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DESIGN OF A COMPOSITE CHARGE FOR A 12.7MM SMOOTH-BORE EXPERIMEN--ETC(U)
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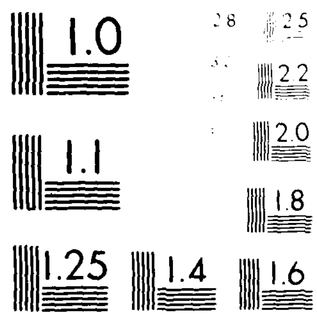
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TECHNICAL NOTE

MRL-TN-451

DESIGN OF A COMPOSITE CHARGE FOR A 12.7 MM

SMOOTH-BORE EXPERIMENTAL GUN

Michael J. Chung

Approved for Public Release

MAY, 1981

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A mathematical model describing the interior ballistics of a smooth bore experimental gun has been used to optimise the composition of a composite propellant charge for achieving muzzle velocities of 1500 m/s with projectiles of 23 g (0.051 lb). Comparison of predicted and experimental results indicate, however, that this gun is subjected to excessive leakage. If this problem can be overcome, muzzle velocities of 1900 m/s may be attained using the recommended composite charge and existing gun specification.

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16. ABSTRACT (if this is security classified, the announcement of this report will be classified):

A mathematical model describing the interior ballistics of a smooth bore experimental gun has been used to optimise the composition of a composite propellant charge for achieving muzzle velocities of 1500 m/s with projectiles of 23 g (0.051 lb). Comparison of predicted and experimental results indicate, however, that this gun is subjected to excessive leakage. If this problem can be overcome, muzzle velocities of 1900 m/s may be attained using the recommended composite charge and existing gun specification.

CONTENTS

DESIGN OF A COMPOSITE CHARGE FOR A 12.7 MM SMOTH-BORE EXPERIMENTAL GUN

1. INTRODUCTION

A smooth bore experimental gun has been constructed for the study of penetration mechanics at MRL. This device is intended to produce reliable muzzle velocities of greater than 1500 m/s. The limited volume available for the propellant and the maximum pressures that this chamber can withstand have led to an investigation of suitable propellants.

The characteristics of a propellant which achieves high muzzle velocities with low maximum pressures are those which enable maximum pressures to be reached rapidly and are maintained at a relatively high level while the projectile is in the barrel.

Maximum pressures are reached quickly by rapid burning propellants whilst persistent pressures require a more slowly burning propellant. From this simplified picture, a composite charge consisting of two or more propellants with different burning characteristics warrants theoretical and experimental investigation.

This Note develops a mathematical model for the performance of a two-propellant charge suitable for the MRL experimental gun.

2. NOTATION USED IN THE TEXT

Quantity	Units	Description
A	cm^2	Cross-sectional area of gun bore.
b	cm^3/g	Co-volume of propellant gas.
C	g	Mass of propellant charge.
$\bar{C}$	g	Mass of composite charge.
C'	g	Reduced charge mass due to leakage effects in gun.
Cap	cm^3	Chamber capacity of gun.
D	cm	Ballistic size of propellant.
$\bar{D}$	cm	Ballistic size of composite propellant.
F	MPa per gcm^{-3}	Force constant of propellant.
$\bar{F}$	MPa per gcm^{-3}	Force constant of composite propellant.
F'	MPa per gcm^{-3}	Reduced force constant of composite propellant due to leakage effects in gun.
f	-	Fraction of D remaining unburnt at a given time t.
g	m/s	Acceleration due to gravity.
k	-	Propellant mass ratio of AR5401:FNH025.
ℓ	cm	Length of air gap in chamber containing the propellant charge.
M	-	Ballistic constant.
P	MPa	Mean gas pressure behind the projectile.
Pm	MPa	Maximum gas pressure achieved.
Po	MPa	Shot start pressure.
P*	MPa	Mean gas pressure behind projectile due to incremental change in projectile mass.
R	J/mol K	Molar gas constant.

Quantity	Units	Description
S	cm^2	Leakage area around the projectile.
To	K	Flame temperature of propellant.
tr	m	Length of barrel.
V	m/s	Velocity of projectile.
V*	m/s	Velocity of projectile due to incremental changes in projectile mass.
W_E	g	Effective projectile mass.
W	g	Projectile mass at rest.
W_E^*		Effective projectile mass due to mass increment dW_E.
x	m	Projectile travel at time t.
z	-	Fraction of charge burnt.
β	$cm.s^{-1}$ per MPa	Burning rate constant of the propellant.
γ	-	Ratio of the specific heats of the propellant gas.
δ	g/cm^3	Density of the propellant.
$\bar{\delta}$	g/cm^3	Density of the composite charge.
Ψ	-	Leakage factor of the gun.
Θ	-	Form factor of the propellant.
$\bar{\Theta}$	-	Form factor of the composite charge.
Θ'	-	Form factor of the composite charge due to leakage effects in gun.

3. THE MATHEMATICAL MODEL OF A COMPOSITE CHARGE IN A SMOOTH BORE GUN

3.1 *Goldie's Method of Internal Ballistics*

Dewis [1] and Tawakely [2] have presented analytical methods which consider the burning of two propellants to describe the interior ballistics of a composite charge. Both writers assume a linear law of burning and the same rate of burning of the two propellants.

An alternative method of analysis is available whereby the composite charge is reduced to a single equivalent charge.[3] An existing computer program written at MRL and based on Goldie's method of internal ballistics [4] can then be used in examining the properties of such a composite charge. Goldie's analysis of the internal ballistics of a gun assumes:

(i) the rate of burning of the propellant is proportional to the gas pressure,

(ii) shot start pressure accounts for initial conditions such as band engraving and bore resistance, and

(iii) no energy losses occur from the propellant gas.

The equations used to describe Goldie's system are shown in Appendix I.

3.2 Reduction of a Composite Charge to a Single Effective Charge

We define [3] the parameters of the composite charge as follows, with the subscripts denoting the individual components:

Force constant $$\bar{F} = R\left[\frac{C_1 To_1 + C_2 To_2}{C_1 + C_2}\right] \qquad (1)$$

Density $$\bar{\delta} = \frac{C_1 + C_2}{\left(\dfrac{C_1}{\delta_1} + \dfrac{C_2}{\delta_2}\right)} \qquad (2)$$

Mass $$\bar{C} = C_1 + C_2 \qquad (3)$$

Form Factor $$\bar{\Theta} = \frac{3C_1 \cdot (D_2 - D_1)}{D_2 \cdot (C_1 + C_2)} \quad \text{where } D_2 > D_1 \qquad (4)$$

Web size $$\bar{D} = D' \text{ where } D' \text{ is the greater of } D_1 \text{ \& } D_2 \qquad (5)$$

These equations reduce a composite charge to a single equivalent charge by initially obtaining a composite charge of the same size and shape as the original components but of single composition and then reducing this composite charge to one of a single web size. This ensures that the gas is evolved at the same rate by both charges and that the equivalent charge burns for the same time as the composite charge.

