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THE REDUCTION OF MUZZLE PRESSURE WITHOUT THE REDUCTION OF MUZZLE VELOCITY IN A DAVIS GUN

William J. Lewandowski
Capt USAF

TECHNICAL REPORT NO. AFWL-TR-70-15

May 1970

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AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base
New Mexico

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FOREWORD

This research was performed under Project 5704.

Inclusive dates of research were June 1969 through August 1969. The report was submitted 22 January 1970 by the Air Force Weapons Laboratory Project Officer, Captain William J. Lewandowski (WLDM).

Information in this report is embargoed under the US Export Control Act of 1949, administered by the Department of Commerce. This report may be released by departments or agencies of the US Government to departments or agencies of foreign governments with which the United States has defense treaty commitments, subject to approval of AFWL (WLDM), Kirtland AFB, NM, 87117.

This technical report has been reviewed and is approved.

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ABSTRACT

(Distribution Limitation Statement No. 2)

This study devises a means of reducing the maximum pressure at the counterweight muzzle of a Davis Gun without reducing the muzzle velocity of the primary projectile. A new counterweight is designed, with constant area ducts placed longitudinally through the counterweight. A proper combination of duct lengths, duct cross-sectional area, frictional resistance, and the number of ducts, allows the right mass of propelling gas to flow through the counterweight, so that the pressure of the gas fore and aft of the counterweight never reaches the maximum allowable pressure at the muzzle, even when additional propellant is placed in the chamber to keep the primary projectile velocity constant.

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ILLUSTRATIONS

SYMBOLS

h_o	Stagnation enthalpy
h	Enthalpy
V	Velocity
g_c	Conversion factor
J	778.2 ft-lbf/Btu
$\dot{m}$	Mass flow
A	Area
ρ	Density
S,s	Entropy
Q	Heat
T	Temperature
P_1,P_2	Pressure
M	Mach Number
P_o	Stagnation pressure
F	Impulse function
k	Ratio of specific heats
P_B	Back pressure
P_E	Exit pressure
M_E	Mach number at duct exit

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SECTION I

INTRODUCTION

1. HISTORY

The United States Air Force is in the midst of a program to develop a recoilless launcher system based on Davis Gun principles. The Davis Gun is a recoilless system consisting of a smooth-bore tube with a combustion chamber midway in the length of the tube.* A propellant cartridge fired in this chamber provides the energy required to launch two projectiles of equal weight. These projectiles are placed in the tube, one on each side of the combustion chamber. When the propellant cartridge is ignited in the chamber, the resultant gases propel the projectiles in opposite directions down the tube. This creates the necessary time rate of change of momentum balance to produce the recoilless effect (figure 1).

The Davis Gun theory is not limited to projectiles of equal weights. If the weights are unequal, the velocities change to maintain the balance. In the Davis Gun considered in this study, one projectile is referred to as the counterweight, the other projectile is referred to as the primary projectile. The weight ratio of primary projectile to counterweight is 1:3. To allow both masses to exit the tube muzzles at the same time, the stroke of the counterweight is 1/3 the stroke of the primary projectile (figure 1).

The specific environment in which the launcher must operate, coupled with the purpose of the launcher (which is to accelerate the primary projectile to a specific muzzle velocity), dictates the design criteria of this version of the Davis Gun. One specific design requirement, dictated by the environment, is a maximum value of pressure at the muzzle from which the counterweight exits. In the present system, the maximum value of muzzle pressure, caused by the propelling gases behind the counterweight at the muzzle, is the design muzzle pressure limit of 250 psi.** The purpose of this study is to devise a means of

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*Davis patented this principle in 1917.

**Experimental data acquired at Goodyear Aerospace Corporation, Phoenix, Arizona, July 1968, and Kirtland AFB, New Mexico, June 1969.

reducing this maximum muzzle pressure without reducing the muzzle velocity of the primary projectile, which is 370 ft/sec. The proposed solution to the problem consists of designing a new counterweight which allows some of the propelling gas to escape through the weight as it is accelerated down the tube.

