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RESULTS OF CHAMBRAGE EXPERIMENTS ON GUNS WITH
EFFECTIVELY INFINITE LENGTH CHAMBERS

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RESULTS OF CHAMBRAGE EXPERIMENTS ON GUNS
WITH EFFECTIVELY INFINITE LENGTH CHAMBERS

Prepared by:

A. E. Seigel and V. C. D. Dawson

ABSTRACT: In previous work the effect of chambrage, the ratio of the diameter of the propellant chamber to the barrel bore of a gun, has been analyzed theoretically. This analysis has been applied to a gun of effectively infinite chamber length and of varying chamber diameters in which the propellant is all burned before the projectile begins to move. The present paper describes experiments performed to check the theoretical results. These were conducted with two different length 0.50 caliber gun barrels and with chambers of various diameters up to 2.44 inches. Air was compressed in the chamber behind light plastic projectiles, which were released at the proper pressures. The projectiles broke timing wires outside of the gun barrel, yielding projectile velocities. The experimental and theoretical results are in very good agreement.

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This report presents the results of an experimental study of gun chambrage (the ratio of the propellant chamber diameter to barrel bore) on the muzzle velocity of guns. The experiments were performed on a simplified gun system to which the theoretical results described in NAVORD Reports 2691 and 3635 were applicable. The ultimate aim of this study is to obtain high gun velocities from an increase in our knowledge of interior ballistics. The work was carried out under project No. FR-33-(54). The authors are indebted to Dr. Z. I. Slawsky for his aid in designing these experiments and also wish to express their thanks to Mr. C. Crist and Mr. J. Fitzpatrick for their help in performing the experiments.

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By direction

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RESULTS OF CHAMBRAGE EXPERIMENTS ON GUNS
WITH EFFECTIVELY INFINITE LENGTH CHAMBERS

INTRODUCTION

1. In ballistic calculations the effect of chambrage, the ratio of the diameter of the propellant chamber to the barrel bore, on the muzzle velocity of guns is usually taken into account by assuming that the actual chamber can be replaced by an equal-volume, imagined chamber of cross-sectional area equal to the bore cross-sectional area. Experimental results of gun firings are inconclusive as to the validity of this assumption.
2. In an effort to understand the geometric effect of chambrage in guns, theoretical work was done on a simplified gun system with well-determined initial conditions. The results of the theoretical work are reported in references (a) and (b), where a qualitative picture of the effect of chambrage in guns, as well as quantitative results applicable to the simplified gun system, are presented. In order to check the theoretical results, chambrage experiments were performed at the Naval Ordnance Laboratory. This paper presents the results of these experiments.

PREVIOUS THEORETICAL WORK

3. In references (a) and (b) it is shown that the junction between unequal cross-sectional areas of the chambered gun gives rise to compression impulses which increase the projectile velocity. This increase in projectile velocity is greater for the cases of large chambrage and vanishes for the constant-cross-sectional-area gun.
4. The quantitative analysis of chambrage was performed for the following conditions:
 - a. The chamber and the bore are cylindrical.
 - b. The propellant gas is all burned and at rest at known pressure and temperature before the projectile begins to move.
 - c. The propellant gas is an ideal gas, and each part expands isentropically.
 - d. The chamber is of sufficient length so that the breech has no effect on the projectile motion.

Thus, by (b) and (d) above the effects of the propellant burning during firing and of the breech are not present (but the influence of chambrage

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is). The change of state of the propellant gas in passing through the transition section between the chamber and barrel bore was obtained by applying the steady state equations of continuity and energy. One-dimensional unsteady flow was assumed in all other parts of the gun.

5. With the above assumptions, the influence of chambrage is calculated in references (a) and (b). The term "optimum chambrage" designates an infinite ratio of chamber diameter to barrel bore. It is shown that this most favorable condition of chambrage yields a maximum possible projectile velocity for given values of projectile mass, projectile travel, bore cross-sectional area, propellant gas sound velocity, and peak gas pressure. Curves of the dimensionless projectile velocity versus dimensionless travel for the optimum-chambrage gun and for the constant-diameter gun (i.e., with chambrage equal to one) are shown in Figure 1 (taken from reference (a)). The propellant gas was assumed to have a specific heat ratio $\gamma = 1.4$.

6. The optimum-chambrage gun gives velocities which can be as much as 28 percent higher than those given by the constant-diameter gun for a $\gamma = 1.4$ gas. Reference (b) demonstrates that the velocity increase, expressed as a percentage of the maximum possible velocity increase above that for no chambrage, is a function of the chamber-to-bore diameter ratio, D_1/D_2 . This relation is shown in Figure 2 as the solid line. For example, it is seen from this figure that for a gun with D_1/D_2 equal to 1.5, 50 percent of the possible chambrage increase is achieved.

DESIGN OF THE EXPERIMENT

7. From the theoretical analysis it is evident that the muzzle velocity is a function of chambrage and the gun system parameter, $p_0 A_x / M_0^2$, only. This makes it possible to simulate 60,000 psi propellant behavior by performing experiments with low-pressure air. Further, low-pressure air is approximately an ideal gas; and the theoretical analysis assumes a propellant gas which is ideal.

8. Laboratory guns with various degrees of chambrage were constructed. To insure effectively equilibrium conditions, the low-pressure air at room temperature is bled very slowly into the chamber. The projectile is released at the desired pressure by the rupture of a shear disc made integral with it. Muzzle velocities are obtained by the breaking of timing screens outside of the gun by the projectile.

9. Since the theory predicts that the effect of chambrage is relatively large only for muzzle velocities more than about 1.5 times the sound speed in the undisturbed propellant gas, a barrel length and projectile mass were chosen to give muzzle velocities about two times this sound speed (see Figures 1 and 2). After the barrel length was known, the chamber length was chosen as follows: Picturing the gas expansion as a

transient traveling wave phenomenon, one sees that the maximum useful chamber length is that which just permits the rarefaction front generated at the beginning of projectile motion to overtake the projectile at the muzzle after having been reflected at the breech. This length was obtained from reference (b) (where it was designated as the effectively infinite length), and the chambers were made considerably longer.