If $\bar{\Theta} < 1$, these equations can be used in a normal ballistic method.

3.3 *Smooth Bore Gun*

The ballistics of a smooth bore barrel differ from a rifled barrel in that propellant gases may leak past the projectile if the obturating device on the projectile does not provide a satisfactory seal. The degree of leakage is described by a factor [3] Ψ, where

$$\Psi = \frac{\omega S D}{\beta C F^{1/2}} \tag{6}$$

Here, ω is a numerical factor which equals 0.66 for no energy loss in a nozzle.

Values of Ψ lie between 0.1 and 0.4 for smooth bore guns and 0.4 to 0.6 for recoiless guns. [3] The factor Ψ enables the ballistics of a smooth bore gun to be studied by means of an 'effective charge' which is defined by the equations: [3]

$$C' = \bar{C}(1 - \Psi) \tag{7}$$

$$F' = \bar{F}(1 - \Psi) \tag{8}$$

and

$$\Theta' = \frac{\bar{\Theta}}{1-\Psi} \tag{9}$$

Ψ

for $\bar{\Theta} < 1$ and for fast burning propellants.

3.4 *Pressure and Velocity Increment Factors*

In the current study, a variation in the mass of the projectile is considered. A change in the projectile mass alters peak chamber pressure and the muzzle velocity. An effective projectile mass W_E, which may be considered as the moving mass in the barrel, is defined [4] by

$$W_E = W\left[1 + \frac{C'}{3W}\right] \tag{10}$$

It can be shown that a change in pressure dP, due to a change in projectile mass, dW_E, may be expressed [5] by

$$\frac{dP}{P} = \frac{K_1 dW_E}{W_E} \tag{11}$$

OR

$$\frac{P^* - P}{P} = K_1 \frac{(W_E^* - W_E)}{W_E}$$

where $$K_1 = \frac{3MW_E}{(M+1.24\theta')(3W_E + C')} - \frac{C'W_E}{(2W_E + C')(3W_E + C')}$$

and $$M = \frac{6006.56 . A^2 D^2}{F'\beta^2 C' W_E}$$

Similarly the muzzle velocity [3] can be written as

$$V^* = V \left[\frac{W_E + \frac{C'}{3}}{W^*_E + \frac{C'}{3}} \right]^{1/2} \tag{12}$$

4. RESULTS AND DISCUSSION

Three Australian-produced propellants were chosen for examination to obtain a suitable composite charge. The propellants were FNH016, FNH025 and AR5401. The composite charges produced from these propellants were a mixture of FNH016/FNH025 and AR5401/FNH025. The physical and thermodynamic constants of these propellants, gun and projectile are shown in Appendix II. [6]

Experimental results for the maximum chamber pressure and muzzle velocity from these formulations are listed in Table 1. These values can now assist in the study of the internal ballistics of the experimental gun since closed-vessel data are unavailable. Predictions of muzzle velocities were made assuming typical leakage factors of 0.1, 0.2 and 0.3 and are shown in Figure 1; the measured muzzle velocities are also indicated for comparison.

These results indicate that the composite charge AR5401/FNH025 achieves higher muzzle velocities for a particular loading density and projectile mass than the composite charge FNH016/FNH025. They also show that this particular composite charge has the potential to achieve muzzle velocities of up to 1900 m/s for leakage factors of $\Psi = 0.1$. This may be considered a low leakage factor which a typical smooth-bore gun may attain. For this reason the composite charge AR5401/FNH025 was chosen for further study.

Initial comparison between experimental and predicted muzzle velocities indicates that reasonable agreement occurs if leakage factors of the order of

0.3 are assumed. For a leakage factor of $\Psi = 0.28$, muzzle velocities of 1467 m/s can be calculated which compare favourably with experimental results. As leakage factors of 0.3 are considered excessive, several obturators for the sabot were examined in an effort to reduce leakage effects in the gun.

Experimental firings were carried out using two sets of similar charges of AR5401/FNH025. These results are shown in Table 2. Predictions of muzzle velocities using these composite charges for copper obturators are recorded in Figure 2. The experimental results in Table 2 indicate that, for similar composite charges, copper obturators yield higher muzzle velocities with small increases in maximum chamber pressures. Plotting the experimental results from Table 2 on the predicted curves in Figure 2 show that the copper obturator has reduced the leakage factor to about 0.25.

To ensure the mathematical model more accurately described the burning process of the propellant within the cartridge and to enable more readily reproducible muzzle velocities to be achieved, a redesigned cartridge was recommended. The initial propellant cartridge consisted of a cylindrical container, with excess propellant grains loosely packed into the conical section between the sabot and cartridge case. The redesigned cartridge included a conical section matching the volume between the projectile's sabot and the cylindrical chamber. This cartridge enabled more propellant at a uniform packing density to be obtained.

A series of firings was conducted for k values of 0.6, 0.7, 0.8 and 0.9 to examine the relationship between Pm and k and also muzzle velocity and k. Results, shown in Table 3 and plotted in Figure 3, indicate that high muzzle velocities (1500 m/s) may be achieved at relatively low pressures (of about 400 MPa) by using a composite charge whose mass ratio is 0.6. The muzzle velocities measured using the recommended composite charges, copper obturator and redesigned propellant cartridge in general lie between 1500 and 1550 m/s. These results also indicate that maximum pressures obtained by this particular type of composite charge are reasonably estimated by the empirical relationship

$$(Pm-415) = 176(k-0.75)$$

OR

$$Pm = 176k + 283 \quad \text{where Pm is in MPa}$$

whose correlation coefficient is 0.995.

Muzzle velocities were calculated for these composite charges and plotted in Figure 4. These results indicate that the leakage factor is again of the order of 0.25. Results from Figures 2 and 4 show that the mathematical model describes the action of the gun if a leakage factor of 0.25 is assumed.

Figure 5 shows pressure/distance along the barrel profiles for a typical alue of $\Psi = 0.2$ and charge mass ratios of 0.6, 0.7, 0.8 and 0.9. These profiles indicate a flattening of the pressure/distance profile for a reduction in values of the charge mass ratios. This reduction in k effectively reduces the burning rate of the composition because it introduces a greater proportion of FNH025 into the composite charge. This propellant is the slower burning of the two and, as pressures are related to burning rates, reduced pressures would be expected for a given mass of propellant. This is also shown by pressure results in Figure 3.

Assuming the leakage factor of the gun is 0.25 and selecting charge mass ratios of 0.75 and 0.85, the expected peak pressures for these particular composite charges can be calculated as 415 and 433 MPa. Using these pressures, muzzle velocities were calculated and the results shown in Table 4 and plotted in Figure 6. Experimental firings of three charge mass ratios of 0.75 and one of 0.85 were made and the measured pressures and muzzle velocities tabulated in Table 5. The predicted and measured values agree very well for the composite charge of mass ratio 0.75. Similar results were not obtain for the mass ratio of 0.85. As only one firing was carried out with this particular ratio, this result is considered inconclusive in view of the results obtained for the charge ratio 0.75. The high pressure and low muzzle velocity obtained from the mass ratio of 0.85 may be due to variation in propellant loading density causing burning with peak pressure occurring for a short duration with a resulting loss in muzzle velocity.