The solution of the problem is presented in the following form: first, a theoretical analysis of thermodynamic principles is made to show that if constant area ducts, opened at each end, are inserted into the counterweight, the gas flow through this counterweight reduces the maximum pressure at the muzzle; second, an experimental test series consisting of a number of launcher firings is made, employing the newly designed counterweight to verify the theoretical work.

2. DAVIS LAUNCHER SPECIFICATIONS

The launch tube consists of a 90-inch-long main barrel and three end extensions (10-inch, 20-inch, and 7-inch). The inside diameter is 2 inches throughout, with a 1-inch wall thickness for the main barrel and a 1/2-inch wall thickness for the end extensions. The main barrel and extensions are flanged at each end. A circular tongue-and-groove arrangement on the mating surfaces of the barrel and extensions ensures proper bore alignment and sealing (figure 2).

One cartridge assembly is screwed into the launch tube, perpendicular to the bore circumference, 34 inches from the closest muzzle. The outer covering of this cartridge assembly is a steel pipe, 1-inch inside diameter and 3 inches long. An Air Force ARD-446 bomb rack cartridge casing with igniter is placed in the cartridge assembly. The inside diameter of the steel pipe is machined so that the cartridge is always seated in the same position. A firing pin assembly is screwed down on the ARD-446 cartridge, the firing pin contacting the cartridge igniter. The cartridge is filled with the proper weight of propellant for a specific muzzle velocity, and is sealed with a plastic disc (figure 3).

The present counterweight is solid steel, center-drilled and threaded to accept a 1/2-inch diameter aluminum rod and female clevis attachment. This entire counterweight assembly weighs 12 pounds. The primary projectile is solid stainless steel, center-drilled and threaded to accept an aluminum rod and male clevis attachment. This clevis is mated in the tube and both projectiles are connected by a shear pin. This pin is designed to shear when the pressure in the chamber reaches 500 psi. Both projectiles then accelerate in opposite directions.

A steel detent (acceleration stop), bolted to the tube extends between the male and female portions of the clevis to keep the projectiles from moving before firing. This acceleration stop in no way interferes with projectile separation (figure 4).