DESCRIPTION OF EXPERIMENTAL APPARATUS

10. The test scheme was to use the shear-type projectile mentioned above, which ruptured at approximately 3,000 psi of air at room temperature. Supersonic velocities (referred to the sound speed in the undisturbed propellant gas) were obtained by limiting the projectile weight to approximately 1 gram. Five chambers of different diameter were used in the tests in conjunction with two barrels having different lengths of travel. It was thus possible to have ten different firing conditions. Approximately ten rounds were fired with each combination. Muzzle velocity was determined by a chronograph system consisting of three screens, which operated two electronic counters. The projectile was caught in a butt from which it was recovered and weighed.

11. Figures 3 - 6 are pictures of the experimental apparatus. Chamber diameters of 0.520", 0.575", 0.75", 1.125", and 2.44" were used. The length of each chamber was somewhat over 16 inches to insure that no reflected rarefaction would reach the projectile before shot ejection (see Figure 7 for schematic drawing). Both barrels had smooth bores and were 0.520" in diameter. Their lengths were 77.5 cm. and 42.5 cm.

12. Figure 3 shows the 77.5 cm. barrel mounted in the 1.125" chamber. A steel nut was used to join the chamber and barrel. On the chamber side of this nut a 60° included angle was machined to facilitate smooth flow of the air in this section (Figure 7).

13. Figure 4 shows a disassembled view of the 1.125" chamber. The tube shown in the foreground is the 0.75" chamber, which was so constructed that it fit snugly into the 1.125" chamber, being anchored at the front by the nut and in the back by the spiral spring shown in the picture. Two projectiles are also shown in this figure. These were designed as shown in Figure 7. Part 1 fit into the barrel, which was then screwed into the nut tight enough so that Part 2 seated against an "O" ring and sealed the chamber. At about 3,000 psi the projectile sheared, leaving a ring (Part 2) in the gun chamber, while Part 1, weighing approximately 1 gram, acted as the projectile. The projectiles were constructed from a linen-base phenolic plastic.

14. The loading was accomplished by bleeding air from a 1500 psi supply bottle into an air-operated compressor, which compressed it

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slowly into the chamber (see figures 5 and 6). Control of the rate of feed was maintained by suitable valves.

15. Figure 5 shows two of the arrangements used. To the right is the 0.575" chamber and 42.5 cm. barrel, and to the left is the 2.44" chamber and 77.5 cm. barrel. The compressor appears in the center. In front of the larger chamber the chronograph can be seen. This consisted of an aluminum frame on which the three screens were mounted. These screens were spaced at 50 cm. intervals, the first being placed 50 cms. from the muzzle of the gun. The screens were a fine grade of light drafting paper upon which a printed grid was made with silver conducting paint. When the screens were punctured by the bullet, the electrical continuity was interrupted and the counters were operated in proper sequence.

PROCEDURE FOR FIRING

16. The shear-type projectile was placed in the barrel, which was then screwed into the nut attached to the chamber. Air was bled slowly from the supply bottle, compressed by the air compressor, and fed to the chamber. At about 3,000 psi, the design shear pressure, the projectile would shear and travel down the barrel. During free flight it would break the screens and operate the counters, and it would finally come to rest in the butt. Temperature was read during the pumping process, and the bullet weight was measured after firing, so that all of the parameters were determined.

METHOD OF ANALYSIS

17. For each of the ten sets of firings made, the initial pressure (P_0), bore area (A), length of travel (x), and room temperature were all determined at the time of firing. The mass of projectile (M) was determined by weighing after each set of tests. From the temperature it was possible to calculate the initial sound velocity (a_0), or the impetus, which is proportional to a_0^2 . In addition, the counter readings provided the average velocity at 75 cm. (u_1) and 125 cm. (u_2) from the muzzle. It was thus possible to plot directly u_1/a_0 vs ($p_0 Ax/Ma_0^2$) for all the tests.

18. Since u_1 and u_2 were both known, an approximate drag coefficient could be determined and the muzzle velocity (u_m) calculated. For a given set of firings u_1 and u_2 were averaged, and a drag coefficient based on this average was determined and roughly checked against drag coefficients of blunt-nosed missiles. Figure 11 is a plot of the experimental drag coefficient vs Mach number. The correction for drag was made as outlined in Appendix I. This experimental value of drag coefficient was then used to calculate the average muzzle velocity

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(u_m) based upon the average experimental velocity at 75 cms. (u_1) for each set of firings.

19. It was thus possible to plot u_m/a_0 vs ($P_0 \Delta x/M_0^2$) for each set. This provided ten points, representing the ten possible combinations of barrels and chambers. The points for each size chamber (e.g., 0.75" chamber, 42.5 cm. barrel; and 0.75" chamber, 77.5 cm. barrel) were joined by a straight line to give curves of u_m/a_0 vs ($P_0 \Delta x/M_0^2$) with chamber diameter as parameter.

20. By using the results given in reference (1), a curve of u_m/a_0 vs ($P_0 \Delta x/M_0^2$) can be obtained for the case of optimum chambrage and also for that of uniform bore. These curves hold for vacuum ahead of the projectile and must be corrected for the experimental conditions. This was accomplished by calculating the back pressure effect of the air in the barrel in front of the projectile.

21. The pressure ahead of the projectile can be calculated by use of the method of characteristics. The unsteady characteristic equations with terms to account for the entropy change are used with the shock equations in a step-by-step numerical computation. This calculation was done for a constant-diameter gun with initial conditions the same as those of the experiments reported here. (The details of this calculation will be given in a future report.)

22. It was found from the calculation that the pressure-velocity relation for the air directly in front of the projectile in this case of relatively low Mach number is approximately the same as for unsteady compression without shocks or reflected impulses:

$$p = \left(1 + \frac{u}{5a_0}\right)^7$$

where p is the pressure in atmospheres in front of the projectile, u is the projectile velocity, and a_0 is the initial sound velocity of the air in the barrel. The above pressure-velocity relation was used to account for the effect of the resistance of the air in the barrel on the projectile in the chambered guns.

23. By applying a correction for air resistance to the theoretical curves, it is possible to compare them directly with the experimental one as plotted on a u_m/a_0 vs ($P_0 \Delta x/M_0^2$) = X graph. If this is done, it is found that the experimental curve for a uniform bore falls below the theoretical one. This is to be expected, since friction and gas leakage are ignored in the theoretical considerations.

