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THEORETICAL STUDIES OF THE USE OF MULTIPROPELLANTS IN HIGH VELOCITY GUNS

by

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P. G. Baer

August 1968

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THEORETICAL STUDIES OF THE USE OF MULTIPROPELLANTS IN HIGH VELOCITY GUNS

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BBGrollman/PGBaer/ams
Aberdeen Proving Ground, Md.
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THEORETICAL STUDIES OF THE USE OF MULTIPROPELLANTS IN HIGH VELOCITY GUNS

ABSTRACT

The use of propellant mixtures in high velocity guns, as means of increasing projectile muzzle velocity, is compared with the use of a single propellant. The propellant mixtures vary in chemical composition, web, and burning rate. A theoretical study is made using the M68 105mm high velocity tank gun as a test case. Gun geometry, projectile weight, and propellant shape are not changed from that of the standard gun. Interior ballistic trajectories in the parametric study are computed using a multipropellant interior ballistic digital computer code. Graphical methods are used to determine the optimum propellant mixture needed to maximize muzzle velocity at a given allowable maximum gun breech pressure. The effect of propellant grain shape on the performance of a gun is considered in a separate study. Results from the interior ballistic computer model are also compared with experimental results from the firing of propellant mixtures in the 5-inch and 16-inch guns used to launch high altitude atmospheric probes.

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I. INTRODUCTION

Many methods have been considered by interior ballisticians to increase the muzzle velocity of a gun without increasing the gun's maximum breech pressure above a value set by the mechanical strength of the gun's propellant chamber. In 1956 improvements in gun propellants, during the decade following World War II, were reviewed by Jackson.[1*] In the 11 years since the publication of Jackson's review, little progress has been made on gun propellant improvement. This paper outlines several approaches toward solving the problem of increasing muzzle velocity without increasing breech pressure above the mechanical strength of the steel in the gun.

The objective of this theoretical study is to increase the muzzle velocity of the 105mm M68 high velocity tank gun, the characteristics of which are given in Table I. The following constraints were imposed on the problem:

a. Projectile weight was held constant.

b. Total propellant weight was held constant.

c. The geometric configuration of the gun was not to be altered; that is propellant chamber volume and maximum projectile travel in the gun was held constant.

In order to increase the muzzle velocity of the gun without violating these constraints one must increase the piezometric efficiency of the gun by several possible means.

a. Varying propellant web.

b. Using mixes of varying web of the same propellant (multi-grain case).

c. Using mixes of propellant which vary in composition and web (multipropellant case).

d. Vary the propellant grain shape.

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* References are found on page 47 of this report.

Table I. Characteristics of 105mm Gun System

Gun Parameters		
Travel of Projectile - in.		188
Chamber Volume - in^3		395
Bore Area - in^2		13.81
Bore Diameter - in.		4.134
Projectile Weight - lb		12.8
Propellant Properties	**Propellant**	**Igniter**
Type	M30	Benite
Force - in-lb/lb	4,374,000	2,550,000
Specific Heat Ratio	1.238	1.25
Covolume - in^3/lb	29.26	
Molecular Wt - lb/lb-mole	23.193	39.26
Isochloric Flame Temp ^oK	3040	3000
Burning Rate Coef. - in/sec-psi$^\alpha$	.004819	
Burning Rate Exponent	.6697	
Weight - lb	12.1	.12
Propellant Dimensions		
Outside Dia. of Grain - in.		.2820
Dia. of Perforation - in.		.03267
Length of Grain - in.		.6769
Web - in.		.046
Number of Perforations		7
L/D Ratio		2.409
D/D_p Ratio		8.632
Gun Simulation Data		
Shot Start Pressure - psi		6,000
Frictional Resistance Pressure psi		200
Propellant Erosion Constant		.00005

In the following sections, the potential of the above methods to increase gun performance will be evaluated.

The gun selected for this study, 105mm M68 tank gun, had never been fired experimentally using multigrain or multipropellant charges. Therefore, it was necessary to compare the computer program results with some experimental high velocity guns which used multigrain or multipropellant charges. Two experimental guns used to launch high altitude research probes (HARP) were using multipropellant charges. The results from the computer program are compared with some experimental firings of these guns.

II. EXPERIMENTAL PROCEDURE

In conducting this study, it was necessary to simulate the performance of a gun on a digital computer. The computer program developed for this purpose, called the Multipropellant Gun Simulator (MPGS) program, will be described in a subsequent BRL report.[2] This program is a more versatile version of an earlier gun simulation program.[3] The program is organized to have the following characteristics:

a. One can evaluate the performance of propellant mixes containing up to five different propellants which may vary in:

(1) propellant grain shape.

(a) Cylindrical grains with 0, 1, 7, or 19 perforations,

(b) rectangular grains, or

(c) spherical grains.

(2) thermodynamic properties of propellant gases. These are

(a) propellant force,

(b) specific heat ratio,

(c) covolume correction, and

(d) adiabatic flame temperature.

(3) propellant density.

(4) propellant burning rate. The propellant burning rate is considered to be a function of propellant pressure and projectile velocity. The projectile velocity constant is designated the propellant erosion constant.

b. One can optionally obtain plots of the important interior ballistic parameters as a function of time or of projectile travel.

c. Program input is designed for parametric studies. Program can read in a base case, run it, and then automatically run additional cases. For the additional cases, certain input variables are designated together with a set of values for each variable. The program will run all permutations and combinations of these values as the additional cases. Up to 10 variables and 10 values for each variable can be run. (It is unlikely anyone will ever use the full range of variables and values allotted in the program since using the full range would amount to 10^{10} cases.) This feature of the program has proved to be very useful in this study.

The MPGS program, like other interior ballistic simulation programs, has certain input variables, the values of which are not known for any particular gun. In the MPGS program these variables are: (1) projectile shot start pressure; (2) projectile frictional resistance pressure, here assumed to be a constant for the entire motion of the projectile; and (3) propellant erosion constant. Before a parametric study can be made on a particular gun, values for these variables must be determined for a gun firing and then held constant for the remainder of the study. Determination of these values is called a "gun matching study".

To conduct the gun matching study in the 105mm M68 gun, the following procedure was used:

a. Standard deviations (1 σ value) from the rated muzzle velocity and maximum breech pressure were obtained from about 1000 experimental firings of the gun. These values were 8.8 f/s in muzzle velocity and 460. psi in maximum breech pressure.

b. All the variables characterizing the gun, propellant, and projectile were read into the program. Initial estimates for shot start pressure, projectile frictional resistance pressure, and propellant erosion constant were read in and the interior ballistic trajectory computed for that case.

c. Using the parametric variation feature of the program; the values of shot start pressure, projectile frictional resistance pressure, and propellant erosion constant were systematically varied until values of the computed maximum breech pressure and muzzle velocity were within the range of values set by the standard deviation. Table II illustrates the values of muzzle velocity and maximum breech pressure obtained by this procedure.

d. The following values of shot start pressure, projectile frictional resistance pressure, and propellant erosion constant were obtained by the above procedure:

Shot Start Pressure: 6000 psi

Projectile Frictional Resistance Pressure: 200 psi

Propellant Erosion Constant: .000050

These values were held constant throughout the remainder of the study. A plot of the computed interior ballistic trajectory for the standard case, called the "key" case is illustrated in Figure 1.

Table II. Matching Muzzle Velocity and Maximum Breech Pressure in the 105mm M68 Gun

Experimental Muzzle Velocity: 4850 f/s $1\sigma = 8.8$ f/s

Variation: 4841 to 4859 f/s

Experimental Maximum Breech Pressure: 59,400 psi $1\sigma = 460$ psi

Variation: 58,940 to 59,860 psi

* Key Case

Frictional Resistance Pressure psi	Propellant Erosion Constant	Shot Start Pressure - PSI					
		4000		5000		6000	
		V	P	V	P	V	P
150	.000050	4828	57656	4841	58573	4855	59533
150	.000051	4833	57770	4846	58684	4860	59645
150	.000052	4838	57884	4851	58797	4865	58755
200	.000050	4825	57780	4838	58687	4852*	59642*
200	.000051	4830	57893	4843	58799	4857	59752
200	.000052	4835	58006	4848	58911	4862	59863
250	.000050	4821	57903	4835	58802	4848	59749
250	.000051	4826	58016	4840	58914	4853	59860
250	.000052	4832	58128	4845	59026	4858	59971

