison Between Theoretical and Experimental Impact Distributions.

REFERENCES

1. K. Oswatitsch, "Intermediate Ballistics," Deutsche Luft und Raumfahrt FB 64-37, December 1964. AD 473249.

2. E. M. Schmidt and D. D. Shear, "The Flow Field About the Muzzle of an M-16 Rifle," BRL Report No. 1692, U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, January 1974. AD 916646L.

3. W. Gretler, "Intermediate Ballistics Investigations of Wing Stabilized Projectiles," Deutsche Luft und Raumfahrt Report 67-92, FSTC-HT-23-22-69-72, 1967.

4. K. S. Fansler and E. M. Schmidt, "The Influence of Muzzle Gas-dynamics upon the Trajectory of Fin-Stabilized Projectiles," BRL Report No. 1793, U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1975. AD B005379L.

5. E. M. Schmidt, "The Effect of Muzzle Jet Asymmetry on Projectile Motion," BRL Report No. 1756, U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, January 1975. AD B002159L.

6. E. M. Schmidt and D. D. Shear, "Launch Dynamics of a Single Flechette Round," BRL Report 1810, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1975. AD B006781L.

7. B. Grollman, Private Communication, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1976.

8. H. W. Liepmann and A. Roshko, Elements of Gasdynamics, pp. 125-126, John Wiley & Sons, New York, 1957.

9. A. R. Vick, et al, "Comparison of Experimental Free-Jet Boundaries with Theoretical Results Obtained with the Method of Characteristics," NASA TN D-2327, June 1964. NTIS N64-23032.

10. C. H. Murphy, "Free Flight Motion of Symmetric Missiles," BRL Report 1216, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1963. AD 442757.

11. E. M. Schmidt, E. J. Gion, and D. D. Shear, "Acoustic Thermometric Measurements of Propellant Gas Temperatures in Guns," BRL Report 1919, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1976. (AD #A030359)

LIST OF SYMBOLS

a	speed of sound
A_T	equivalent fin area
C_{L_α} , C_{M_α}	lift and moment coefficients of fins in reverse flow
$\bar{C}_{L_\alpha}$, $\bar{C}_{M_\alpha}$	lift and moment coefficients of projectile in forward flight
D	gun tube diameter
D'	muzzle adaptor diameter ($D' = 2D$)
I_a, I_t	axial and transverse moments of inertia of projectile
ℓ	projectile (shaft) diameter
L	lift
$\bar{L}$	non-dimensional lift
m	coefficient defined in Equation (10)
m_p	projectile mass
M	Mach number
M_r	Mach number of reverse flow relative to projectiles
M_t	overturning moment
n	coefficient defined in Equation (9)
p	pressure
$\bar{P}$	momentum transfer function
R	gas constant
t	time
u	axial flow velocity
v	transverse projectile velocity
V_p	projectile launch velocity

x,y,z	coordinate system: x directed downrange, y directed vertically downward, and z directed according to right hand rule.
α,β	angles of attack and sideslip
γ	ratio of specific heats
Δ	c.p. - c.g. separation
θ_T	total jump due to muzzle blast effects
ρ	local flow density
σ_i	one standard deviation in i