24. It is, therefore, necessary to make some correction for friction. If it is assumed that friction force is a function of velocity or a function of propelling pressure, since the range in velocities and propelling pressures is relatively small for a given X (and, therefore,

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in this case a given barrel), it seems reasonable that the friction effect is approximately the same for all chambers fired with the same initial conditions and the same length barrel.

RESULTS

25. Figure 8 is a plot of u_1/a_0 vs $(P_0 A_x / M_0)^2$ as determined directly from the experimental data. Each straight line* represents the same chamber and was fitted to the data on the basis of the least mean square calculation. The probable error in the experimental values is about 0.02 in u_1/a_0 . The effect of increasing diameter is clearly apparent. The data presented in Figure 9 were obtained by taking the average values of the points given in Figure 8 and correcting them for drag loss in order to obtain muzzle velocity u_m .

26. The next step was to correct the curves given in Figure 9 for bore friction. This was done by shifting the experimental uniform bore curve into coincidence with the theoretical curve.** The same correction for friction was then applied to the experimental results for all chambers. The resulting curves are given in Figure 10.

27. By the use of Figure 10 the velocity increase due to chambrage can be plotted against diameter ratio. The increase is plotted in Figure 2 in terms of percentage of the maximum possible increase for values of $X = 10$ and $X = 20$.

CONCLUDING REMARKS

28. The satisfactory agreement between the experimental and theoretical results (see Figure 2) indicates that the assumptions used in the theory are valid. Thus, the use of the steady state equations at the junction between the chamber and bore seems justified.

29. It is to be emphasized that the conditions for which this study is applicable are not satisfied by conventional guns, and caution must

*The theory indicated that these lines, instead of being straight, are actually curved. In the range under consideration, however, this curvature is small and a straight line approximation is within the accuracy of the data.

** From previous results with an experimental uniform-bore gun of the type used here, it was found that differences between the experimental and theoretical projectile behavior could be attributed to friction between the projectile and the barrel (see reference (c)).

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be exercised in the application of these results to such guns. For conventional guns (i.e., in which the propellant burns during the projectile motion) the velocity gain from chambrage can be less or more than shown in Figure 2, depending on the rate of burning of the propellant. With the aid of Appendix IV of reference (a), it can be demonstrated that for a conventional gun, in which the propellant burns so as to maintain a constant peak chamber pressure during the propellant motion, the maximum velocity gain over a gun with no chambrage is about 7 percent. This percent velocity gain is smaller than the 28 percent obtainable from a preburned propellant in a gun of the type considered here; the smaller gain is due to the fact that the conventional gun can achieve a pressure-sustaining effect behind the projectile from the continued burning of the propellant, thus leaving less room for gain from chambrage. This pressure-sustaining effect from continued burning is more and more difficult to obtain as projectile velocities are increased (because of the high rates of burning required to maintain the chamber pressure), but a pressure-sustaining effect from chambrage is obtainable at high velocities. Thus, the use of chambrage is particularly advantageous in high-velocity conventional guns.* NAVORD Report 3717 (in preparation) gives an approximate method of treating chambrage in conventional gun calculations.

30. The conditions of preburned propellant and long chamber for which this study is applicable are approached in some unorthodox guns. Such guns are now in use by the Aeroballistic Research Department of the Naval Ordnance Laboratory. The results of this study are being applied directly to these guns.

*Note that this discussion assumes that the propellant burns only in the chamber; if unburned propellant is pushed along the barrel and then is burned, an additional pressure-sustaining effect behind the projectile results.

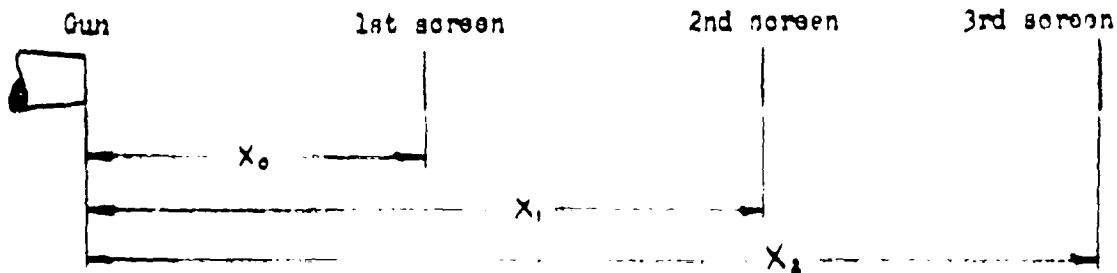
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- (a) Seigel, A. E., "The Effect of the Optimum Chambrage on the Muzzle Velocity of Guns With a Qualitative Description of the Fundamental Phenomena Occurring During Gun Firing," NAVORD Report 2691.
- (b) Seigel, A. E., "The Influence of Chamber Diameter Size on the Muzzle Velocity of a Gun With Effectively an Infinite Length Chamber," NAVORD Report 3635.
- (c) Seigel, A. E., The Rapid Expansion of Compressed Gases Behind a Piston, (Doctoral Thesis, University of Amsterdam, Jan., 1952), or NAVORD Report 2692, "A Study of the Applicability of the Unsteady One-Dimensional Isentropic Theory to an Experimental Gun."

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APPENDIX I



Symbols

u_1 - Average velocity over range $x_1 - x_0$

u_2 - Average velocity over range $x_2 - x_1$

u_m - Muzzle velocity

ρ - Air Density

c_d - Drag coefficient

A - Area of bullet

M - Mass of bullet

The deceleration of the projectile in free flight is

$$\frac{du}{dt} = -\frac{1}{2} \rho \frac{c_d A}{M} u^2 = u \frac{du}{dx}$$

Letting $\beta = \frac{1}{2} \rho \frac{c_d A}{M}$ and assuming c_d is constant over the range considered,

$$-\beta x \Big|_{x_a}^x = \ln u \Big|_{u_a}^u$$

$$\beta = \frac{1}{x_a - x} \ln \frac{u}{u_a}$$

where subscript "a" refers to any reference point.