The ballistic constant M is a function of β and F'. β would be expected to vary with k and Ψ varies with F'. Profiles of M vs k and M vs Ψ for the projectile of mass 23 g are shown in Figures 7 and 8 respectively. For a given charge mass ratio, known increments in projectile mass and the profiles from Figures 7 and 8, maximum pressures and muzzle velocities may be predicted from equations 11 and 12 respectively. Using the experimental pressure results from Figure 3 and the predicted results from Figure 4, pressures and muzzle velocities were calculated for a projectile mass of 70 g and shown in Figures 9 and 10 respectively.

For the particular case of a projectile mass of 70 g and a composite charge of AR5401/FNH025 whose mass ratio is 0.75, predicted muzzle velocities and maximum pressures were found to be 1203 m/s and 636 MPa respectively. An experimental firing of a 70 g projectile with this composite charge produced muzzle velocities and maximum pressures of 1211 m/s and 599 MPa. The accuracy of this method of prediction is uncertain because only one experimental result was available to compare the two results. The incremental pressure equation was derived for incremental changes in projectile mass and the example illustrated uses a mass of 70 g which is significantly greater than the projectile mass (23 g) used in the earlier work.

5. CONCLUSION

A composite charge consisting of AR5401/FNH025 is considered suitable to achieve muzzle velocities of 1500 m/s for a projectile mass of 23 g (0.051 lb). The optimum charge is one whose charge ratio k equals 0.8. This particular charge ratio enables high muzzle velocities to be attained with low peak pressures.

Predicted and experimental values of muzzle velocities indicate that the experimental gun experiences leakage greater than may be expected from a smooth bore gun. The predicted results cannot determine the cause of the propellant gas leakage as the leakage factor has been derived to allow for leakage around the projectile alone. In this case, the high leakage factor may be due to a combination of leakage around the projectile and also in the breech of the gun.

The interior ballistics of the smooth bore experimental gun using a composite charge can be modelled satisfactorily in conjunction with experimental results. The experimental results are necessary because the burning rate of the composite charge, under pressures of 494 MPa (32 ton/in^2) experienced in the gun, cannot be satisfactorily calculated from propellant proof data. Closed vessel work is limited to 278 MPa (18 ton/in^2) and documented propellant data provides for a linear extrapolation to gun pressures of 371 MPa (24 ton/in^2).

6. ACKNOWLEDGEMENT

The experimental results listed in this note were obtained by Mr. B.J. Baxter of the Metallurgical Mechanics Group, Metallurgy Division, Materials Research Laboratories.

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    Part 2. Numerical Solution of equations.

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APPENDIX I

GOLDIE'S SYSTEM OF INTERNAL BALLISTICS

The equations used to describe Goldie's system [4] are:

1. The energy equation

$$AP(x + \ell) - 27.68PC\left(b - \frac{1}{\delta}\right)z + (\gamma - 1)\int_{0}^{x} AP\,dx = FCz \qquad (1)$$

2. The rate of burning of the propellant

$$-10^3 D \frac{df}{dt} = \beta P^{\alpha} \qquad \text{where } \alpha = 1 \qquad (2)$$

3. The form functions of the propellant

$$z = (1 - f)(1 + \Theta f) \qquad (3)$$

4. The motion of projectile

$$10^6.V \frac{dV}{dx} = \frac{2240\ APg}{12W_E} \qquad (4)$$

The equations used to describe the pressure, shot travel and velocity after the propellant charge is all burnt are:

$$P = \frac{FC - \tfrac{1}{2}(\gamma - 1)W_E V^2}{A(x + \ell) - C\left(b - \frac{1}{\delta}\right)} \qquad (5)$$

$$\frac{dV}{dx} = \frac{2240.APg}{12\times10^6 W_E V} \qquad (6)$$

and $\frac{dt}{dx} = \frac{1}{V}$ respectively (7)

APPENDIX II

THERMOCHEMICAL AND PHYSICAL CONSTANTS OF AR5401, FNH025 AND THE SMOOTH BORE GUN

Propellant Constants

Quantity	Practical Unit	AR5401	FNH025
b	cm^3/g	0.941	1.0
D	in	0.019	0.025
F	ton in^{-2} per lb cm^{-3}	1700.0	1680.0
To	K	2678.0	2511.0
γ	-	1.241	1.276
δ	g/cm^3	1.623	1.57
Θ	-	0	0

Gun Constants

Quantity	Practical Unit	Value
A	in^2	2.36
C	lb	0.135
Cap	in^3	4.32
Po	ton in^{-2}	1.62
tr	ft	8.5
W	lb	0.051

These constants are expressed in units which are convenient for ballistic calculations.

TABLE 1

MUZZLE VELOCITIES & MAXIMUM PRESSURES OBTAINED FROM EXPERIMENTAL COMPOSITE CHARGES

Propellant	Mass g	Pressure MPa	Muzzle Velocity m/s
FNH016 FNH025	32.5 15.0	331 (21.4 ton/in^2)	1380
FNH016 FNH025	31.5 11.0	303 (19.6 ton/in^2)	1337
AR5401 FNH025	30.0 32.4	524 (33.9 ton/in^2)	1474

TABLE 2

MUZZLE VELOCITIES & MAXIMUM PRESSURES OBTAINED FROM AR5401/FNH025 CHARGES USING CORK & COPPER OBTURATORS

Propellant	Mass g	Mass Ratio k	Pressure MPa	Muzzle Velocity m/s	Obturator
AR5401 FNH025	31.7 32.0	0.991	483 (31.3 ton/in^2)	1519	Copper
AR5401 FNH025	26.5 35.0	0.757	428 (27.7 ton/in^2)	1591	Copper
AR5401 FNH025	23.7 37.0	0.651	380 (24.6 ton/in^2)	1505	Copper
AR5401 FNH025	30.6 32.0	0.956	462 (29.9 ton/in^2)	1430	Cork
AR5401 FNH025	26.8 35.0	0.767	414 (26.8 ton/in^2)	1550	Cork
AR5401 FNH025	24.0 37.0	0.650	380 (24.6 ton/in^2)	1159	Cork

TABLE 3

MUZZLE VELOCITIES & MAXIMUM PRESSURES OBTAINED FROM AR5401/FNH025 USING COPPER OBTURATOR

Propellant	Mass g	Mass Ratio k	Pressure MPa	Muzzle Velocity m/s
AR5401 FNH025	29.13 32.37	0.90	448 (29 ton/in^2)	1530
AR5401 FNH025	27.33 34.17	0.80	414 (26.8 ton/in^2)	1499
AR5401 FNH025	25.3 36.0	0.70	406 (26.3 ton/in^2)	1440
AR5401 FNH025	23.06 38.40	0.60	392 (25.4 ton/in^2)	1500