Subscripts

e	muzzle exit conditions
r	relative flow conditions
∞	ambient conditions

Superscripts

$(\ )'$	spatial rate of change of property

DISTRIBUTION LIST

No. of Copies	Organization
2	Commander Defense Documentation Center ATTN: DDC-TCA Cameron Station Alexandria, VA 22314
1	Director Defense Nuclear Agency Washington, DC 20305
1	Commander US Army Materiel Development and Readiness Command ATTN: DRCDMA-ST 5001 Eisenhower Avenue Alexandria, VA 22333
1	Commander US Army Materiel Development and Readiness Command ATTN: DRCDL 5001 Eisenhower Avenue Alexandria, VA 22333
3	Commander US Army Aviation Systems Command ATTN: DRSAV-E DRSAV-EQA, CPT Schrage DRCPM-AAH, G. Smith 12th and Spruce Streets St. Louis, MO 63166
1	Director US Army Air Mobility Research and Development Laboratory Ames Research Center Moffett Field, CA 94035
1	Commander US Army Electronics Command ATTN: DRSEL-RD Fort Monmouth, NJ 07703
4	Commander US Army Missile Command ATTN: DRSMI-R DRSMI-RBL DRSMI-RDK Mr. R. Becht Mr. R. Deep Redstone Arsenal, AL 35809
1	Commander US Army Tank Automotive Development Command ATTN: DRDTA-RWL Warren, MI 48090
2	Commander US Army Mobility Equipment Research & Development Command ATTN: Tech Docu Cen, Bldg. 315 DRSME-RZT Fort Belvoir, VA 22060
4	Commander US Army Armament Command ATTN: P. Ehle E. Haug Tech Lib DRSAR-RDT, J. Blick Rock Island, IL 61202
2	Commander US Army Armament Command ATTN: Rodman Laboratories S. Thompson S. Burley Rock Island, IL 61202
4	Commander US Army Frankford Arsenal ATTN: Mr. T. Boldt SARFA-J8000, J.Mitchell SARFA-K3000, S.Fulton SARFA-J6300, S.Hirshman Philadelphia, PA 19137

DISTRIBUTION LIST

No. of Copies	Organization
4	Commander US Army Frankford Arsenal ATTN: SARFA-J3000, A.Cianciosi L4100-150-2 C. Sleischer, Jr. SARFA-MDS-D 220 F. Puzycki C. Rueter Philadelphia, PA 19137
5	Commander US Army Picatinny Arsenal ATTN: SARPA-DR-D, S.Wasserman SARPA-DR-V, A. Loeb Mr. D. Mertz Mr. F. Friedman SARPA-D, Mr. Lindner Dover, NJ 07801
5	Commander US Army Picatinny Arsenal ATTN: SARPA-FR, E. Walbrecht Mr. S. Verner SARPA-VE, Dr. Kaufman SARPA-FR-M-MA E. Barrieres SARPA-PA-S, W.Dzingala Dover, NJ 07801
5	Commander US Army Watervliet Arsenal ATTN: Tech Lib SARWV-PDR-S, F. Sautter SARWV-PDR-AMM, J. Zweig SARWV-RDD-SE, P.A. Alto SARWV-RR-AM Dr. G. C. Carofano Watervliet, NY 12189
1	Commander US Army Jefferson Proving Ground ATTN: STEJP-TD-D Madison, IN 47250
2	Commander US Army Harry Diamond Labs ATTN: DRXDO-TI DRXDO-DAB, H.J. Davis 2800 Powder Mill Road Adelphi, MD 20783
1	Commander US Army Materials and Mechanics Research Center ATTN: DRXMR-ATL Watertown, MA 02172
1	Commander US Army Natick Research and Development Command ATTN: DRXRE, Dr. D. Sieling Natick, MA 01762
1	Director US Army TRADOC Systems Analysis Activity ATTN: ATAA-SA White Sands Missile Range NM 88002
1	Commander US Army Research Office ATTN: CRD-AA-EH P. O. Box 12211 Research Triangle Park NC 27709
1	Director US Army BMD Advanced Technology Center P. O. Box 1500 West Station Huntsville, AL 35807
1	Commander US Army Ballistic Missile Defense Systems Command Huntsville, AL 35804

DISTRIBUTION LIST

No. of Copies	Organization
3	Commander US Naval Air Systems Command ATTN: AIR-604 Washington, DC 20360
3	Commander US Naval Ordnance Systems Command ATTN: ORD-9132 Washington, DC 20360
2	Commander and Director David W. Taylor Naval Ship Research & Development Ctr ATTN: Tech Lib Aerodynamic Lab Bethesda, MD 20084
3	Commander US Naval Surface Weapons Ctr ATTN: Code 312, Mr. F. Regan Mr. S. Hastings Code 730, Tech Lib Silver Spring, MD 20910
3	Commander US Naval Surface Weapons Ctr ATTN: Code GX, Dr. W. Kemper Mr. F. H. Maille Dr. G. Moore Dahlgren, VA 22448
1	Commander US Naval Weapons Center ATTN: Code 553, Tech Lib China Lake, CA 93555
3	Commander US Naval Research Laboratory ATTN: Tech Info Div Code 7700, D. A. Kolb Code 7720, Dr. E.McClean Washington, DC 20375
1	Commander US Naval Ordnance Station ATTN: Code FS13A, P. Sewell Indian Head, MD 20640
1	AFRPL/LKCB, Dr. Horning Edwards AFB, CA 93523
2	ADTC (ADBPS-12) Eglin AFB, FL 32542
1	AFATL (DLDL, Dr. D.C. Daniel) Eglin AFB, FL 32542
1	AFWL (DEV) Kirtland AFB, NM 87117
1	ASD (ASBEE) Wright-Patterson AFB, OH 45433
1	Director NASA Scientific and Technical Information Facility ATTN: SAK/DL P. O. Box 8757 Baltimore/Washington International Airport, MD 21240
1	Director Jet Propulsion Laboratory ATTN: Tech Lib 2800 Oak Grove Drive Pasadena, CA 91103
2	Director National Aeronautics and Space Administration George C. Marshall Space Flight Center ATTN: MS-I, Lib R-AERO-AE, A. Felix Huntsville, AL 35812