$$\text{and } u = u_a e^{\beta(x_a - x)}$$

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In connection with the experimental firings, u_1 and u_2 are known from the counter readings. Therefore,

$$\beta = \frac{1}{\left(\frac{x_1 - x_0}{2} + x_0 - \frac{x_2 - x_1}{2} - x_1\right)} \ln \frac{u_2}{u_1}$$

or

$$\beta = \frac{2}{x_2 - x_0} \ln \frac{u_1}{u_2}$$

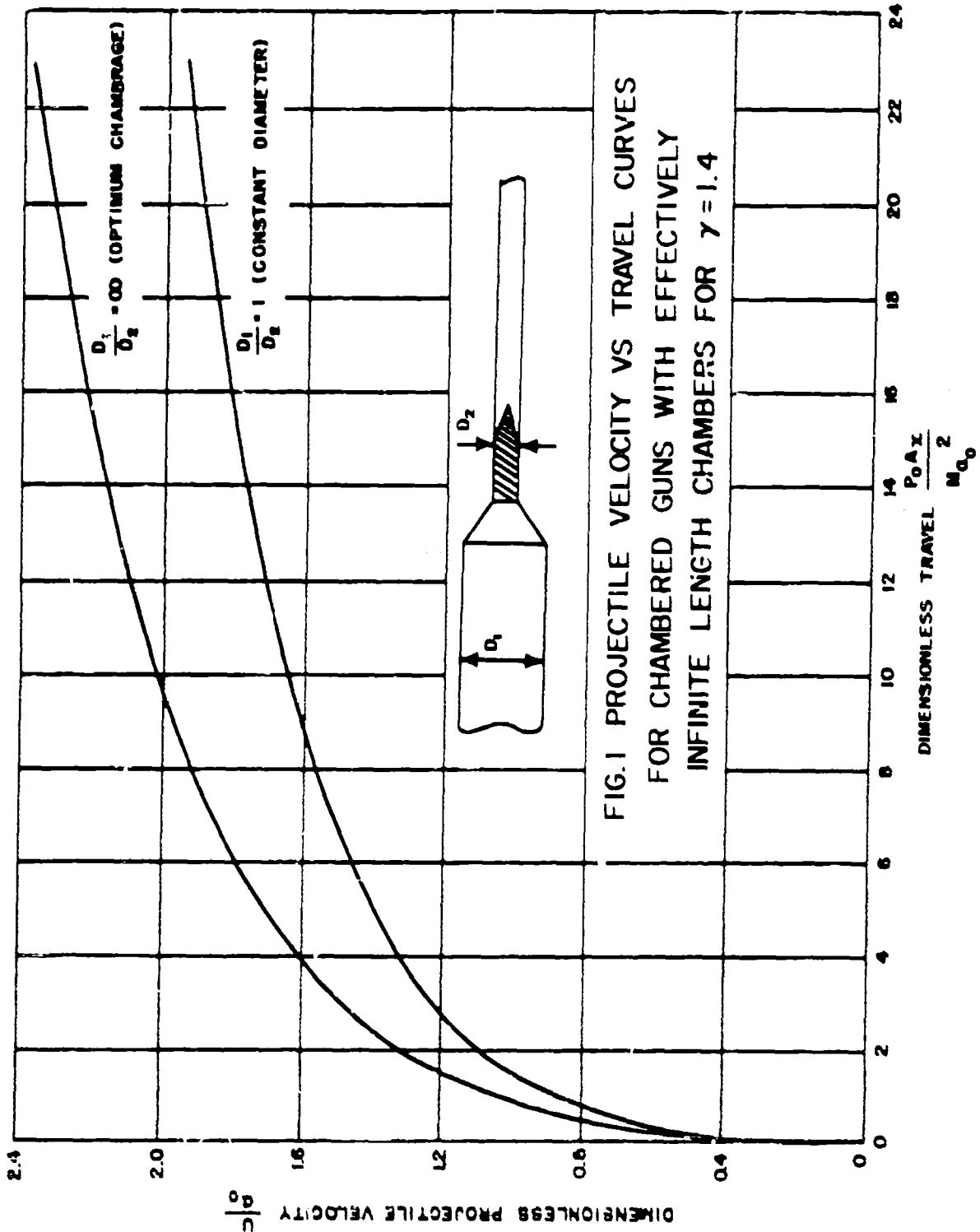
Since everything is known on the right side of this equation, β can be calculated. Figure 11 represents the best straight line through the β values calculated from the experiments. Next, by using the value of β taken from this curve, it is possible to obtain the muzzle velocity, since

$$u_m = u_1 e^{\beta \left(\frac{x_1 - x_0}{2} + x_0\right)} = u_1 e^{\beta \left(\frac{x_1 + x_0}{2}\right)}$$

In all of the experimental firings $x_0 = 50$ cm., $x_1 = 100$ cm., and $x_2 = 150$ cm. Therefore,