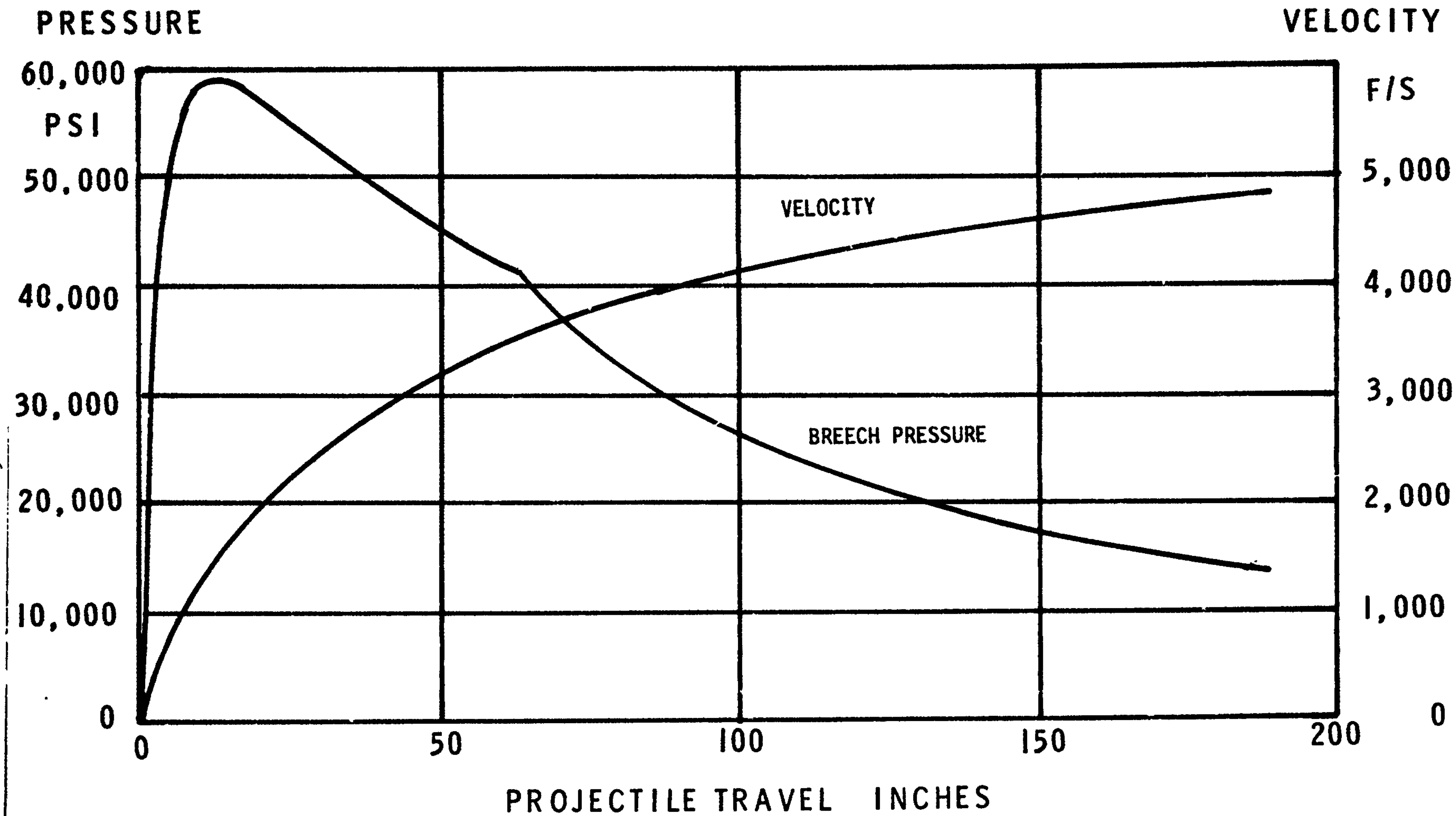

Figure 1. Interior Ballistic Trajectory for 105mm M68 Gun "Key" Case

III. PARAMETRIC STUDIES AND RESULTS

Once the characteristics of the "key" case had been established, interior ballistic simulation experiments were run on the computer. The grain shapes used in the simulations were:

a. cylindrical, cords (no perforation), or grains with 1, 7, or 19 perforations, or

b. spherical grains.

The dimensions of the grains were defined in terms of the grain web (minimum thickness of grain) and in the case of cylindrical grains two ratios:

a. D/D_p - ratio of outside diameter of grain to diameter of perforation.

b. L/D - ratio of length of grain to outside diameter of grain.

The grain shapes with dimension terms and ratios are illustrated in Figure 2. With the web and two ratios, it is possible to compute the grain dimensions. One of the options in the computer code allows us to read in web and the two ratios and, compute grain dimensions before running the problem. With this option it is possible to hold the two ratios constant and vary the web of the propellant grain.

In the first parametric study, designated Propellant Web Effect, the following conditions were imposed:

a. Only one propellant at a time would be used in the gun for a simulated firing. Three propellants were tried: M30 (the standard propellant), M1, and M8.

b. The D/D_p and L/D ratios of the 7 perforated propellant used in the "key" case were held constant. The value of these ratios were:

$$D/D_p = 8.632; \; L/D = 2.409$$

c. The grain web was varied over wide limits in the experimental simulation with each of the propellants. The lower limit of the web which could be used in the gun would be set by the maximum breech

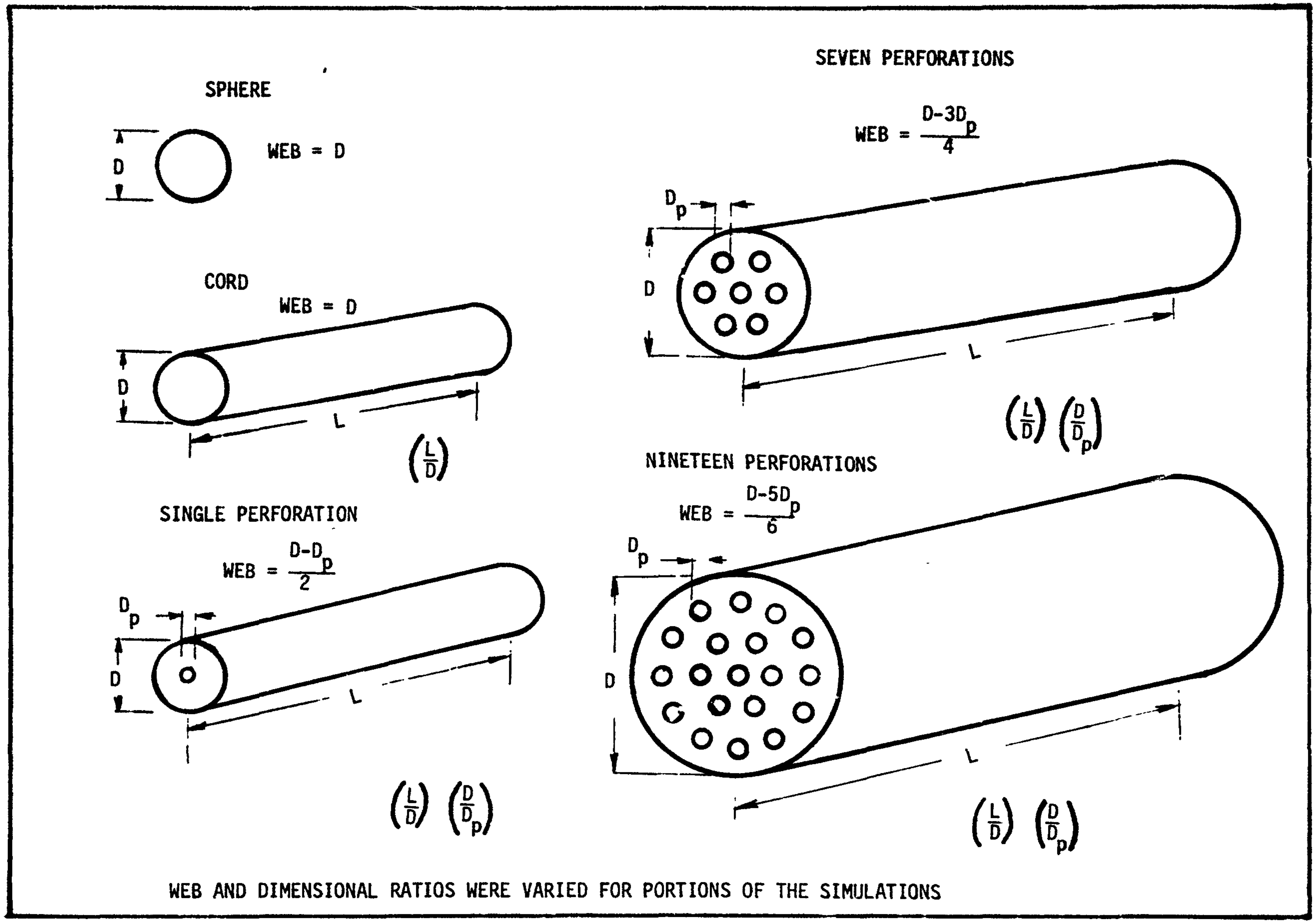

Figure 2. Propellant Grain Shapes, Dimensions, and Ratios

pressure which would be tolerated in the gun (here arbitrarily set at 100,000 psi). The upper limit of web would be set at a point at which an appreciable fraction of the propellant would be blown out of the gun unburnt.

The results of this simulation for the three propellants is illustrated in Figure 3. These curves are maximum breech pressure-muzzle velocity curves with propellant web indicated at each of the plotted points. It will be noted, from the curve for M1 propellant that if we adjust the propellant web so that the maximum breech pressure developed by firing is equal to the maximum breech pressure in the "key" case (59,400 psi); then the muzzle velocity will be 210 f/s lower than for the "key" case. The reason for the drop in muzzle velocity for M1 propellant, in contrast to that for M30, is that the propellant chemical energy per unit weight for M1 is less than that for M30 (1,158,600 ft-lb/lb for M1; 1,544,500 ft-lb/lb for M30). In contrast to M1, the muzzle velocity developed by a gun using M8 propellant at the "key" case maximum breech pressure is 90 f/s greater than for the "key" case muzzle velocity. This occurs because the chemical energy per unit weight for M8 propellant is greater than for M30 propellant (1,880,300 ft-lb/lb for M8).

In the second parametric study, designated Effect of Varying the Web of the Propellant Mixes, the following conditions were imposed:

a. Only one propellant composition was considered, namely M30 propellant.

b. All the 7 perforated propellant grains used in this study had the same D/D_p and L/D ratios, namely the ratios used in the "key" case.

c. At each simulated firing, a propellant mix consisting of a fine web and a coarse web was used (dual grain case).

On this, and succeeding figures, in which gun performance is plotted on maximum breech pressure-muzzle velocity curves; curves of constant piezometric efficiency are also plotted. Piezometric efficiency e_p, is defined as the ratio of the average pressure, $\overline{P}$, which does useful work