DISTRIBUTION LIST

No. of Copies	Organization
1	Director National Aeronautics and Space Administration Langley Research Center ATTN: MS 185, Tech Lib Langley Station Hampton, VA 23365
1	AAI Corporation ATTN: Dr. T. Stastny Cockeysville, MD 21030
1	Advanced Technology Labs ATTN: Dr. J. Erdos Merrick and Stewart Avenues Westbury, NY 11590
1	Aerospace Corporation ATTN: Dr. T. Taylor P. O. Box 92957 Los Angeles, CA 90009
2	ARO, Inc. ATTN: Tech Lib Arnold AFS, TN 37389
1	ARTEC Associates, Inc. ATTN: Dr. S. Gill 26046 Eden Landing Road Hayward, CA 94545
1	AVCO Systems Division ATTN: Dr. W. Reinecke 201 Lowell Street Wilmington, MA 01887
1	Calspan Corporation ATTN: Mr. G.A. Sterbutzel P. O. Box 235 Buffalo, NY 14221
1	Technical Director Colt Firearms Corporation 150 Huyshore Avenue Hartford, CT 14061

No. of Copies	Organization
1	General Electric Corporation Armaments Division ATTN: Mr. R. Whyte Lakeside Avenue Burlington, VT 05401
1	Martin Marietta Aerospace ATTN: Mr. A. J. Culotta P. O. Box 5387 Orlando, FL 32805
1	Winchester-Western Division Olin Corporation New Haven, CT 06504
1	Rockwell Int'l Science Center ATTN: Dr. Norman Malmuth P. O. Box 1085 1000 Oaks, CA 91360
1	Sandia Laboratories ATTN: Aerodynamics Dept Org 5620, R. Maydew Albuquerque, NM 87115
1	S&D Dynamics Inc. ATTN: Dr. M. Soifer 755 New York Avenue Huntington, NY 11743
1	Guggenheim Aeronautical Lab California Institute of Technology ATTN: Tech Lib Pasadena, CA 91104
2	Franklin Institute ATTN: Dr. Carfagno Dr. Wachtell Race & 20th Streets Philadelphia, PA 19103

DISTRIBUTION LIST

No. of Copies	Organization
1	Director Applied Physics Laboratory The Johns Hopkins University Johns Hopkins Road Laurel, MD 20810
1	Massachusetts Institute of Technology Department of Aeronautics and Astronautics 77 Massachusetts Avenue Cambridge, MA 02139
1	Ohio State University Department of Aeronautics and Astronautical Engineering ATTN: Tech Lib Columbus, OH 43210
2	Polytechnic Institute of Brooklyn Graduate Center ATTN: Tech Lib Dr. G. Moretti Farmingdale, NY 11735
1	Director Forrestal Research Center Princeton University Princeton, NJ 08540
1	Princeton University Forrestal Campus Library P. O. Box 710 Princeton, NJ 08540
1	Southwest Research Institute ATTN: Mr. Peter S. Westine P. O. Drawer 28510 8500 Culebra Road San Antonio, TX 78228

Aberdeen Proving Ground

Marine Corps Ln Ofc
Dir, USAMSAA
Cdr, USAEA
ATTN: A. Flatau, SAREA-DE-W
Bldg. E3516