TABLE 4

PREDICTED MUZZLE VELOCITIES AND MAXIMUM PRESSURES FOR CHARGE WEIGHT RATIOS 0.75 AND 0.85

Propellant	Mass g	Mass Ratio k	Predicted Pressure MPa	Predicted Muzzle Velocity m/s	
				Ψ = 0.25	Ψ = 0.3
AR5401 FNH025	26.5 35.3	0.75	415 (26.9 ton/in^2)	1555	1390
AR5401 FNH025	28.6 33.6	0.85	433 (28.0 ton/in^2)	1588	1408

TABLE 5

MUZZLE VELOCITIES & MAXIMUM PRESSURES FOR COMPOSITE CHARGE RATIO 0.75 AND 0.85

Propellant	Mass g	Weight Ratio k	Measured Pressure MPa	Measured Muzzle Velocity m/s
AR5401 FNH025	26.5 35.3	0.75	406 (26.3 ton/in^2)	1478
AR5401 FNH025	26.5 35.3	0.75	434 (28.1 ton/in^2)	1576
AR5401 FNH025	26.5 35.3	0.75	434 (28.1 ton/in^2)	1545
AR5401 FNH025	28.6 33.6	0.85	483 (31.3 ton/in^2)	1475

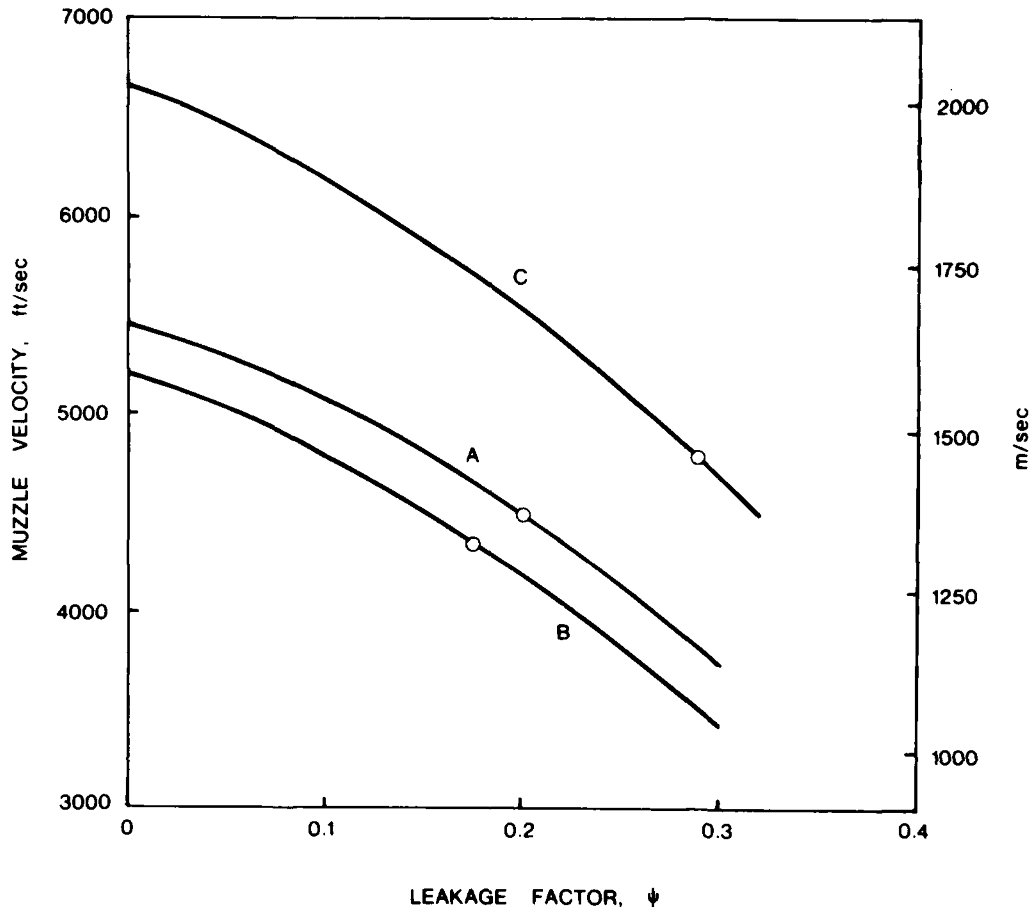

FIG. 1 Predicted Muzzle Velocity vs Leakage Factor for Projectile Mass 23 g

0 Experimental Results

Curve A	FNH016	32.5 g
	FNH025	15.0 g
Curve B	FNH016	31.2 g
	FNH025	11.0 g
Curve C	AR5401	30.0 g
	FNH025	32.4 g