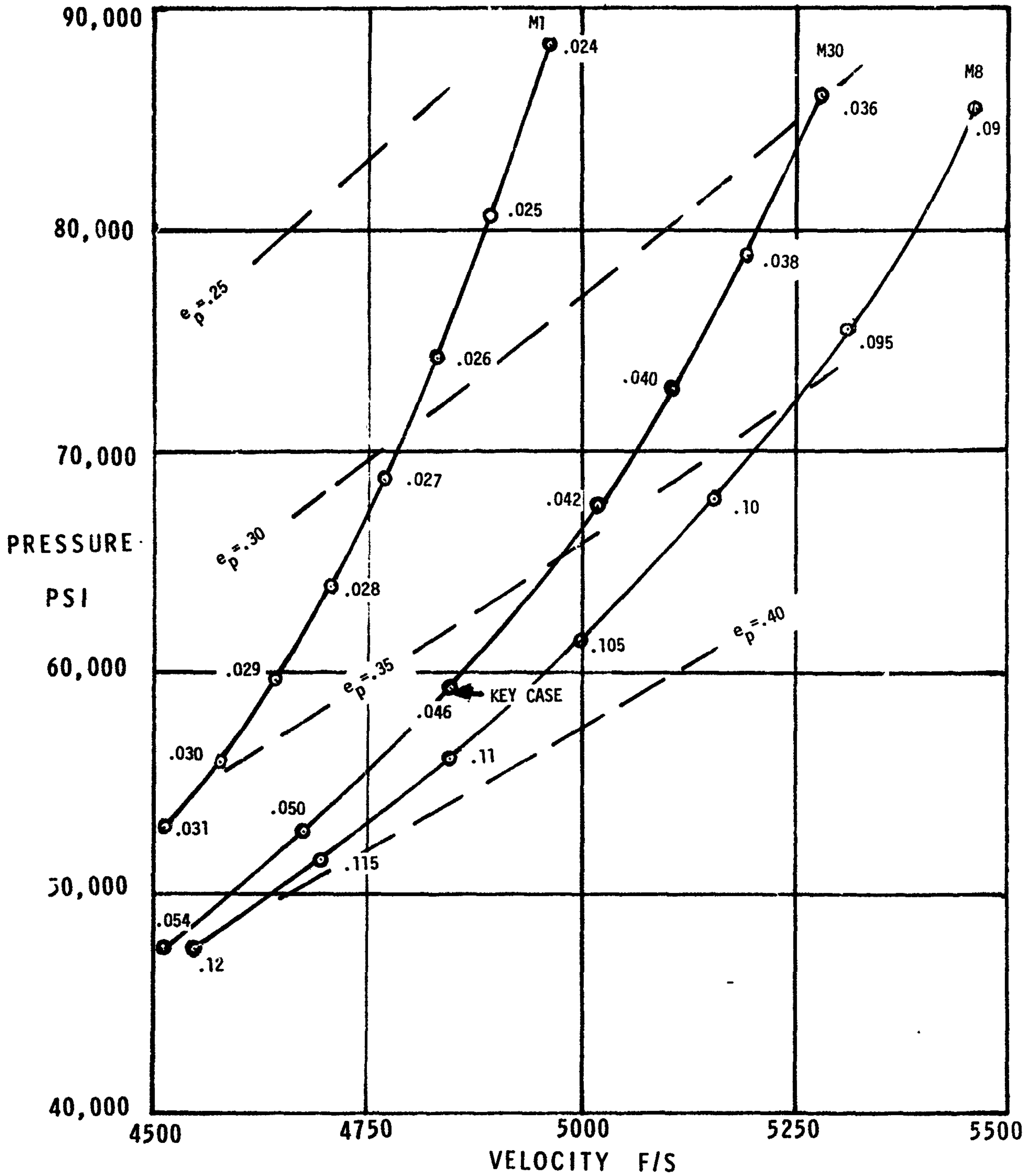

Figure 3. Peak Breech Pressure-Muzzle Velocity for M1, M8, and M30 Propellant

on the projectile, to the maximum breech pressure P_m. The defining equation is:

$$e_p = \frac{\overline{P}}{Pm} = \frac{.5\ wV^2}{g\ A\ L\ P_m}$$

where:

w = projectile weight lb

V = projectile muzzle velocity f/s

g = gravitational constant = 32.174 ft/sec^2

A = cross sectional area of gun bore in^2

L = length of projectile travel ft

P_m = maximum breech pressure psi

Piezometric efficiency is used in this study as a means of quantifying the performance of a gun firing. A gun firing which develops a high maximum breech pressure and a low muzzle velocity relative to the "key" case, has, by comparison, a low piezometric efficiency. On the other hand, a gun firing which develops a high maximum breech pressure and a high muzzle velocity, relative to the "key" case, has, by comparison, a high piezometric efficiency.

From the relative positions of the M1, M8, and M30 curves compared to the curves of constant piezometric efficiency, it will be noted that firings using M8 propellant will have higher piezometric efficiencies than will firings using M1 or M30 propellant; comparisons being made at the same maximum breech pressure. Under the same conditions, firings using M30 propellant will have higher piezometric efficiencies than will firings using M1 propellant.

Seven webs were used. The webs ranged in size from a web which was 80% of the web used in the "key" case to a web which was 150% larger than the web used in the "key" case. Gun firings using dual gran propellant mixes were simulated with the computer program. Propellant mixes consisting of 20%, 40%, 60%, and 80% by weight of the finer web were used in the simulation.

The results of these simulations are illustrated in Figure 4. In this figure, each simulation is represented as a point with the coordinates of maximum breech pressure and muzzle velocity. The solid lines connect points of the same web composition; that is, points of 0%, 20%, 40%, 60%, and 80% finer web. The 0% composition line is identical to the M30 line used in Figure 3 with the exception that the web range is greater. The dotted lines serve to connect points which use the same coarse web. With this type of plot one can see how web composition (in the dual gran case) affects the maximum breech pressure and muzzle velocity.

The "key" case appears on this plot as the .046 web point on the 0% fine web composition line. It will be noted that at the maximum breech pressure of the "key" case, no point has a greater velocity than the "key" case. There are points which have higher velocities than the "key" case, but they also have higher breech pressures. At breech pr sures lower than the "key" case, the muzzle velocities are also lower. There is thus no advantage to using web mixtures under these conditions.

In the third parametric study, designated effects of multi-propellant mixes, the following conditions were imposed:

a. Two or three different propellants were used in the mixes. These were respectively:

(1) M1 and M30 propellants,

(2) M8 and M30 propellants,

(3) M1 and M8 propellants, and

(4) M1, M8, and M30 propellants.

b. As in the first and second parametric studies, D/D_p and L/D ratios were held at the "key" case values.

c. At each simulated firing a propellant mix consisting of two or three propellants varying in composition and web were used.

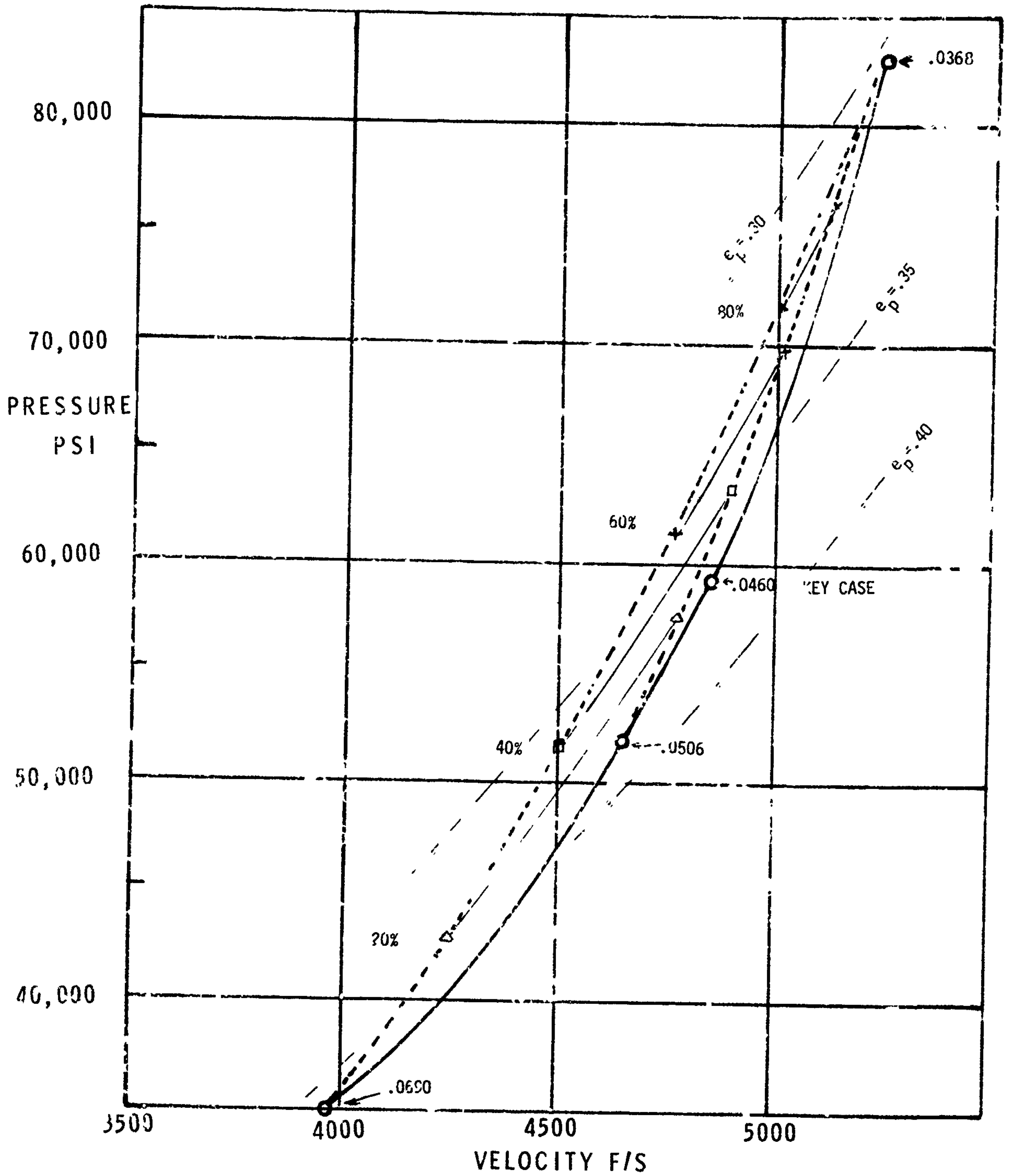

Figure 4. Peak Breech Pressure-Muzzle Velocity for Dual Granulation, 7 Perforated, M30 Propellant

Some of the results of these simulations are illustrated in Figures 5 and 6. As in Figures 3 and 4, the coordinate points on these figures are maximum breech pressure and muzzle velocity. In the simulations represented by each of the two figures, the propellant webs were held constant and the propellant mix composition varied. Both dual and triple propellant mixes are represented on these curves. The webs used in these figures were:

Figure 5: M1 - .028" web
M8 - .115" web
M30 - .046" web

Figure 6: M1 - .026" web
M8 - .110" web
M30 - .046" web.

Composition changes of 20%, 40%, 60%, and 80% by weight were made in the propellant mixes. In the figures, the solid lines connect the points representing the pure and dual propellant mixes. The broken lines connect pure and dual mix points with the triple propellant mix points.

In Figure 5, the "key" case represents the highest velocity obtainable for any combination of dual or triple propellant (for the web combination used in this set). In Figure 6, because of the web combinations chosen, there are a number of combinations in which the velocity is higher than the "key" case, at the "key" case breech pressure. For instance, at the "key" case breech pressure on the M1 - M8 composition line (about 70% M8, 30% M1) the muzzle velocity would be about 50 f/s higher than the "key" case. Similarily, there are other composition points at lower breech pressures than the "key" case in which the muzzle velocity is higher than the "key" case. This occurs, however, only for the webs chosen for the three propellants.