$$\beta = \frac{1}{50} \ln \frac{u_1}{u_2}$$

$$u_m = u_1 e^{75\beta}$$



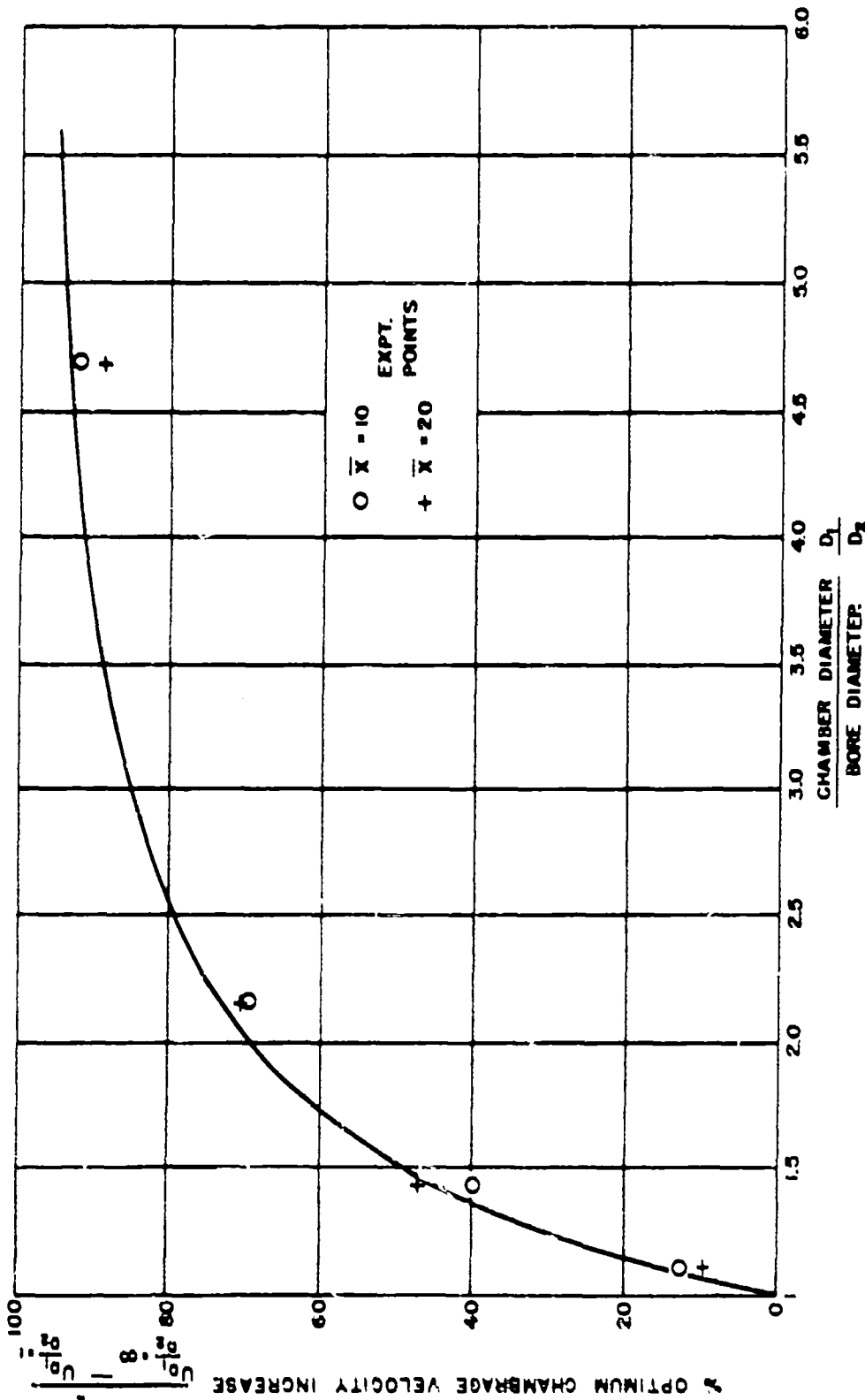


FIG. 2 THE PERCENT OF OPTIMUM CHAMBRAGE VELOCITY INCREASE
AS A FUNCTION OF CHAMBER DIAMETER TO BORE DIAMETER FOR
AN INFINITE CHAMBER LENGTH GUN