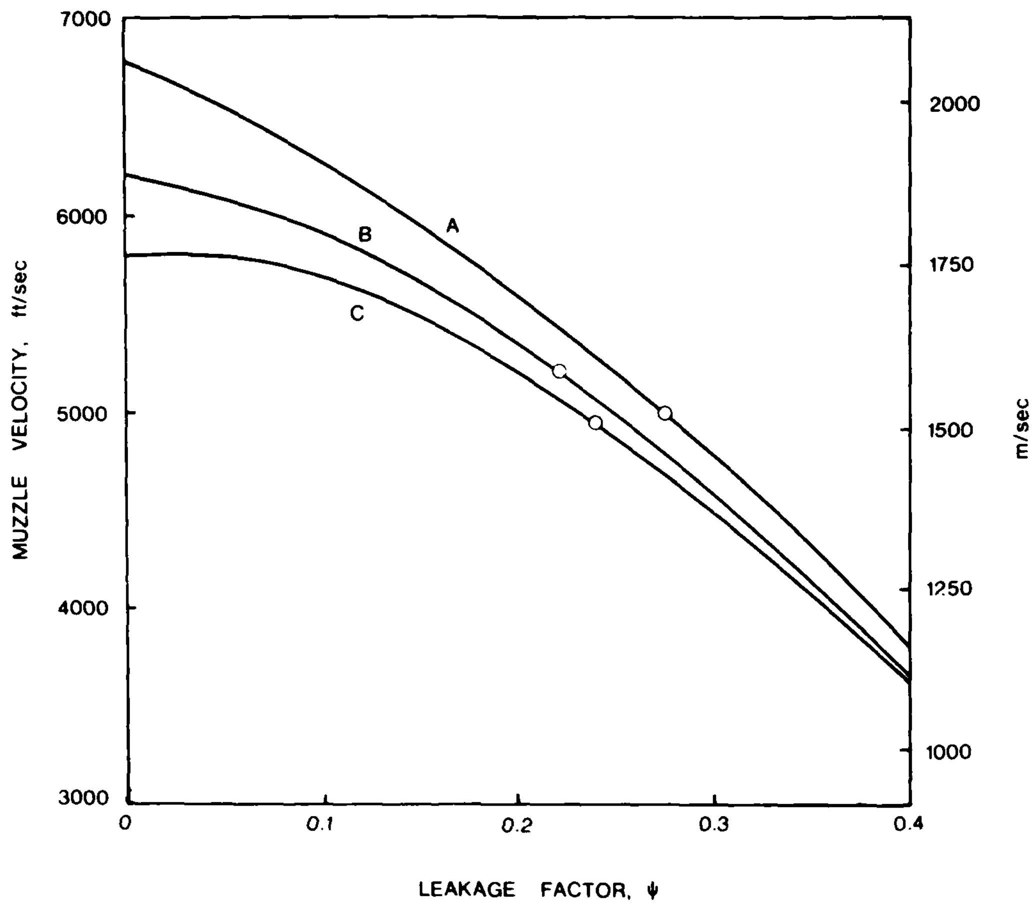

FIG. 2 Predicted Muzzle Velocity vs Leakage Factor for Projectile Mass 23 g

O Experimental Results

Curve A	AR5401	31.7 g
	FNH025	32.0 g
	K =	0.99
Curve B	AR5401	26.5 g
	FNH025	35.0 g
	K =	0.75
Curve C	AR5401	23.7 g
	FNH025	37.0 g
	K =	0.65

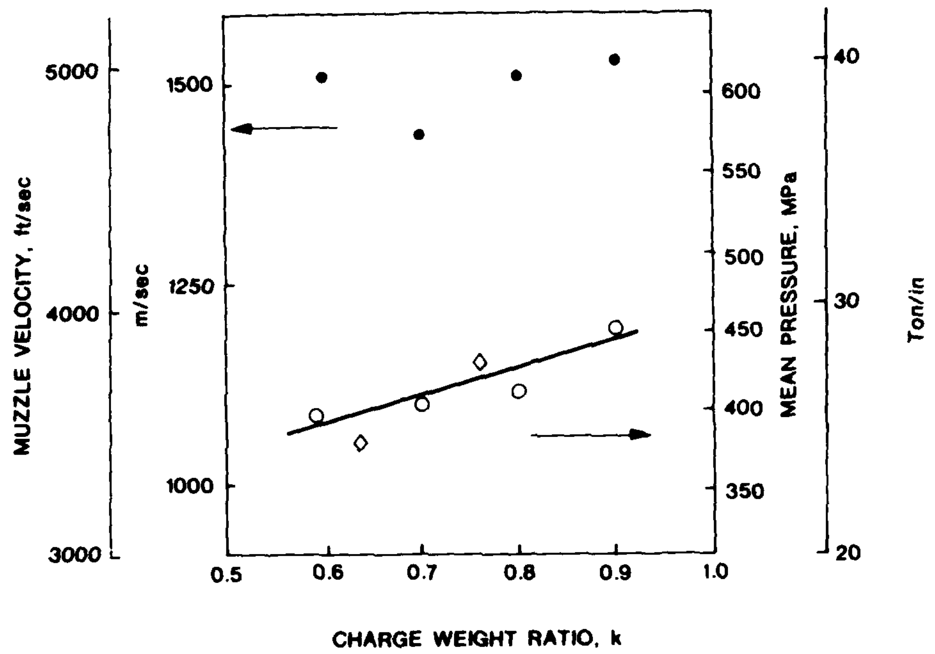

FIG. 3 Variation of Muzzle Velocity and Mean Pressure with Charge Weight Ratio

◆ Experimental values of mean pressure from Table 2

O Experimental mean pressures from Table 3

● Experimental muzzle velocities from Table 3

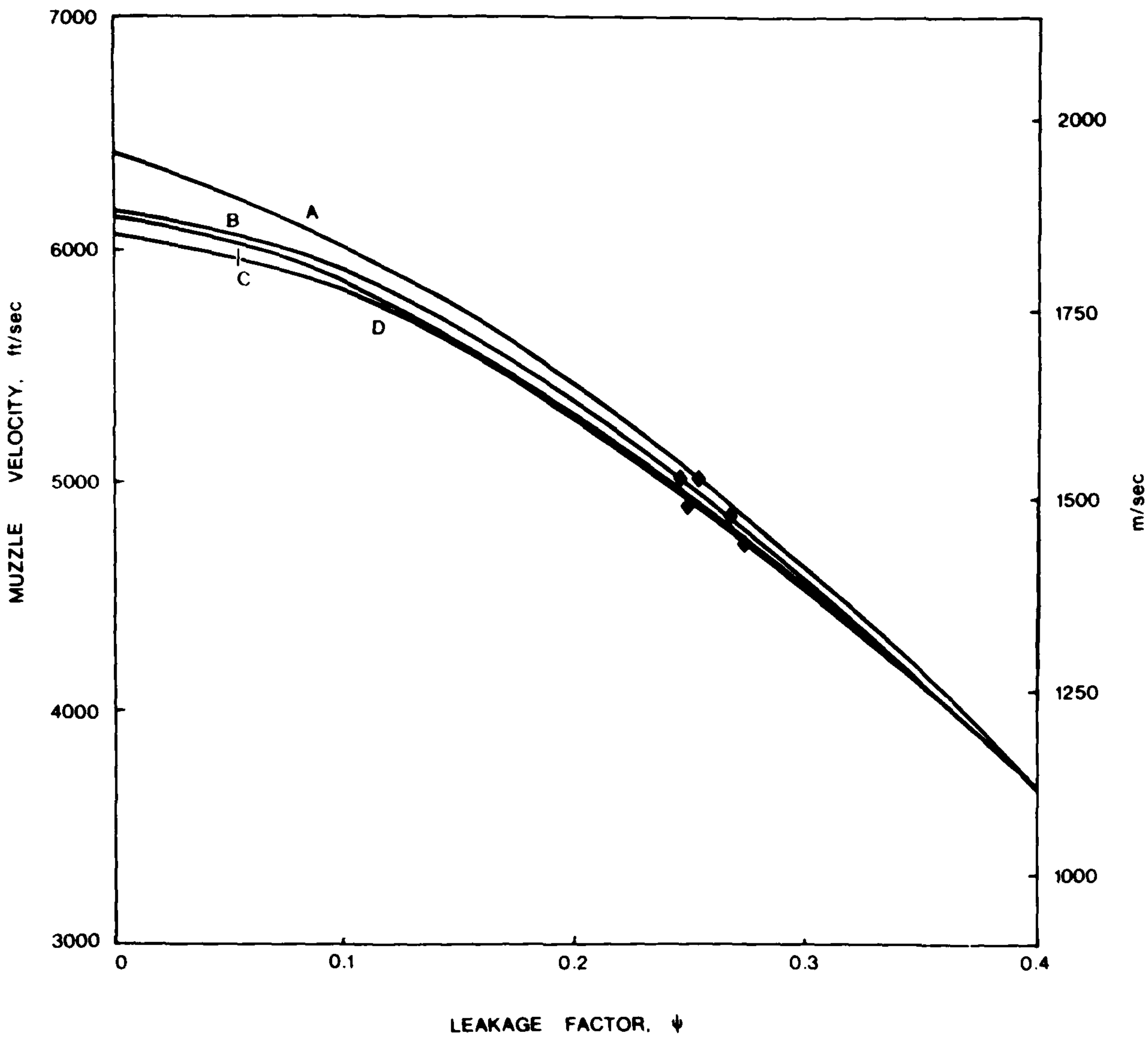

FIG. 4 Predicted Muzzle Velocities vs Leakage Factor for Projectile Mass 23 g

◆ Experimental Results

Curve A	AR5401	29.1 g
	FNH025	32.3 g
	K =	0.9
Curve B	AR5401	27.3 g
	FNH025	34.2 g
	K =	0.8
Curve C	AR5401	25.3 g
	FNH025	36.0 g
	K =	0.7
Curve D	AR5401	23.1 g
	FNH025	38.4 g
	K =	0.6