If one plots on Figures 5 and 6, the values of breech pressure and muzzle velocity for the pure propellants as their webs are varied (the

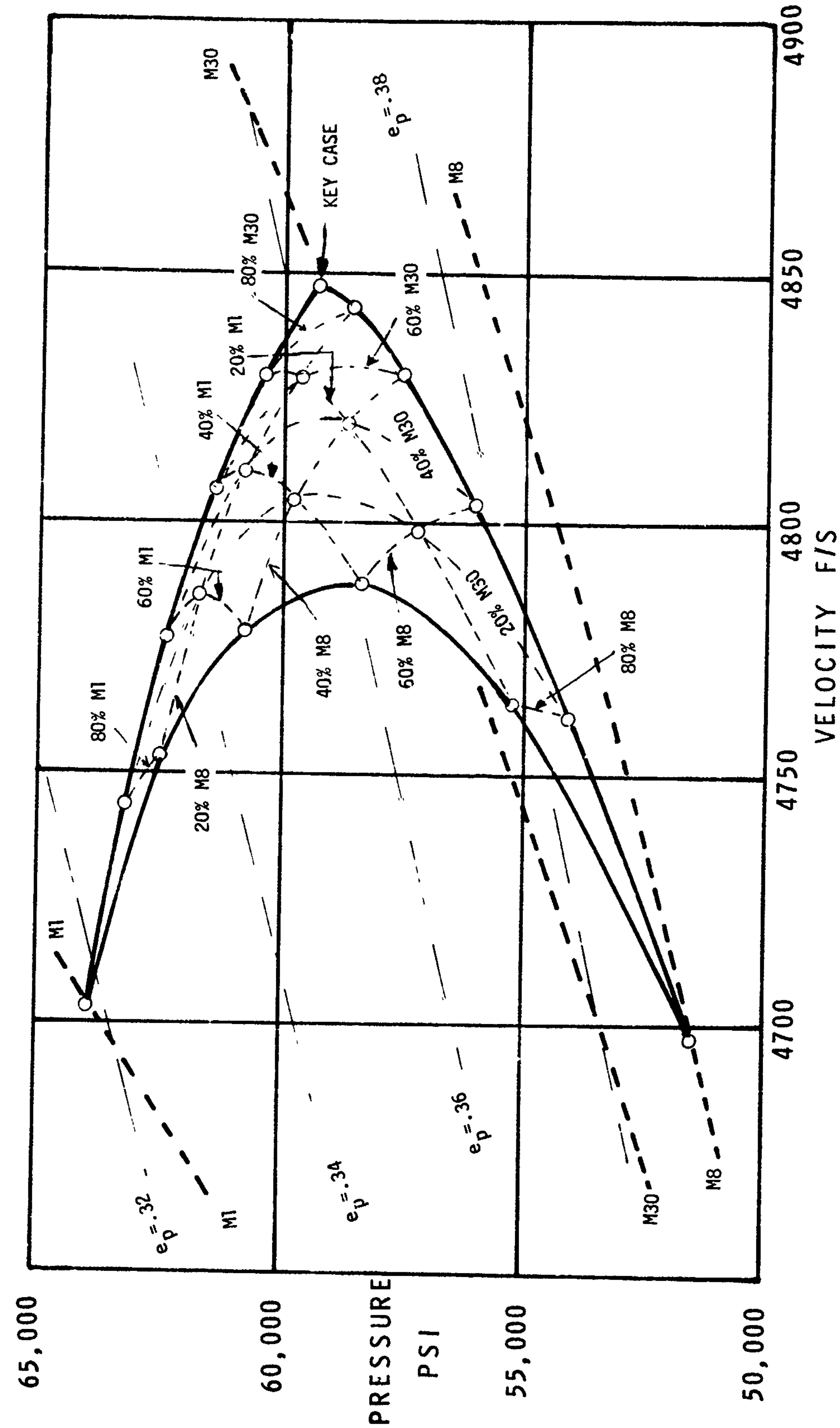

Figure 5. Peak Breech Pressure-Muzzle Velocity for M1, M8, M30 Multipropellant Mixtures

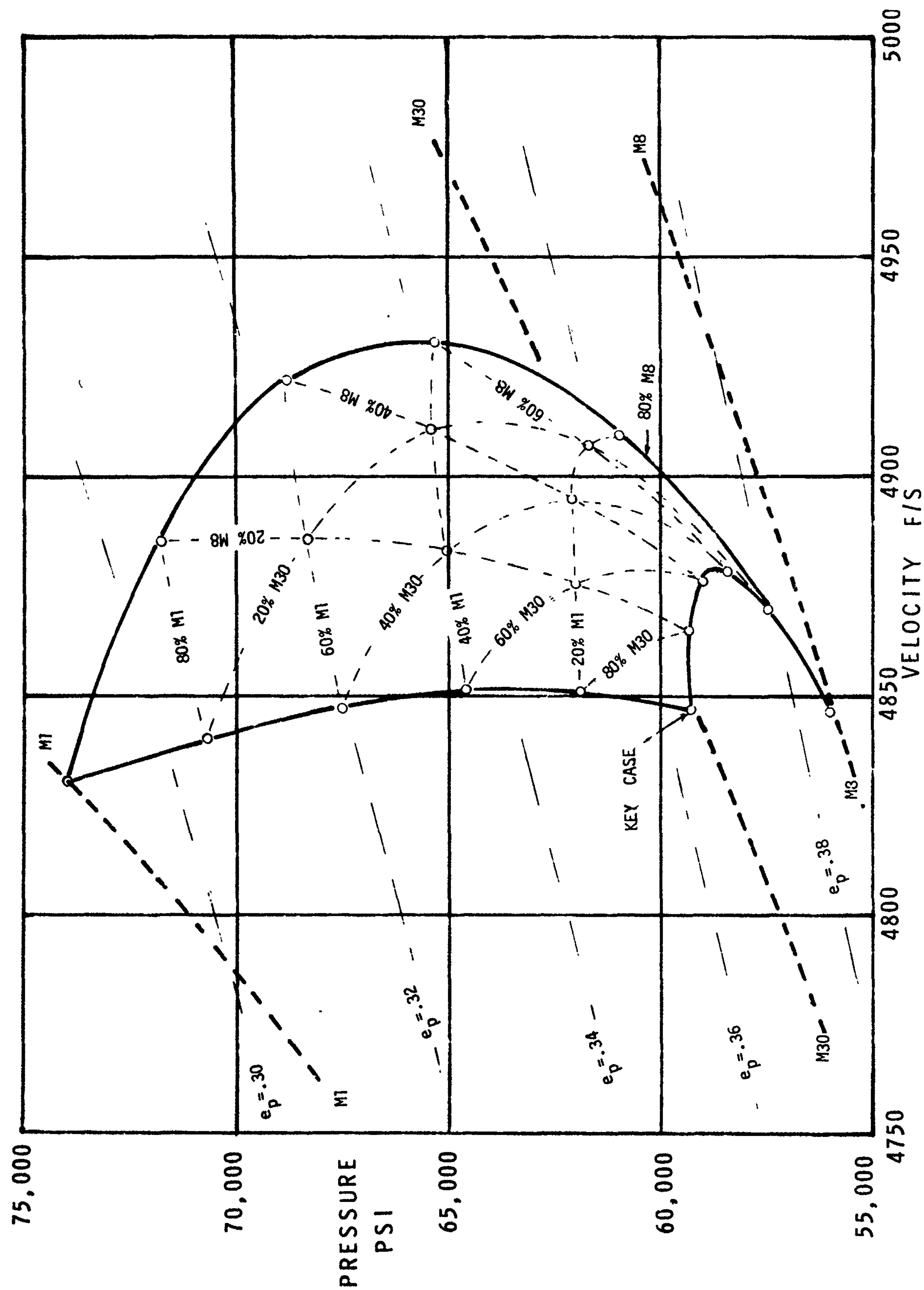

Figure 6. Peak Breech Pressure-Muzzle Velocity for M1, M8, M30 Multipropellant Mixtures

same information as is in Figure 3), three dotted lines are formed, designated M1, M8, and M30. The breech pressure-muzzle velocity points for the pure propellants fall on these lines. Comparison of the breech pressure-muzzle velocity points for the dual and triple composition propellants with the corresponding points for the pure propellants, indicates that none of the propellant mixture points is more favorable (has a higher muzzle velocity for a lower breech pressure) than the most energetic pure propellant, in this case, M8 propellant; provided that one is allowed to vary the web of the pure propellant in an arbitrary manner. For example, in Figure 6, the value of muzzle velocity on the pure M8 line at the "key" case pressure (at a web of about .107 inches) is 4940 f/s, an increase over the "key" case velocity of 95 f/s. This point is also about 45 f/s over the point at the same breech pressure on the M1 - M8 line.

In the fourth parametric study, the effect of propellant grain shape on gun performance, the following conditions were imposed:

a. Only one propellant was used, namely M30 propellant.

b. Sphere, cord, 1, 7, and 19 perforated grain shapes were used in the study. These grains are illustrated in Figure 2.

c. Only the effect of each grain shape on the performance of the gun was studied. Propellant mixes were not used.

As a background to the study of propellant grain shapes on gun performance; we have to consider how the surface area of each grain changes as the propellant burns. Since the surface area of the grain governs the rate at which propellant gas is evolved for use in propelling the projectile, change in the surface area as the propellant burns will influence the gun performance.

The change in grain surface area as the grain burns is illustrated in Figure 7. In this figure the surface area ratio S/S_o (ratio of instantaneous grain surface to initial grain surface) is plotted as a function of the weight fraction of propellant grain burnt, z. For the