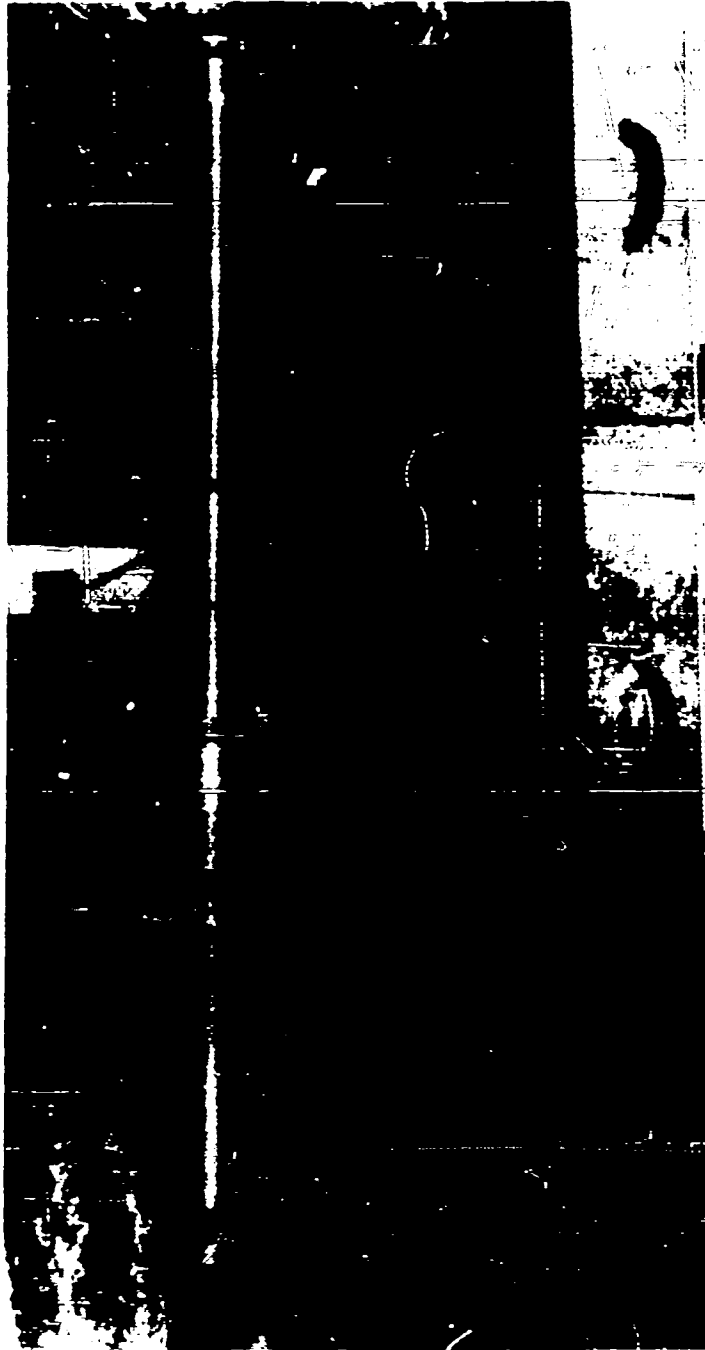


FIG. 3 1.125 INCH DIAMETER CHAMBER WITH 77.5 CM BARREL



FIG. 4 EXPLODED VIEW OF 1.125 INCH DIAMETER CHAMBER
AND 0.75 INCH DIAMETER CHAMBER



FIG. 5 MOUNTING OF 2.44 INCH DIAMETER CHAMBER WITH 77.5 CM BARREL
AND 0.575 INCH DIAMETER CHAMBER WITH 42.5 CM BARREL