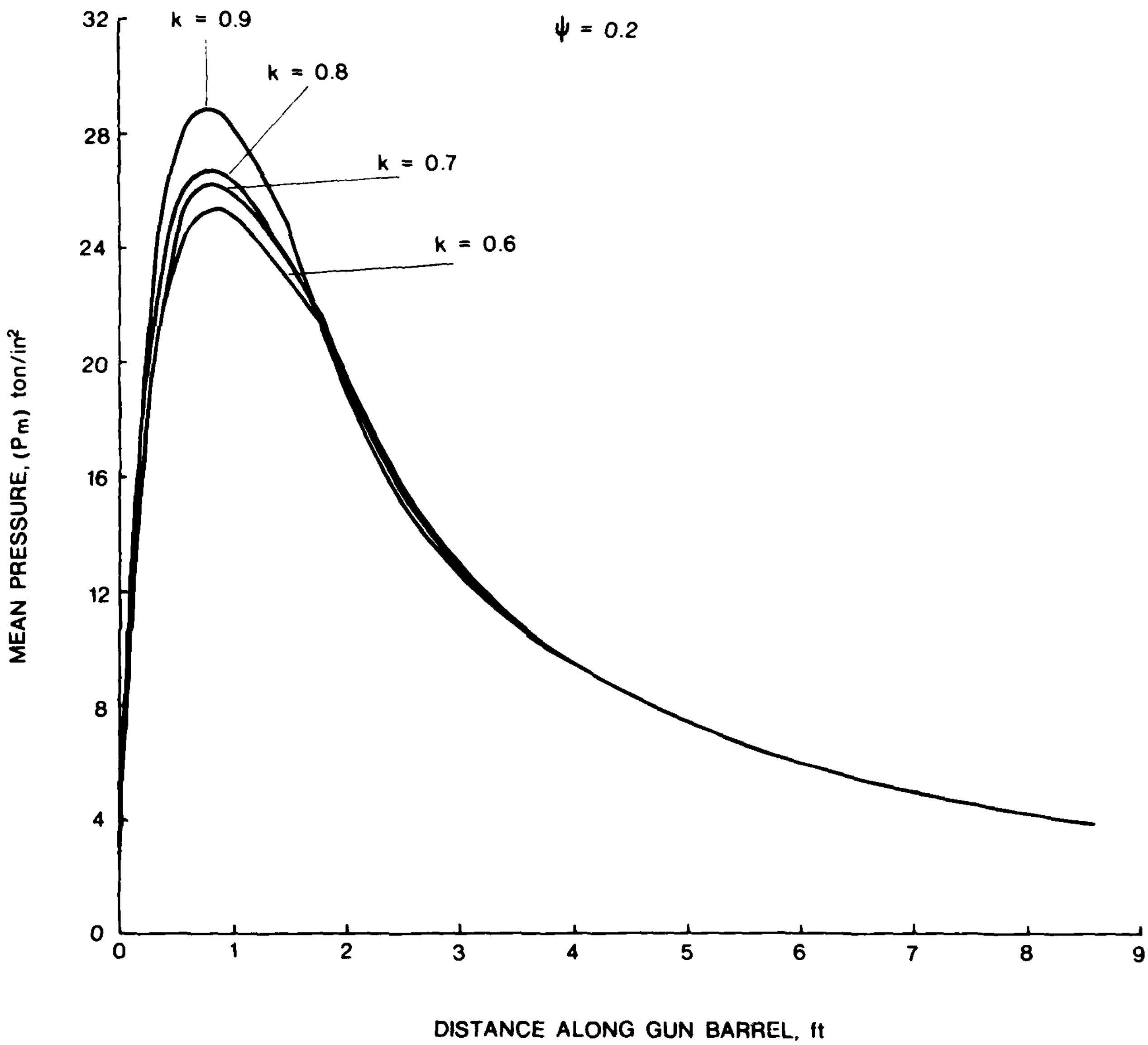

FIG. 5 Mean Pressure Behind Projectile vs Distance along Gun Barrel

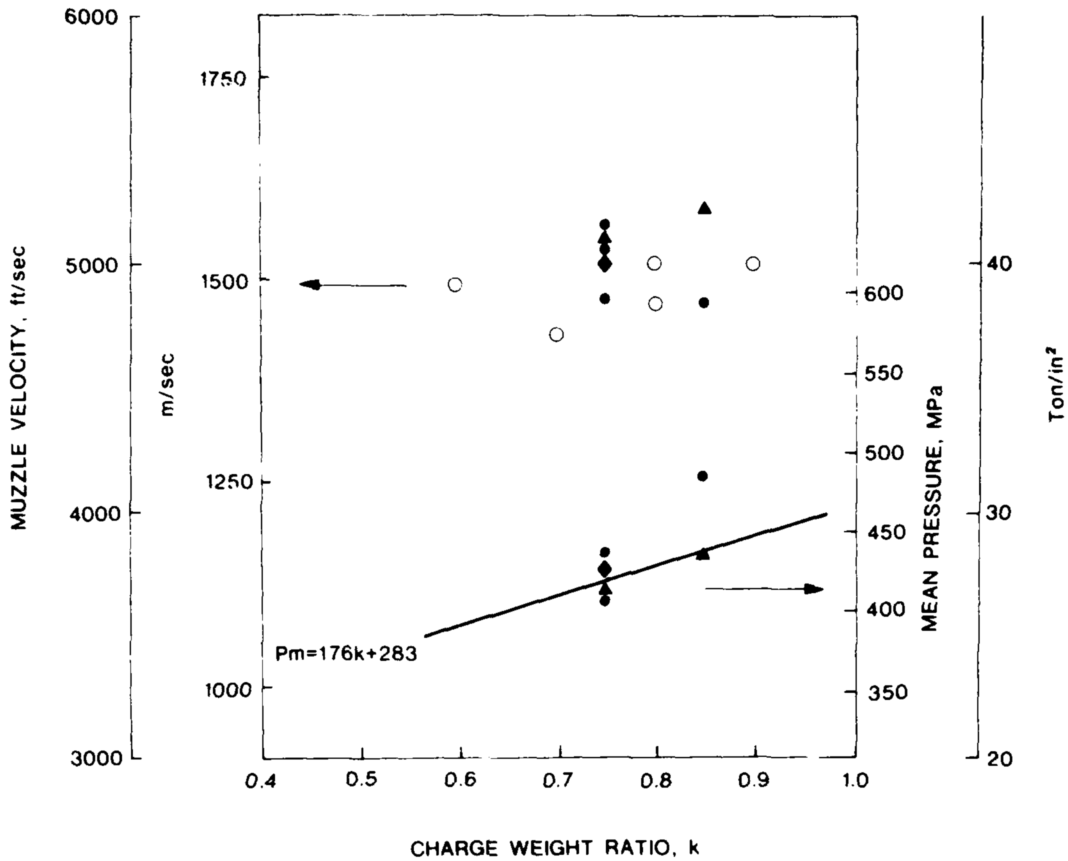

FIG. 6 Variation of Muzzle Velocity and Mean Pressure with Charge Weight Ratio
Shot weight = 23 g