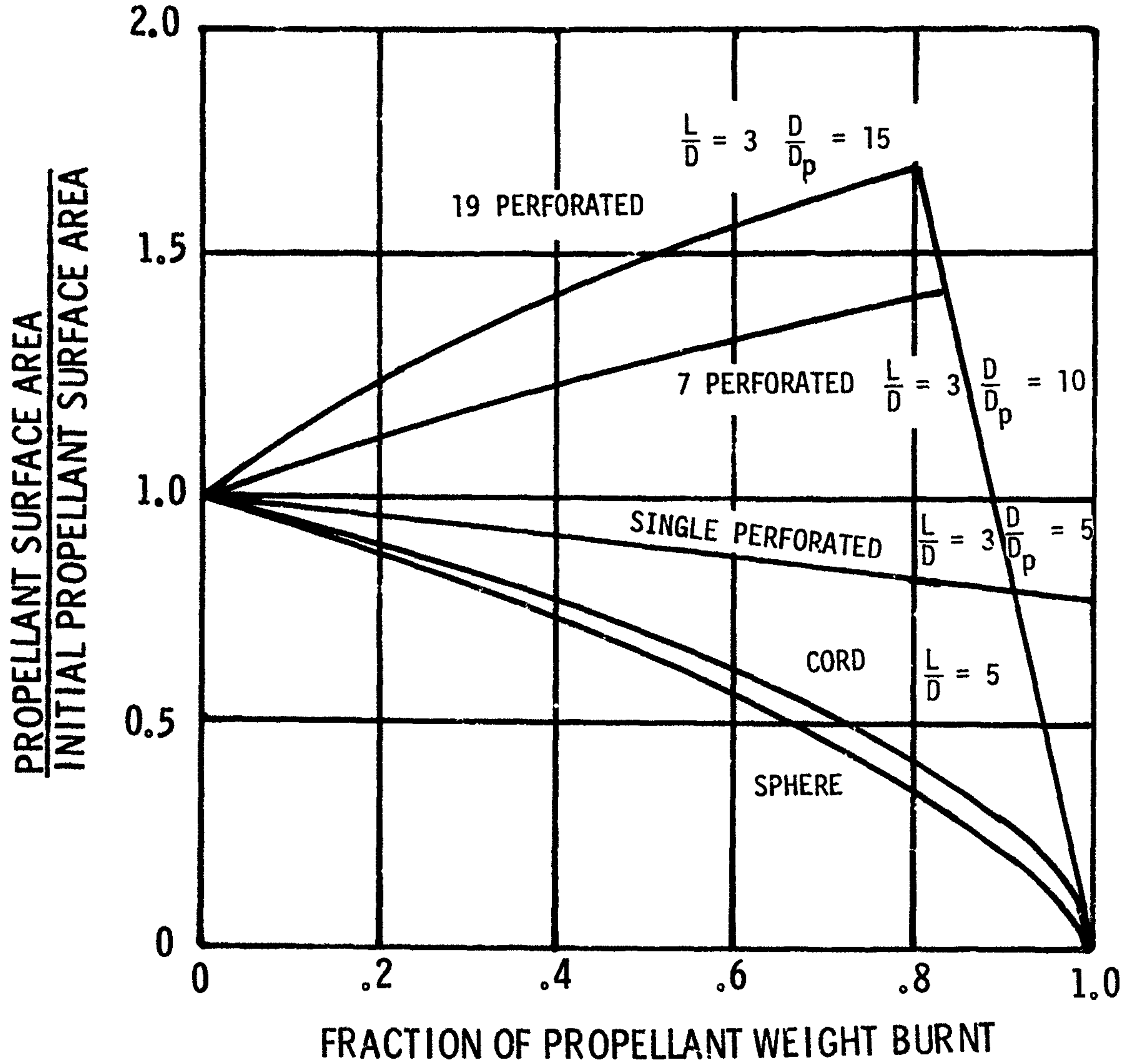

Figure 7. Variation of Propellant Burning Surface Ratio with Fraction Propellant Burnt for Various Grain Shapes.

sphere and cord grains, the surface area ratio decreases from one to zero as the weight fraction of propellant burned increases; this is called degressive burning. For the single-perforated grain, the surface area ratio decreases as the grain burns, but not to zero. The surface area ratio at propellant burnout is generally a large fraction, in this case, 77% of the initial area. Thus, the single perforated grain is considered to be slightly degressive.

For the seven-perforated grain, the surface area ratio increases as the grain burns until about 85% of the initial weight of the grain has been consumed. For the grain dimensional ratios given in Figure 7, the increase in surface area is 41%. This is called a progressive surface area grain. At the 85% burnt point, the grain web has burned out, so only propellant slivers remain. These slivers, like cord propellant, are degressive so the surface area ratio decreases to zero at propellant burnout.

The 19-perforated grain, illustrated in Figure 2, pattern consists of a central perforation, a set of six holes on an inner radius, and a set of 12 holes on an outer radius. The increase in surface area ratio for the 19-perforated grain with increase of weight fraction of propellant burnt is illustrated in Figure 7. For the grain dimensional ratios given in the figure, the increase in surface area ratio is 71% at web burnout. For this grain, web burnout occurs at 80% weight fraction burnt. Thereafter, the propellant slivers burn degressively, until the propellant burns out.

The effect of sphere, cord, 1; 7; and 19-perforated grain shapes on the performance of the M68 105mm gun is illustrated in Figures 8 through 11. As before, the points have coordinates of maximum breech pressure and muzzle velocity. Curves of constant piezometric efficiency are displayed on the plots.

In Figure 8, the effect of sphere and cord propellant on gun performance is illustrated. The curve for spherical propellant illustrates the change in maximum breech pressure and muzzle velocity as the web of

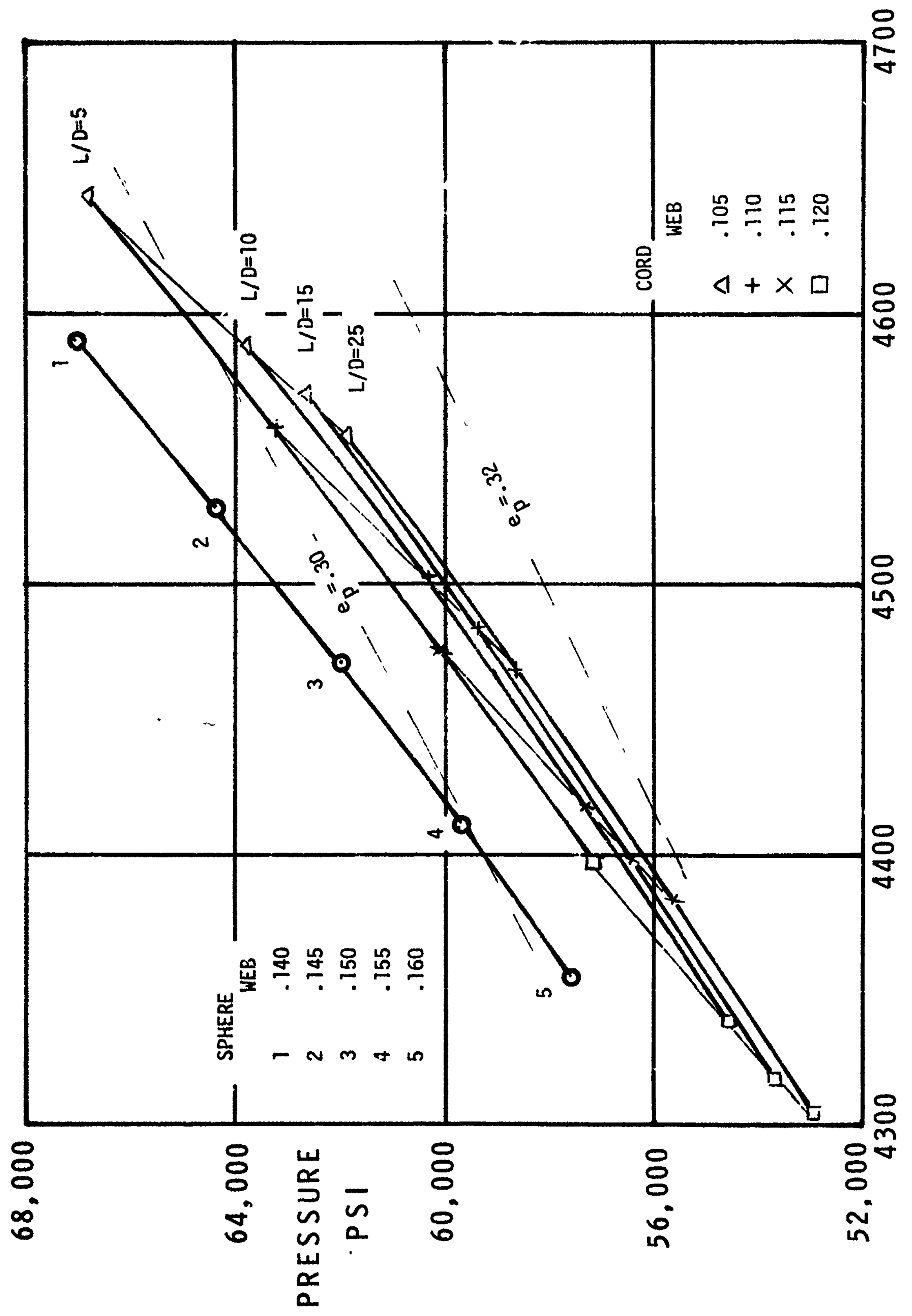

Figure 8. Peak Breech Pressure-Muzzle Velocity for Spherical and Cord Grains

the spheres is changed. Because of the degressive surface area function of spherical grains, the muzzle velocity developed by a gun using spherical propellant (web about .155 inches) at the "key" case maximum breech pressure is lower than the "key" case muzzle velocity by 470 f/s. The piezometric efficiency of the gun using spherical propellant is low, ranging from .29 to .32 for webs varying from .14 to .20 inches.

For cord propellant, the gun performance will vary both with propellant web and L/D ratio. For the cases illustrated the webs varied from .11 inches to .13 inches; and the L/D ratios varied from 5 through 25. From the curves, it will be noted that increases in L/D ratios will give an increase in piezometric efficiency, although the rate of increase of piezometric efficiency decreases with increase in L/D ratio. At the highest L/D ratio, the muzzle velocity developed in the gun using cord propellant, at the "key" case maximum breech pressure, is higher than if spherical is used, but lower (370 f/s) than the "key" case muzzle velocity. Over the range of webs considered, the piezometric efficiencies are higher than those for the spherical propellant (about .015).

The effect of the use of single perforated propellant on the performance of the gun is illustrated in Figure 9. Besides web and L/D ratio, D/D_p ratio influences the performance of the gun. In this case propellant web was varied from .060 to .064, L/D ratio was varied from 3 to 12, and D/D_p varied from 3 to 7. From the curves, it will be noted, as in the cord propellant, that increasing the L/D ratios will increase the piezometric efficiency; increasing the D/D_p ratio will decrease the piezometric efficiency of the gun. These results would indicate that a single-perforated propellant developing the highest piezometric efficiency would have a high L/D ratio and a low D/D_p ratio. Comparison of the most favorable configuration (highest L/D ratio and lowest D/D_p ratio) at the "key" case maximum breech pressure, indicates that the muzzle velocity from this grain configuration is about 60 f/s lower than the "key" case muzzle velocity. The piezometric efficiencies developed by the single-perforated propellant over the range of webs, L/D ratios, and D/D_p ratios considered is higher than for the cord propellant