FIG. 6 0.575 INCH DIAMETER CHAMBER WITH 42.5 CM BARREL

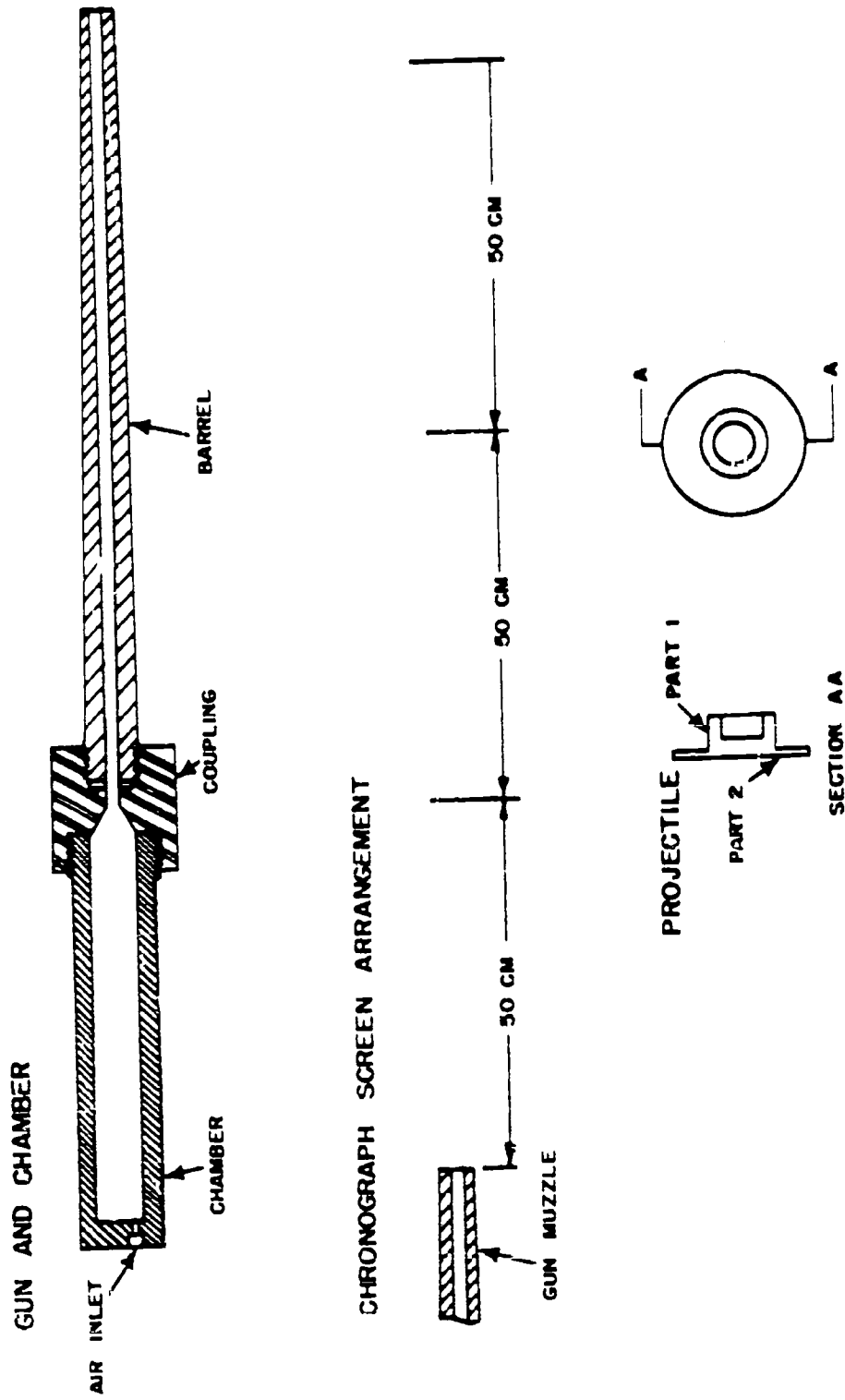


FIG. 7 SCHEMATIC OF GUN SYSTEM

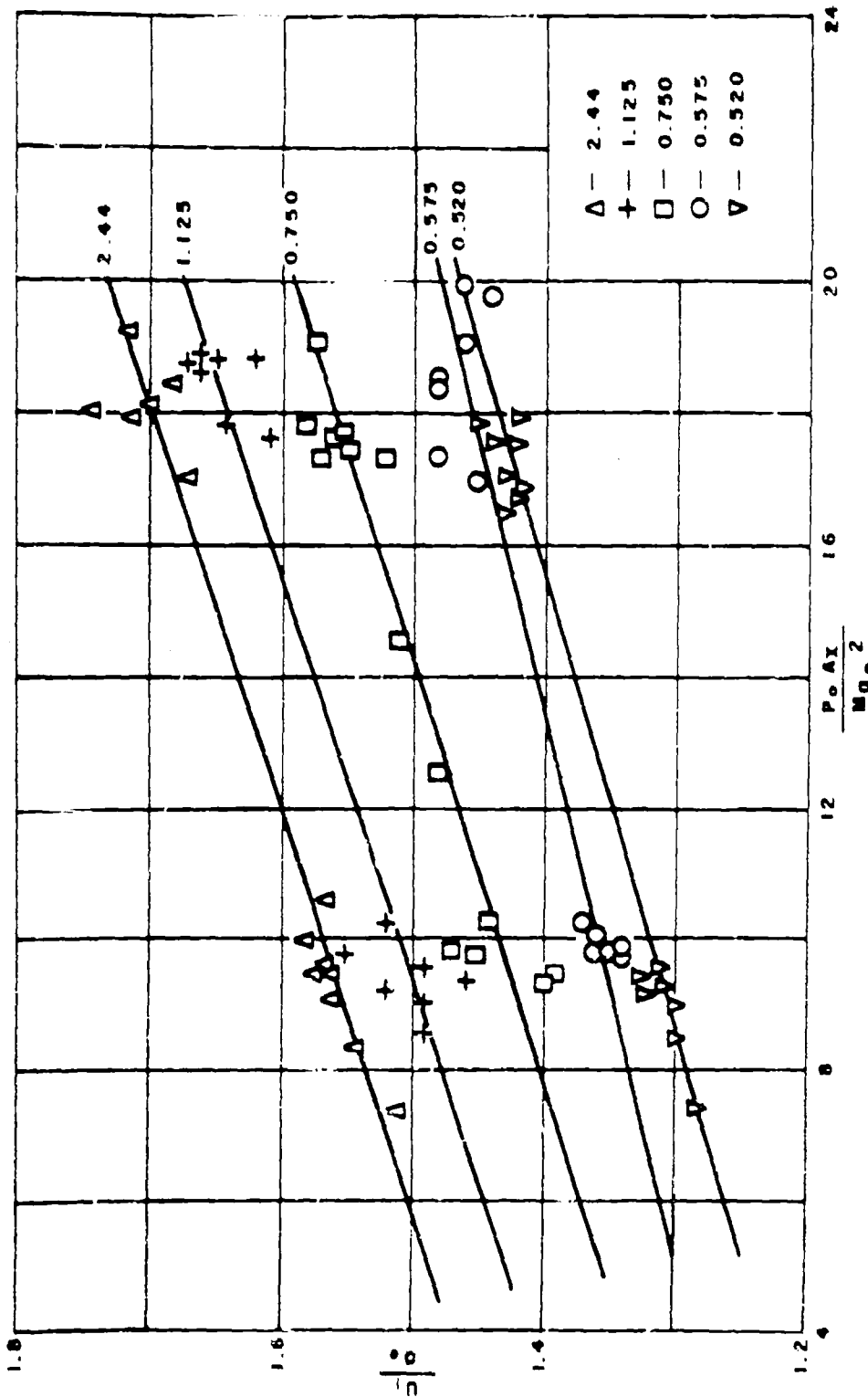


FIG. 8 $\frac{U_1}{q_0}$ vs $\frac{P_0 A X}{M_0^2}$

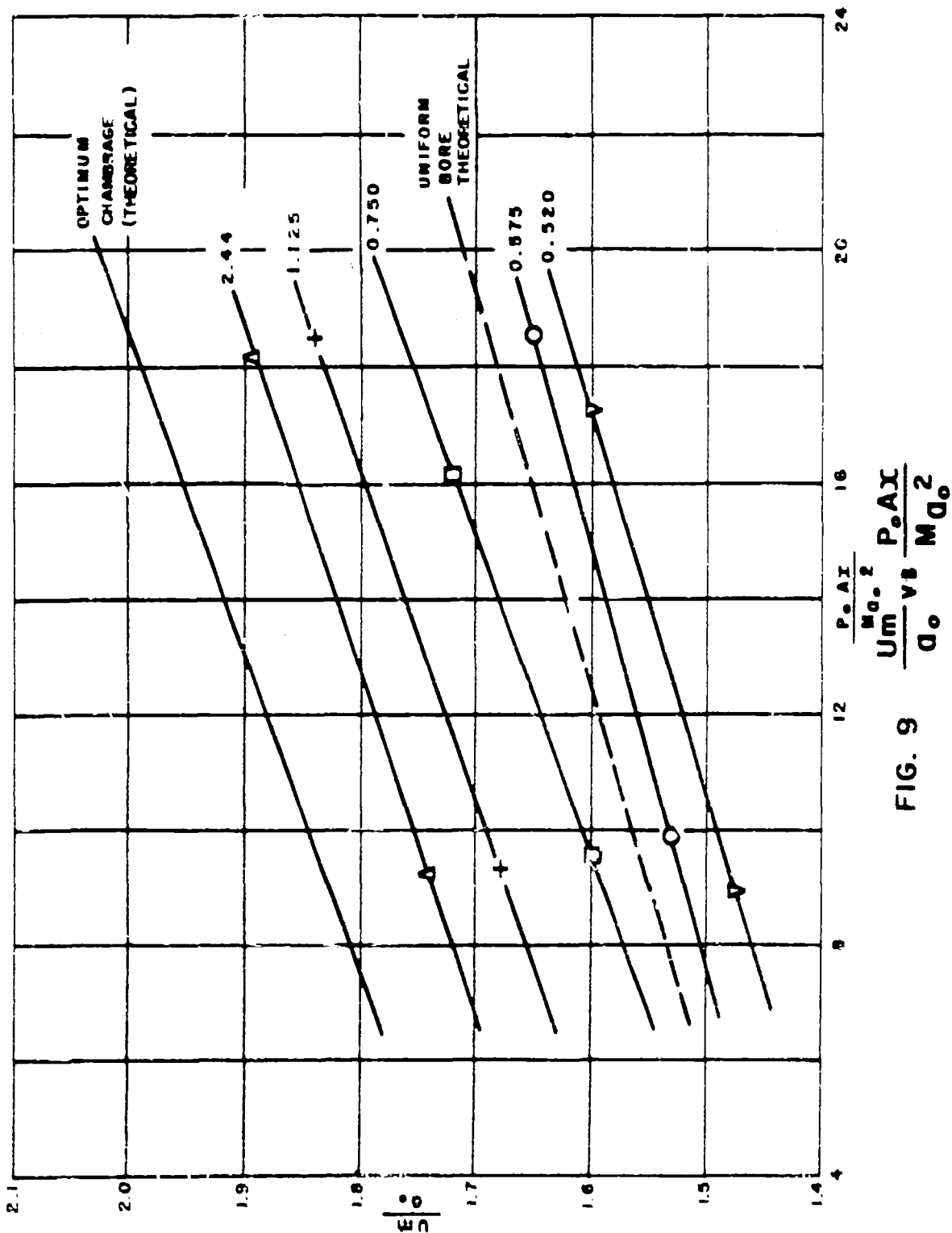