● Experimental values from Table 5

◆ Average of three values from Table 5

▲ Predicted values of mean pressure and muzzle velocities assuming $\psi = 0.25$

O Experimental results from Table 3

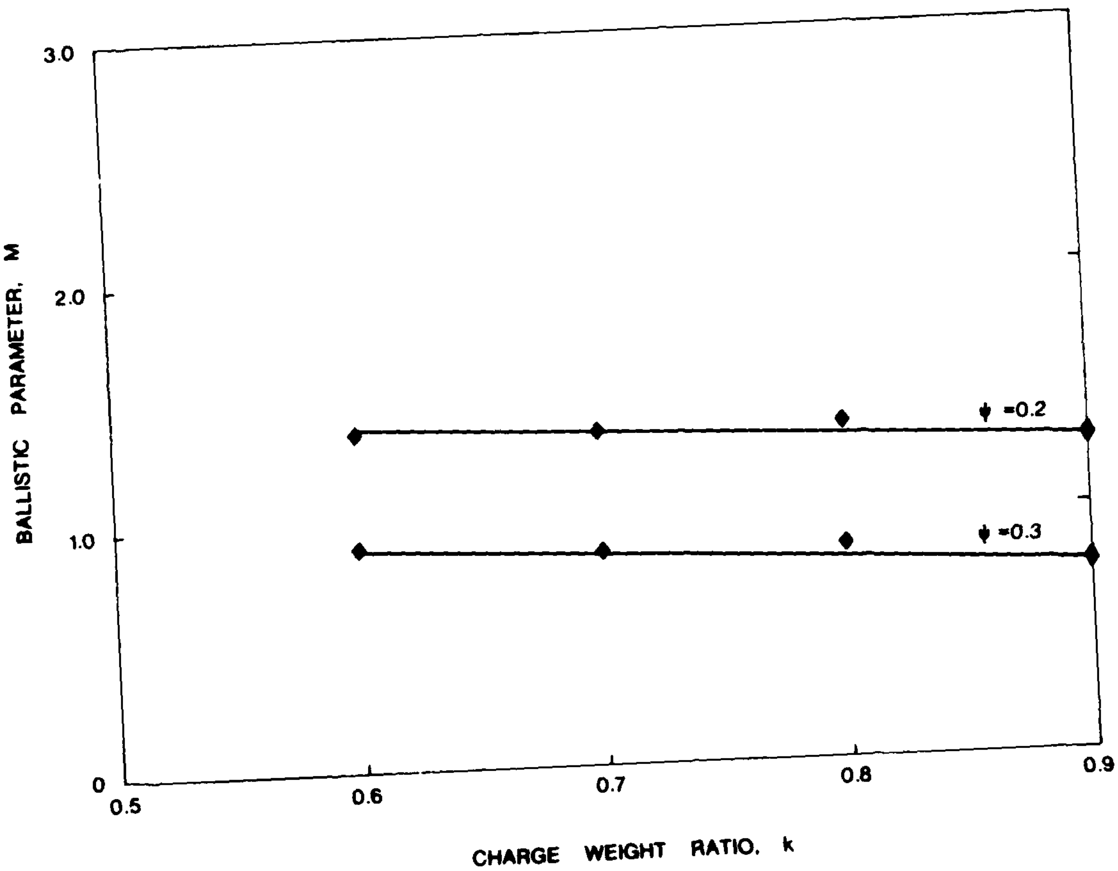

FIG. 7 Central Ballistic Parameter vs Charge Weight Ratio for Projectile mass 23 g