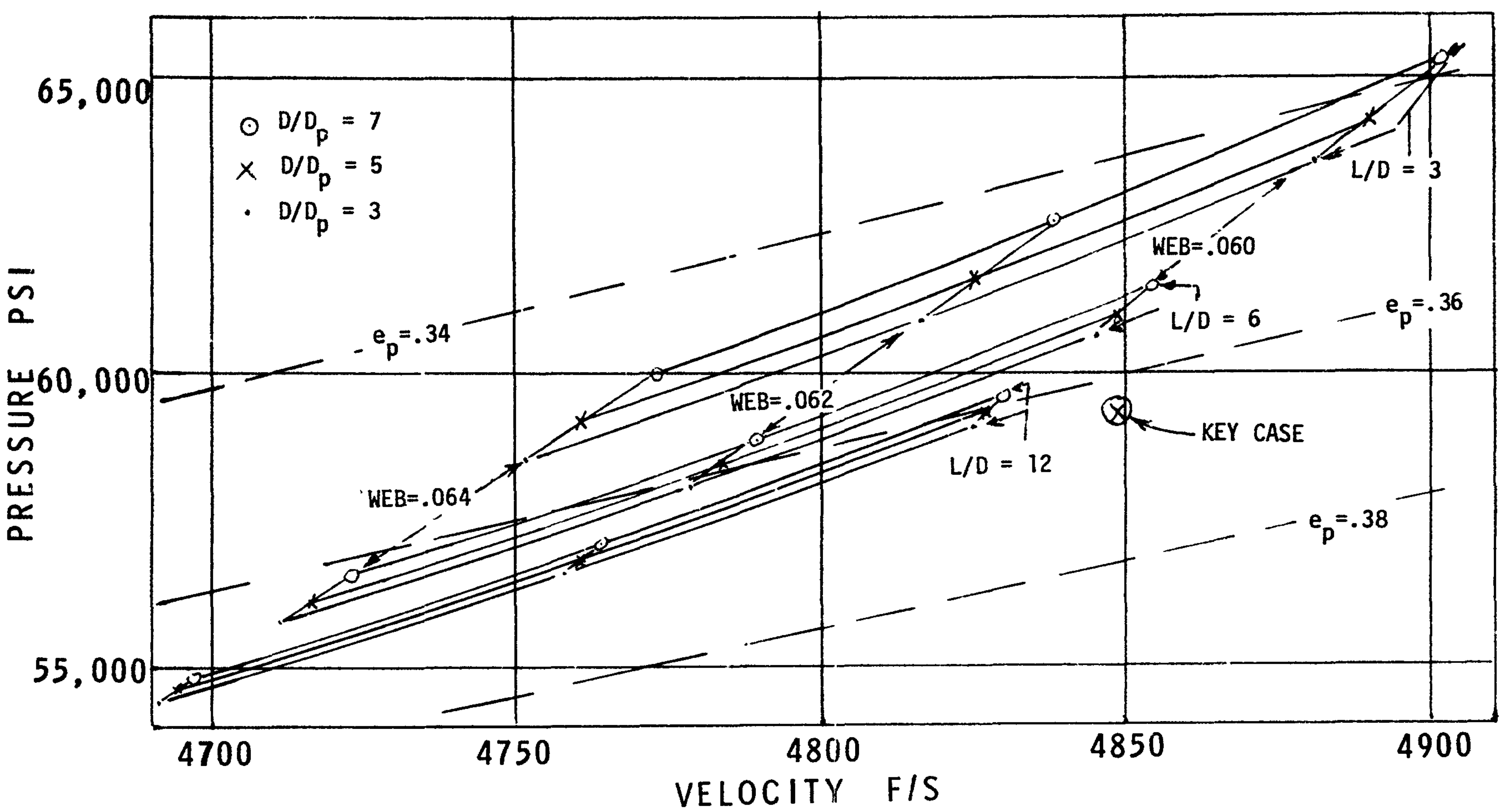

Figure 9. Peak Breech Pressure-Muzzle Velocity for Single Perforated Grains

(about .07). This increase in piezometric efficiency is due to the fact that the curve of propellant surface ratio to weight fraction of propellant burnt (Figure 7) is slightly regressive.

The effect of the use of seven-perforated propellant grains on the performance of the gun is illustrated in Figure 10. In this case three propellant webs were used; .045, .046, and .047. The L/D ratios were varied from 2 to 10 and the D/D_p ratios varied from 8 to 15. Like the cord and single-perforated propellant, increasing the L/D ratios increases the piezometric efficiency of the gun. Unlike the singe-perforated propellant, increasing the D/D_p ratios increases the piezometric efficiency. Examination of these curves indicates that there are a large number of grain configurations which will give higher muzzle velocity at the "key" case maximum breech pressure, than will the "key" case. For instance using a grain with a web of .045, and L/D ratio of 3.5 and a D/D_p ratio of 15 will, if fired in the gun, produce a muzzle velocity of 4960 f/s, an increase of 110 f/s over the "key" case velocity. With a web of .046, and L/D ratio of 10, and a D/D_p ratio of 15; the muzzle velocity of the "key" case can be attained at a maximum breech pressure of 55,000 psi, a reduction of 4,000 psi in the maximum breech pressure. The piezometric efficiencies developed by the seven-perforated propellant over the range of webs, L/D ratios, and D/D_p ratios considered is higher than for the single-perforated propellant (about .04). This increase in piezometric efficiency is due to the fact that the curve of propellant surface ratio to weight fraction of propellant burnt (Figure 7) is progressive.

The effect of the use of 19-perforated propellant grains on the performance of the gun is illustrated in Figure 11. The values of the propellant webs used in the simulated firings were .040, .042, and .044 inches. The L/D ratios for each of the webs was varied from 1.5 to 5 and the D/D_p ratios for each of the webs was varied from 10 to 25. Like the seven-perforated propellant, increasing the L/D ratio increases the piezometric efficiency; also increasing the D/D_p ratio increases the piezometric efficiency. Examination of these curves indicates that