FIG. 9

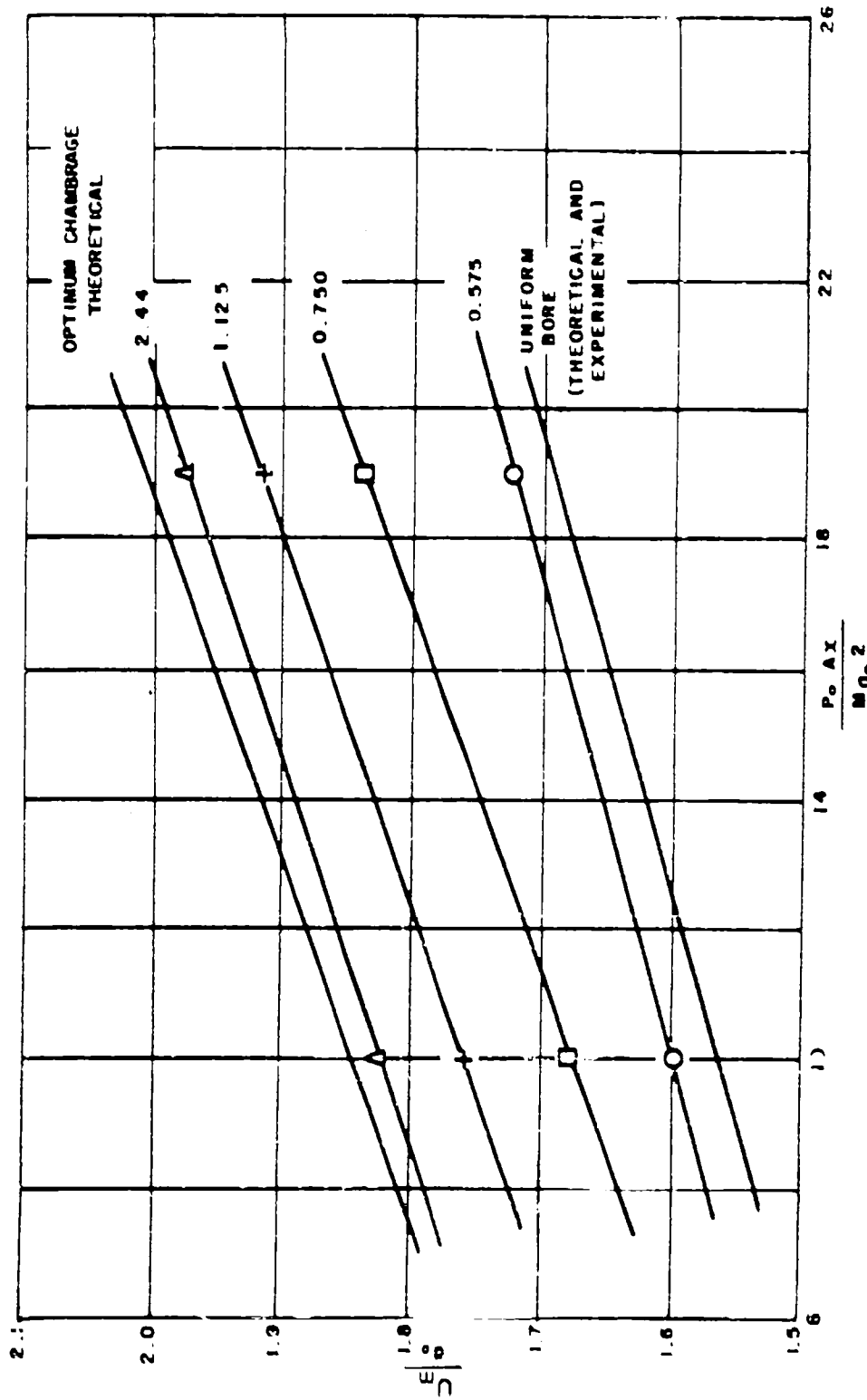


FIG. 10 $\frac{U_m}{a_0} \frac{P_0 A X}{M a_0^2}$ vs $\frac{P_0 A X}{M a_0^2}$

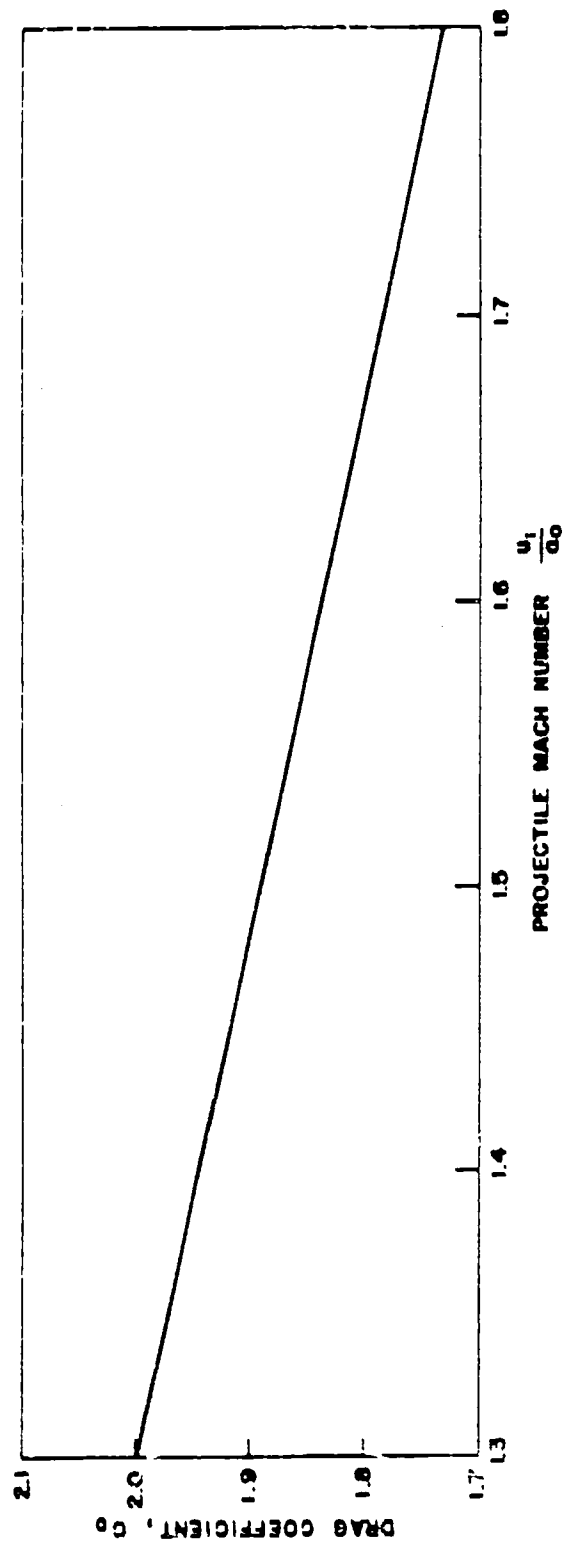


FIG. 11 EXPERIMENTAL DRAG COEFFICIENT OF PROJECTILE

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