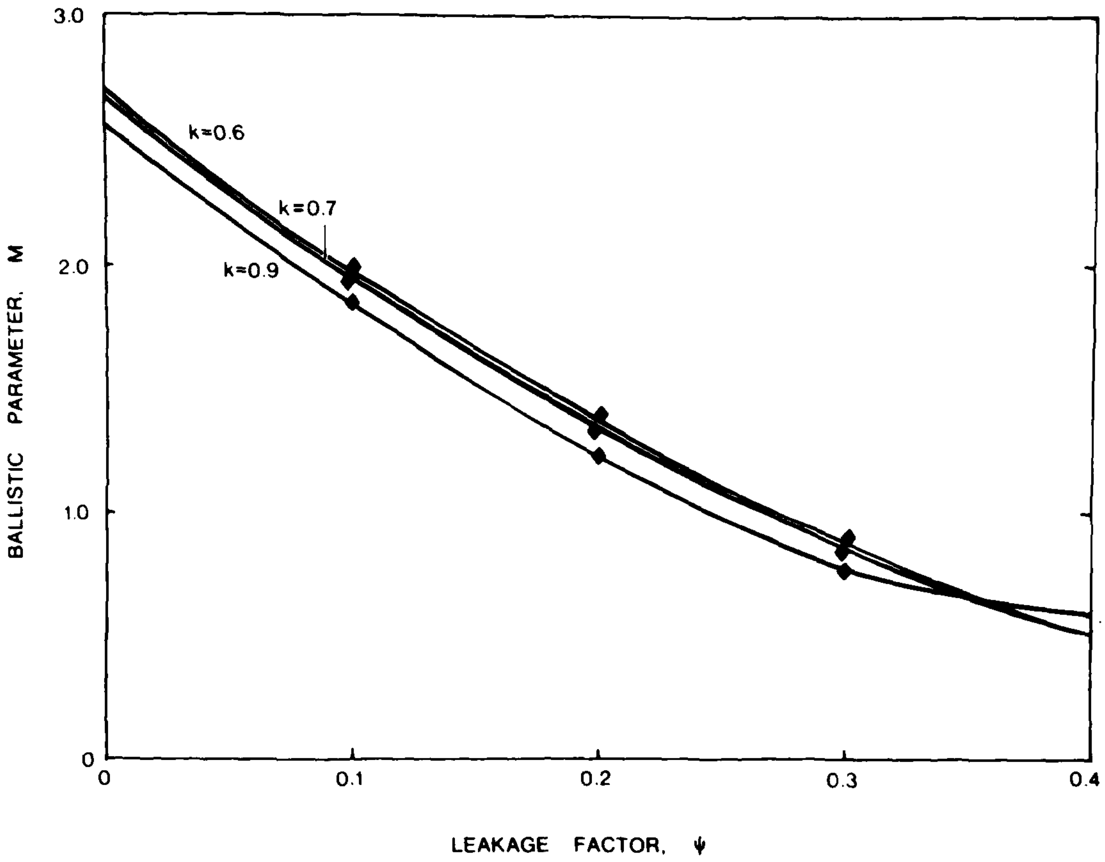

FIG. 8 Central Ballistic Parameter vs Leakage Factor ψ for Projectile Mass 23 g

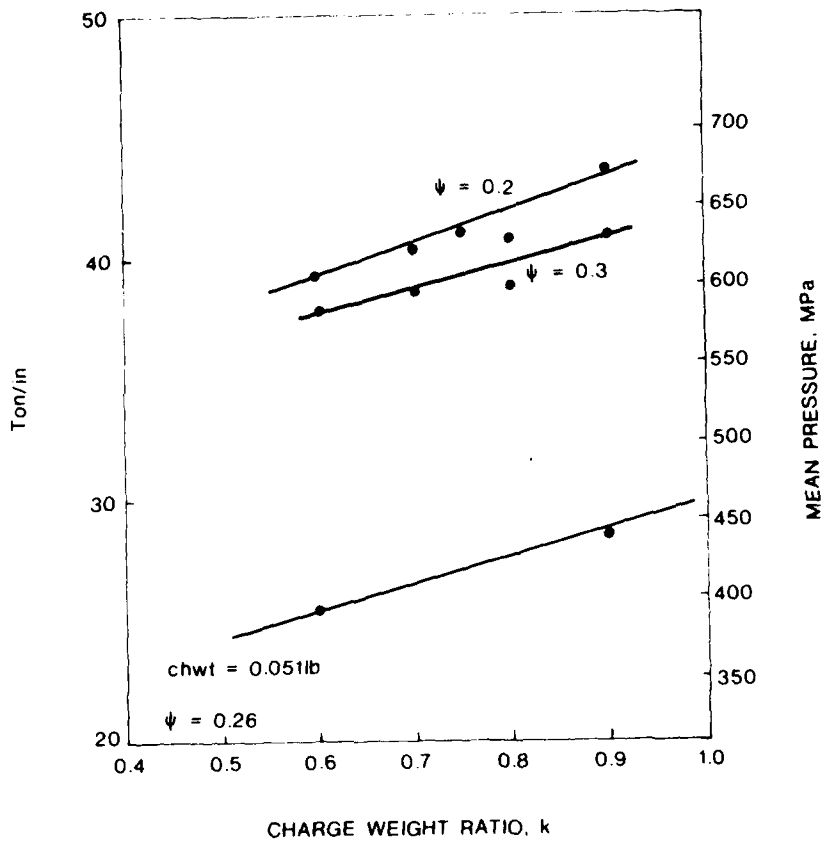

FIG. 9 Predicted Maximum Pressure vs Charge Weight Ratio for Projectile Mass 70 g

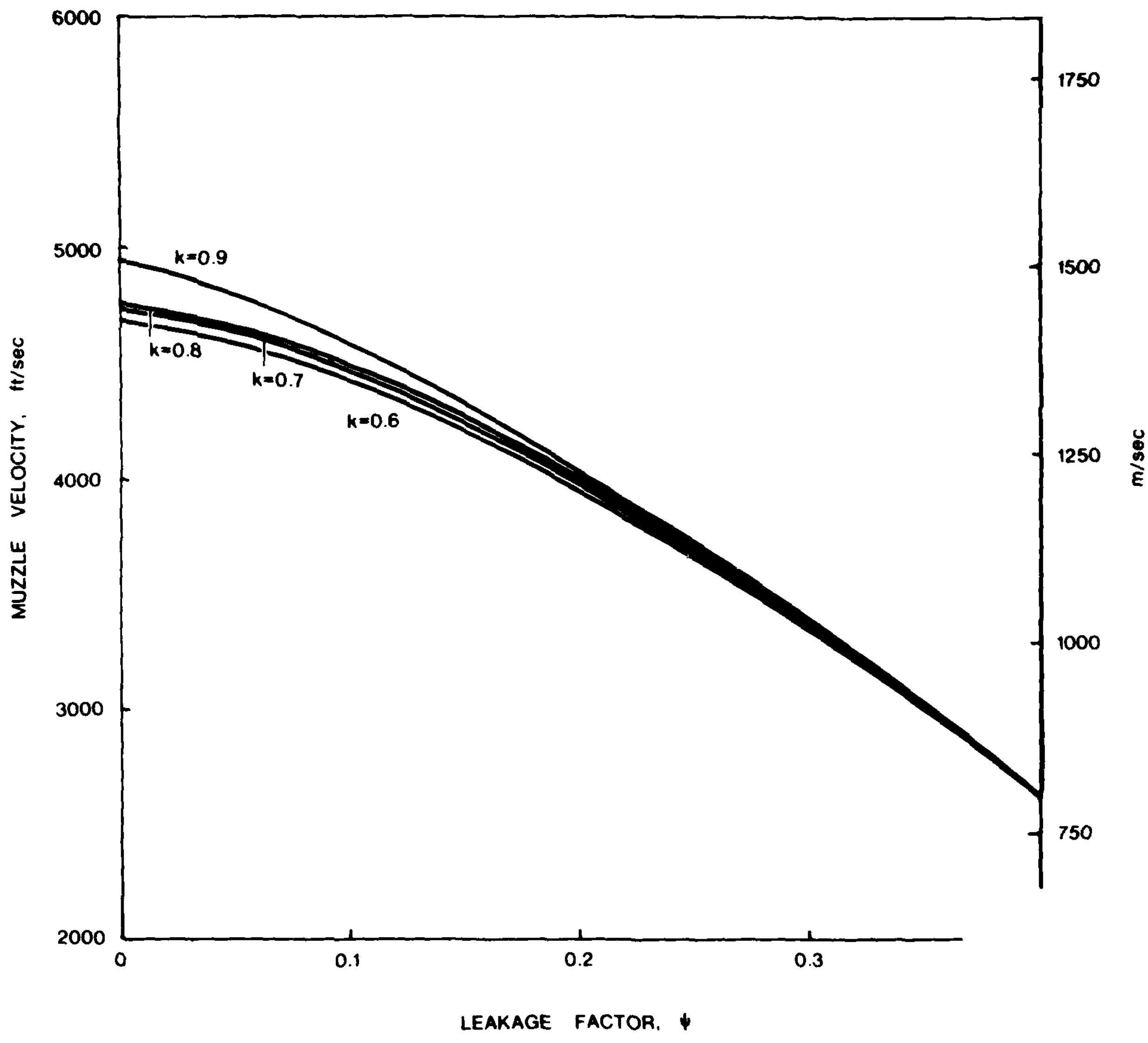

FIG. 10 Predicted Muzzle Velocity vs Leakage Factor ψ for Projectile Mass 70 g

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