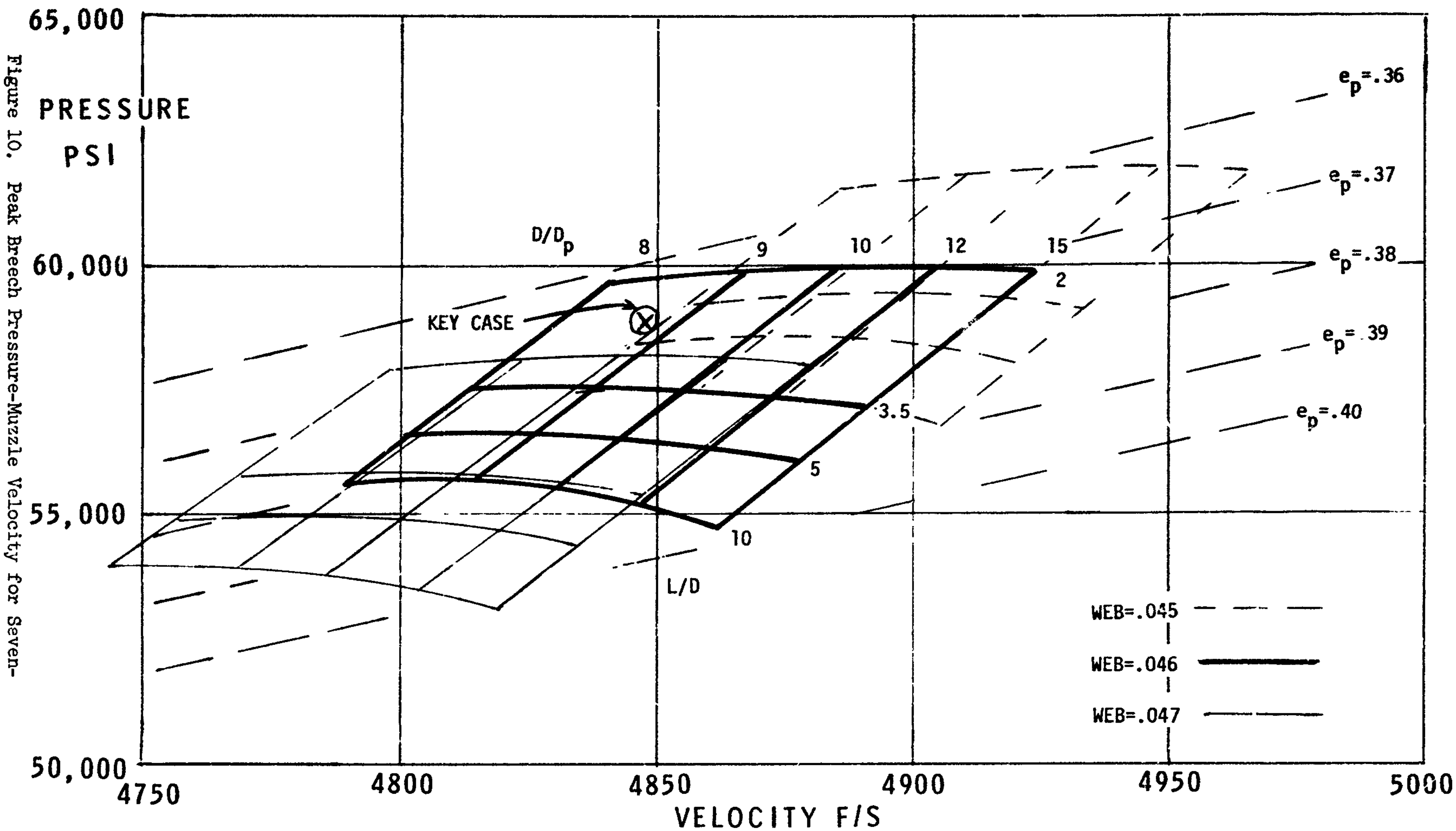

Figure 10. Peak Breech Pressure-Muzzle Velocity for Seven-Perforated Grains

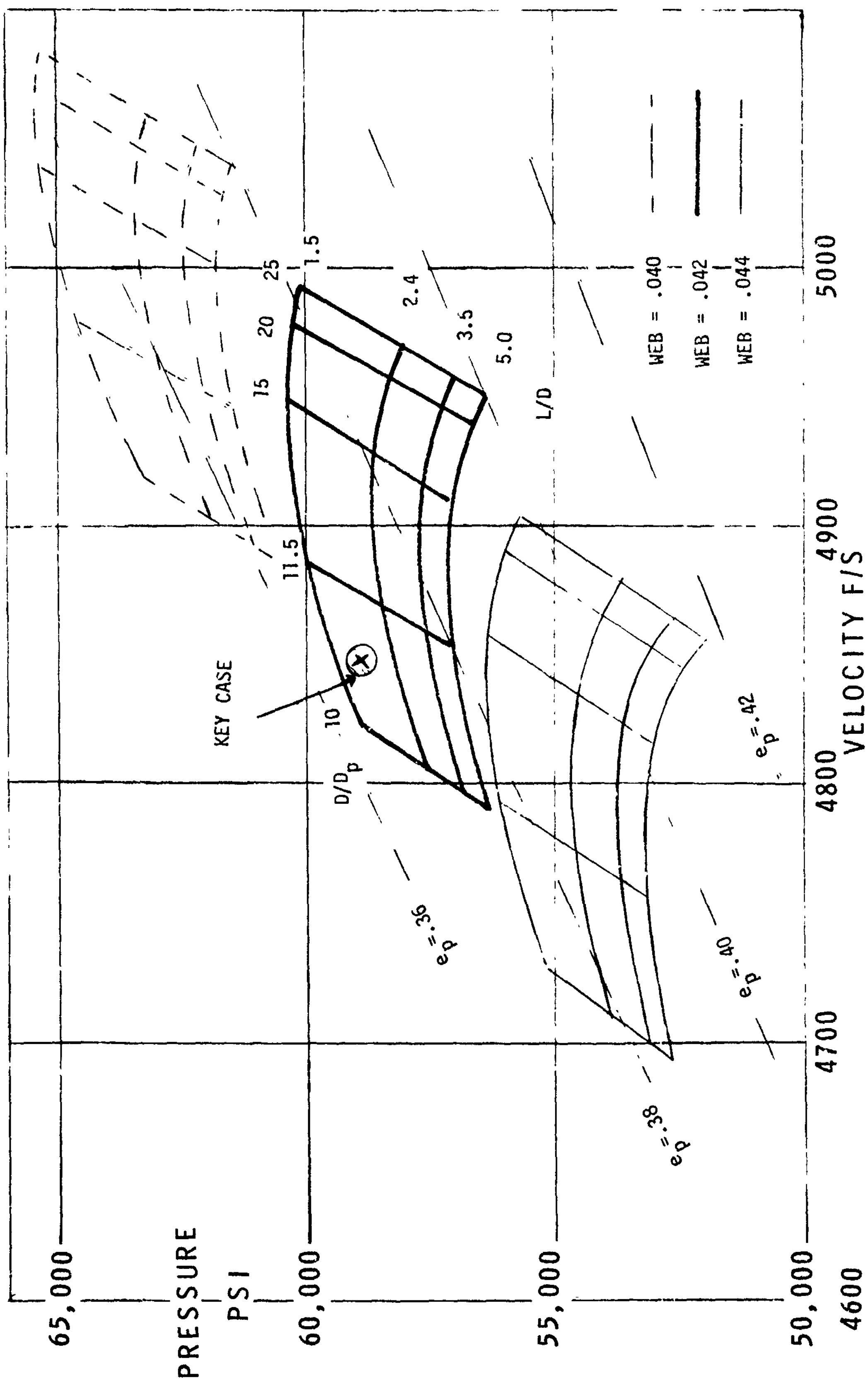

Figure 11. Peak Breech Pressure-Muzzle Velocity for Nineteen-Perforated Grains

there are a large number of grain configurations which will give higher muzzle velocities at the "key" case maximum breech pressure than will the "key" case. For instance, using a propellant grain with a web of .042 inch, a L/D ratio of about 2, and a D/D_p ratio of 25 will give a muzzle velocity of 4980 f/s, an increase of 120 f/s over that of the "key" case. The curves also indicate that one could obtain the "key" case velocity at a maximum breech pressure of 52,500 psi if one uses a web of .044 inches, an L/D ratio of 5, and a D/D_p ratio of 20. This gun simulation has a piezometric efficiency of .41, an increase of .05 over the piezometric efficiency of the "key" case.

IV. COMPARISON OF EXPERIMENT AND THEORY IN MULTI-PROPELLANT HARP GUN FIRINGS

A limited study was made of our ability to match multipropellant program computer results with experimental results from 5.1 inch and 16.7 inch gun firings in the high altitude research probe (HARP) program. The gun geometry and gun propellant characteristics of the 5.1 inch gun and 16.7 inch guns are listed in Table III. The data listed in Table III were also used as input to the computer program simulating the performance of these guns. While a large number of rounds were fired in the HARP program, we could find only 8 multi-propellant rounds which provided the complete muzzle velocity and maximum breech pressure data which our study required. Three of these records were for the 5.1 inch gun using triple propellants and five for the 16.7 inch gun using dual propellants.

There is no set procedure to be used in the matching of predicted and experimental results. Any procedure used will depend upon the nature of the experimental firings to be matched and the ingenuity of the experimenter. The procedure we used to match computer results with experimental firings was as follows:

a. All of the known variables characterizing the gun, propellants, and projectiles for each of the rounds were read into the program. Initial estimates of shot start pressure, frictional resistance pressure, and propellant erosion constant were read in and an interior ballistic trajectory for each round was computed. The values for these initial estimates were based on our matching experience with other guns. The results of using these initial estimates are illustrated in Table IV for the 5.1 inch gun (runs 1 thru 3) and Table V for the 16.7 inch gun (runs 1 thru 5). For the 5.1 inch gun, the predicted maximum breech pressure was 36 to 41% above the measured maximum breech pressure and the predicted muzzle velocity was 11 to 13% above the measured muzzle velocity. For the 16.7 inch gun, the predicted maximum breech pressure was 5 to 20% above the measured maximum breech pressure and the predicted muzzle velocity was 9 to 11% below the measured muzzle velocity.

Table III

Geometric and Propellant Characteristics of 5.1 inch and 16.7 inch HARP Guns

	5.1 in. Gun			16.7 in. Gun	
Gun Constants:					
Chamber Volume - in^3	1458.			32150.	
Projectile Travel - in.	333.			668.8	
Bore Area - in^2	20.43			219.04	
Estimated Constants:					
Shot Start Pressure - psi	11500.			500.	
Frictional Resistance Pressure - psi	1200.			100.	
Propellant Velocity Erosion Constant	.00001			.00005	
Propellant Constants:					
Propellant Igniter:					
Weight - lb.	.143			4.6	
Force - in-lb/lb.	1,152,000			1,152,000	
Specific Heat Ratio - γ	1.25			1.25	
Flame Temperature - ^oK	2000.			2000.	
Propellant:	1	2	3	1	2
Type:	M17	M17	M30	M2	M6
Force - in-lb/lb.	4,313,796	4,313,796	4,374,000	4,771,668	3,813,960
Specific Heat Ratio - γ	1.241	1.241	1.238	1.222	1.258
Flame Temperature - ^oK	2,974.	2,974.	3,040.	3,372.	2,583.
Covolume - $in^3/lb.$	28.92	28.92	29.26	29.67	30.59
Burning Rate Coefficient, β in/sec-psi$^\alpha$	.0008021	.0008021	.004819	.0002799	.0002562
Burning Rate Exponent α	.8501	.8501	.6697	.9976	.9359
Density - ρ lb/in^3	.0603	.0603	.0600	.0596	.0571
Web - in.	.052	.114	.078	.040	.194
Grain Outside Dia. - in.	.2883	.6420	.4750	.2000	.9640
Grain Dia. of Perforation - in.	.0279	.0630	.0530	.0075	.0520
Grain Length - in	.6782	1.545	1.150	.4450	2.075
Number of Perforations	7	7	7	7	7

Table IV. 5.1 Inch Gun

Matching Predicted Maximum Breech Pressure and Muzzle Velocity Data with Experimental Data

$\% \text{ of Exp} = \frac{\text{Pred. Value}}{\text{Exp. Value}} \times 100$

Exp. Rd. No.	Run No.	Pressure Shot Start psi	Pressure Frictional Res. psi	Propellant Erosion Constant	Maximum Breech Pressure psi	Maximum Breech Pressure % of Exp.	Muzzle Velocity f/s	Muzzle Velocity % of Exp.
1	1	1000	500	3×10^{-4}	80,806	135.8	5588	110.9
2	2				78,806	140.7	5562	112.6
3	3				83,160	139.5	5654	111.5
1	4	1100	500	3×10^{-4}	80,832	135.9	5589	111.0
2	5				78,857	140.8	5563	112.7
3	6				83,203	139.6	5655	111.5
1	7	1200	500	3×10^{-4}	80,832	135.9	5589	111.0
2	8				78,891	140.9	5564	112.7
3	9				83,244	139.7	5656	111.5
1	10	10,000	500	$.3 \times 10^{-4}$	58,358	98.1	5171	102.7
2	11				54,669	97.6	5108	103.4
3	12				57,651	96.7	5193	102.4
1	13	11,000	500	$.3 \times 10^{-4}$	59,878	100.6	5196	103.2
2	14				56,115	100.2	5135	104.0
3	15				59,123	99.2	5218	102.9
1	16	12,000	500	$.3 \times 10^{-4}$	61,427	103.2	5220	103.7
2	17				57,585	102.8	5160	104.5
3	18				60,622	101.7	5243	103.4
1	19	11,000	500	$.1 \times 10^{-4}$	57,157	96.1	5095	101.2
2	20				53,715	95.9	5024	101.7
3	21				56,567	[illegible]	5107	100.7
1	22	12,000	500	$.1 \times 10^{-4}$	58,757	98.9	5121	101.7
2	23				55.231	[illegible]	5052	102.3
3	24				58,109	97.5	5134	101.2
1	25	11,000	500	$.2 \times 10^{-4}$	58.492	98.3	5147	102.2
2	26				54.890	98.0	5081	102.9
3	27				57.818	97.0	5165	101.9
1	28	12.000	500	$.2 \times 10^{-4}$	60.065	100.9	5173	102.6
2	29				56,385	100.7	5108	103.4
3	30				59.340	99.6	5191	102.4
1	31	11.000	900	$.1 \times 10^{-4}$	57,940	97.4	5055	100.4
2	32				54 424	97 2	4985	100.9
3	33				57,313	96.2	5069	100.0
1	34	11 000	1000	$.1 \times 10^{-4}$	58.135	97.7	5046	100.2
2	35				54,603	97.5	4975	100.7
3	36				57,501	96.5	5020	99.8
1	37	11 000	1100	$.1 \times 10^{-4}$	58.331	98.0	5036	100.0
2	38				54.783	97.8	4965	100.5
3	39				57.690	96 8	5050	99.6
1	40	11 500	1200	$.1 \times 10^{-4}$	59.294	99.7	5039	100.1
2	41				55,692	99.4	4969	100.[illegible]
3	42				58,621	98.4	5054	99.7

Table V. 16.7 Inch Gun

Matching Predicted Maximum Breech Pressure and Muzzle Velocity Data with Experimental Data

$$\% \text{ of Exp} = \frac{\text{Prede Value}}{\text{Exp Value}} \times 100$$

Exp. Rd. No.	Run No.	Pressure Shot Start psi	Pressure Frictional Res. psi	Propellant Erosion Constant	Maximum Breech Pressure psi	Maximum Breech Pressure % of Exp.	Muzzle f/s	Velocity % of Exp.
1	1	4500	1000	0	23,784	119.5	2600	91.5
2	2				28,062	120.	2766	89.2
3	3				32,300	112.3	2952	89.6
4	4				37,806	110.7	3165	89.3
5	5				27,922	104.9	2817	89.1
1	6	4500	500	0	23,364	117.5	2666	93.9
2	7				27,661	178.2	2830	91.3
3	8				31,837	110.7	3011	91.4
4	9				37,359	109.4	3217	90.8
5	10				27,430	103.1	2886	91.2
1	11	4500	100	0	23,159	116.4	2728	96.1
2	12				27,447	117.4	2884	93.0
3	13				31,472	109.4	3061	93.0
4	14				37,091	108.6	3262	92.0
5	15				27,190	102.2	2944	93.1
1	16	500	100	0	18,797	94.5	2585	91.0
2	17				23,160	99.0	2754	88.8
3	18				27,287	94.8	2937	89.2
4	19				32,757	96.0	3146	88.8
5	20				22,701	85.3	2805	88.7
1	21	500	100	$.5 \times 10^{-4}$	20,399	102.5	2935	103.3
2	22				24,733	105.8	3112	100.4
3	23				28,737	99.9	3310	100.5
4	24				34,396	100.7	3534	99.7
5	25				24,383	91.6	3177	100.4
1	26	500	100	$1. \times 10^{-4}$	21,680	109.0	3229	113.7
2	27				26,050	111.4	3399	109.6
3	28				30,005	104.3	3597	109.2
4	29				35,757	104.7	3812	107.6
5	30				25,722	96.7	3481	110.0

It will be noted that no round to round variation was allowed in the estimates of shot start pressure, frictional resistance pressure, and propellant erosion constant for a particular gun.

b. Using the parametric variation feature of the program, the values of shot start pressure, projectile frictional resistance pressure, and propellant erosion constant were systematically varied until the differences between the computed values of maximum breech pressure and muzzle velocity for each of the rounds and the corresponding experimental values were at a minimum. This is illustrated in runs 4 to 42 in Table IV for the 5.1 inch gun and runs 6-30 in Table V for the 16.7 inch gun.

The procedure used in this systematic variation depended upon the gun. For the 5.1 inch gun both the predicted maximum breech pressure and the predicted muzzle velocity were greater than the corresponding experimental values. Increasing shot start pressure (runs 4 - 9) only increased the predicted values more. It was then decided to increase the shot start pressure by an order of magnitude and decrease the propellant erosion constant by an order of magnitude. This is illustrated in runs 10-18. This resulted in a decrease in maximum breech pressure and muzzle velocity such that predicted maximum breech pressures were very close to their corresponding values and predicted muzzle velocities were about 3 to 4% higher than their corresponding experimental values. From these results, it appeared that further reduction of the propellant erosion constant should be made, keeping the shot start values the same. This change, illustrated in runs 19 thru 30, resulted in further reduction in maximum breech pressure such that it was nearly equal,or less than the corresponding experimental results. Since a propellant erosion constant of $.1 \times 10^{-4}$ gave muzzle velocities close to the experimental results, this value was held constant for the remainder of the runs. For the final adjustment on pressure (runs 31 thru 42) frictional resistance pressure and shot start pressure were varied by small amounts until the difference between predicted maximum breech pressures and the corresponding experimental

Table VI

Comparison of Experiment and Theory in Multipropellant HARP Gun Firings

Gun	5.1 Inch			16.7 Inch				
Round Number	1	2	3	1	2	3	4	5
Projectile Wt. - lb.	24.92	24.92	24.92	726.5	759.5	750.9	757.7	702.
Propellant 1 Wt. lb.	9.24	6.60	6.80	91.3	100.8	169.2	119.3	100.8
Propellant 2 Wt. lb.	1.65	1.65	1.65	403.5	445.7	482.7	527.5	445.7
Propellant 3 Wt. lb.	22.11	24.75	25.50	-	-	-	-	-
Max. Breech Pressure(Exp) psi	59,500	56,000	59,600	19,891	23,386	28,762	34,138	26,611
Max. Breech Pressure(Comp) psi	59,294	55,692	58,621	20,399	24,733	28,737	34,396	24,384
Pressure Difference - psi	206.	- 308.	- 979.	508.	1387.	- 25.	258.	2227.
% Pressure Difference	.33	- .54	- 1.67	2.55	5.93	- .09	.75	8.37
Muzzle Vel. (Exp) f/s	5034.	4938.	5071.	2840.	3100.	3293.	3544.	3163.
Muzzle Vel. (Comp) f/s	5039.	4964.	5054.	2935.	3112.	3310.	3534.	3177.
Velocity Difference f/s	5.	31.	-17.	95.	12.	17.	-10.	14.
% Velocity Difference	.10	.62	.34	3.35	.38	.52	-.28	.44

results were less than 2%. The results of using the final estimates are shown in runs 40 thru 42.

For the 16.7 inch gun the initial estimates gave predicted maximum breech pressures which were too high and predicted muzzle velocities which were too low. Keeping the shot start pressure the same and decreasing the frictional resistance to 500 and then 100 psi (runs 6 thru 16) increased the predicted muzzle velocities by about 4% and decreased the predicted maximum breech pressure by about 3%. Since this change was not enough, we then decreased shot start pressure to 500 psi (runs 16 thru 20). This change brought the predicted maximum breech pressure below the corresponding experimental results and kept the predicted muzzle velocities about tne same. We then increased the propellant erosion constant from 0 to $.5 \times 10^{-4}$ (runs 21 thru 30). Of the two values in propellant erosion constant used, the value of $.5 \times 10^{-4}$ was considered to give predicted results which matched the experimental results considering that we had a round to round variation in agreement between theory and experiment.

The values of shot start pressure, projectile frictional resistance pressure, and propellant erosion constant obtained by the above matching procedure are listed for each of the guns in Table III. Table VI lists the values of projectile weights and propellant weights used in each of the rounds, together with the experimental results and computed results using the final estimated constants.

Comparison of experimental and computed results indicate that percentage error in maximum breech pressure for the 5.1 inch gun varied from .33% to 1.67%. In the 16.7 inch gun, this error varied from .09% to 8.37%. The large value of the pressure error in round 5 of the 16.7 inch gun is attributed to the use of a hollow projectile instead of a solid projectile as in the previous rounds. Such a change in projectile type would be expected to change the frictional resistance between projectile and bore and thus the maximum breech pressure observed. The percentage error in muzzle velocity varied from .10% to .62% in the 5.1 inch gun and .28% to 3.35% in the 16.7 inch gun.

V. DISCUSSION AND CONCLUSIONS

Of the four means of increasing gun muzzle velocity (under the constraints listed in the introduction) only varying propellant grain shape offers any hope of improvement. Varying propellant web alone, shifts maximum breech pressure-muzzle velocity points up and down a smooth curve such that one can not increase the muzzle velocity without increasing the maximum breech pressure.

Mixing a finer web propellant with a coarser web propellant (dual gran case) does not increase the piezometric efficiency of the gun. For any given maximum breech pressure one can obtain a higher muzzle velocity with a single web propellant than with any combination of fine and course webs, provided that one is able to locate or manufacture a propellant of the appropriate web. The only advantage of mixing different webs of the same propellant would be if one was unable to locate the appropriate propellant web.

Mixing two or three different propellants in which one varies the weight percentage of the differing propellants, and their webs (multipropellant case) also does not improve the piezometric efficiency of the gun over that obtained by using the appropriate web of the most energetic propellant. For instance, in place of a mixture of M1, M8, and M30 propellants, one can use a pure M8 propellant (the more energetic propellant) of an appropriate web, which would have a higher piezometric efficiency than the mixture. Again, the only justification of using multipropellant mixtures would be if the most energetic propellant in the appropriate web size were not available or if other factors, such as gun erosion, limited its use.

The use of a single propellant in which the shape is varied, offers great possibilities of improving the muzzle velocity of the 105mm M68 gun. In this investigation, spherical, cord, 1, 7, and 19-perforated propellant were tested. Of the five shapes tested only the propellants exhibiting surface area progressivity, namely 7 and 19-perforated propellant improve the piezometric efficiency of the gun over that of the "key" case. Of these two types of propellants, the 19-perforated propellant exhibits the greatest improvement in piezometric efficiency.

One problem which has not yet been discussed is the problem of propellant packing. The cartridge case of the M68 105mm gun which we used as a "key" case is packed nearly full of the .046 web 7-perforated propellant. For some of the propellant shapes used in this study, there arose the possibility that we might not be able to pack all the required propellant weight in the cartridge case. The alternate possibility is, particularily for the multigran propellant, that we might be able to pack more propellant in the case than it now holds, thus offering the possibility of increasing the velocity of the gun.

The only experimental investigation of the propellant packing problem has been reported by Clautice.[4] Some preliminary work has been done using the formulas in Clautice's report. It appears that for the 7-perforated grains, grains having low values of D/D_p ratio and high values of L/D ratio are difficult to fit into the cartridge case. For the 19-perforated grains the packing problem does not appear to be very much greater than for the 7-perforated grains. Only those grain dimension ratios which, in our opinion, will fit in the cartridge case, appear on the graphs. Because of the limited nature of Clautice's work, further experimental and theoretical work on the propellant packing problem will have to be done.

Any assessment of the ability of the computer program to predict multipropellant gun performance is complicated in the two HARP gun cases by a lack of knowledge of the experimental variability in measured maximum breech pressures and muzzle velocities. This is due primarily to lack of repeated firings in the program with all input variables (projectile weights, propellant weights, etc.) held constant. At the present time we can only say that we can match a group of multipropellant gun firings to within an error of 4% on muzzle velocity and 9% on maximum breech pressure. Future assessment of the program's prediction capability would require that we match one firing and then with the estimated variables (shot start pressure, etc.) held constant, predict future firings of the gun, varying propellant mixes and projectile weights.

REFERENCES

1. W. F. Jackson. Cannon Propellant Developments in the Post War Years. Bulletin of the 12th Meeting of JANAF, Vol. I, 1956, pp 135-157.

2. P. G. Baer. Multipropellant Gun Program - A Gun Interior Ballistic Simulator. To be published as a BRL Report.

3. P. G. Baer and J. M. Frankle. The Simulation of Interior Ballistic Performance of Guns by Digital Computer Program. BRL Report No. 1183, Dec 1962.

4. E. W. Clautice. A Study of the Loading of Cylindrical-Shaped Grains. BRL Memo Report No. 783, May 1954.

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13 ABSTRACT

The use of propellant mixtures in high velocity guns, as means of increasing projectile muzzle velocity, is compared with the use of a single propellant. The propellant mixtures vary in chemical composition, web, and burning rate. A theoretical study is made using the M68 105mm high velocity tank gun as a test case. Gun geometry, projectile weight, and propellant shape are not changed from that of the standard gun. Interior ballistic trajectories in the parametric study are computed using a multipropellant interior ballistic digital computer code. Graphical methods are used to determine the optimum propellant mixture needed to maximize muzzle velocity at a given allowable maximum gun breech pressure. The effect of propellant grain shape on the performance of a gun is considered in a separate study. Results from the interior ballistic computer model are also compared with experimental results from the firing of propellant mixtures in the 5-inch and 16-inch guns used to launch high altitude atmospheric probes. ( )

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