$\text{MASS}_A = \text{MASS}_B$

$\text{VELOCITY}_A = \text{VELOCITY}_B$

DAVIS GUN

FIGURE 1A

$1/3\ \text{MASS}_B = \text{MASS}_A$

$\text{VELOCITY}_B = \sqrt{1/3}\ \text{VELOCITY}_A$

MODIFIED DAVIS GUN

FIGURE 1B

Figure 1. Davis and Modified Davis Gun

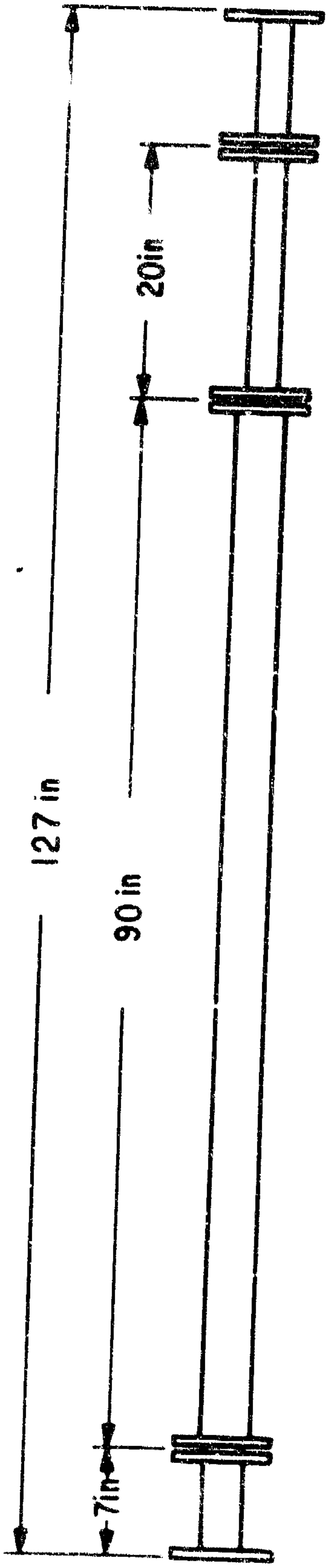


Figure 2. Length Dimensions of the USAF Davis Gun

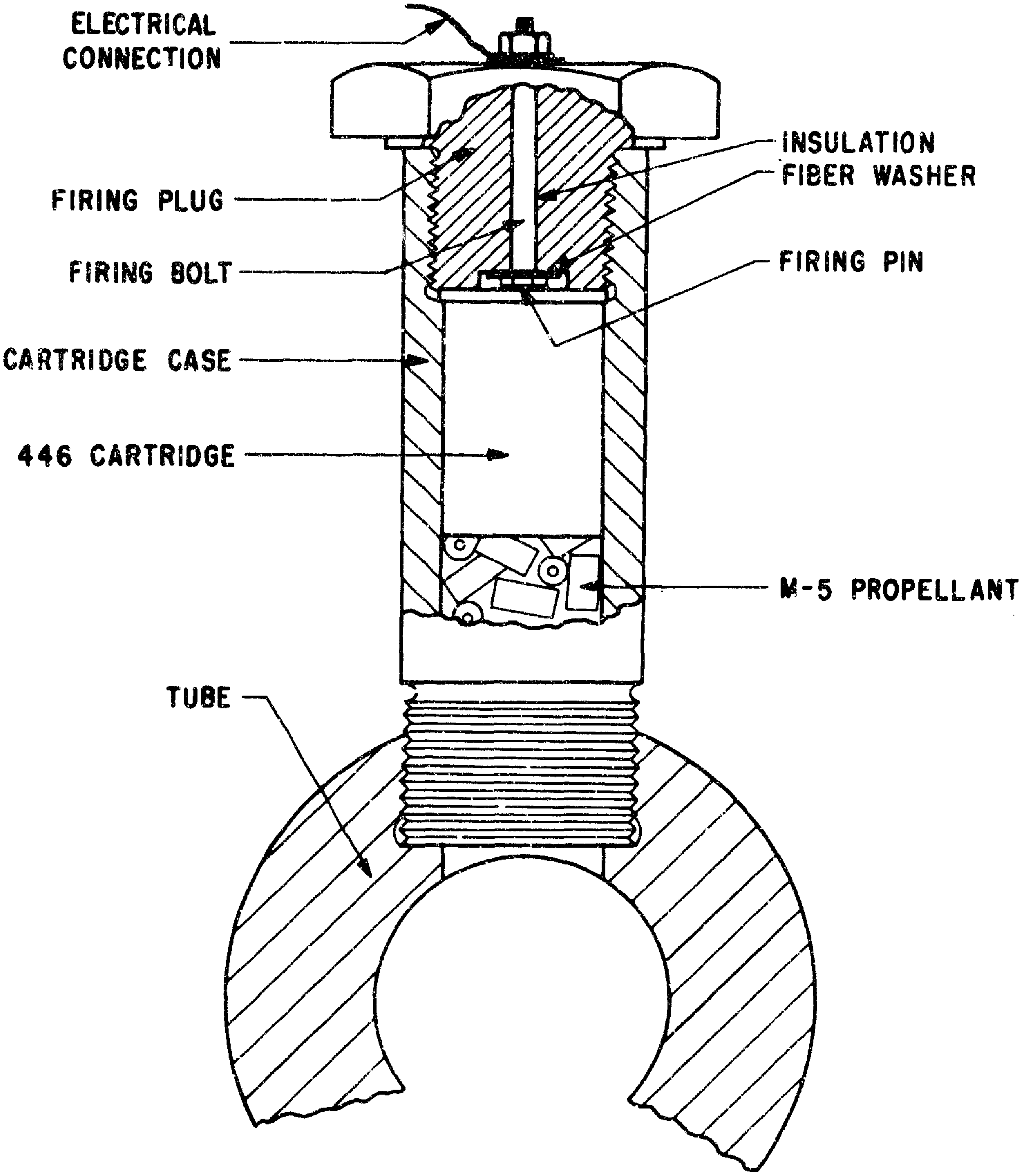


Figure 3. Cartridge Assembly

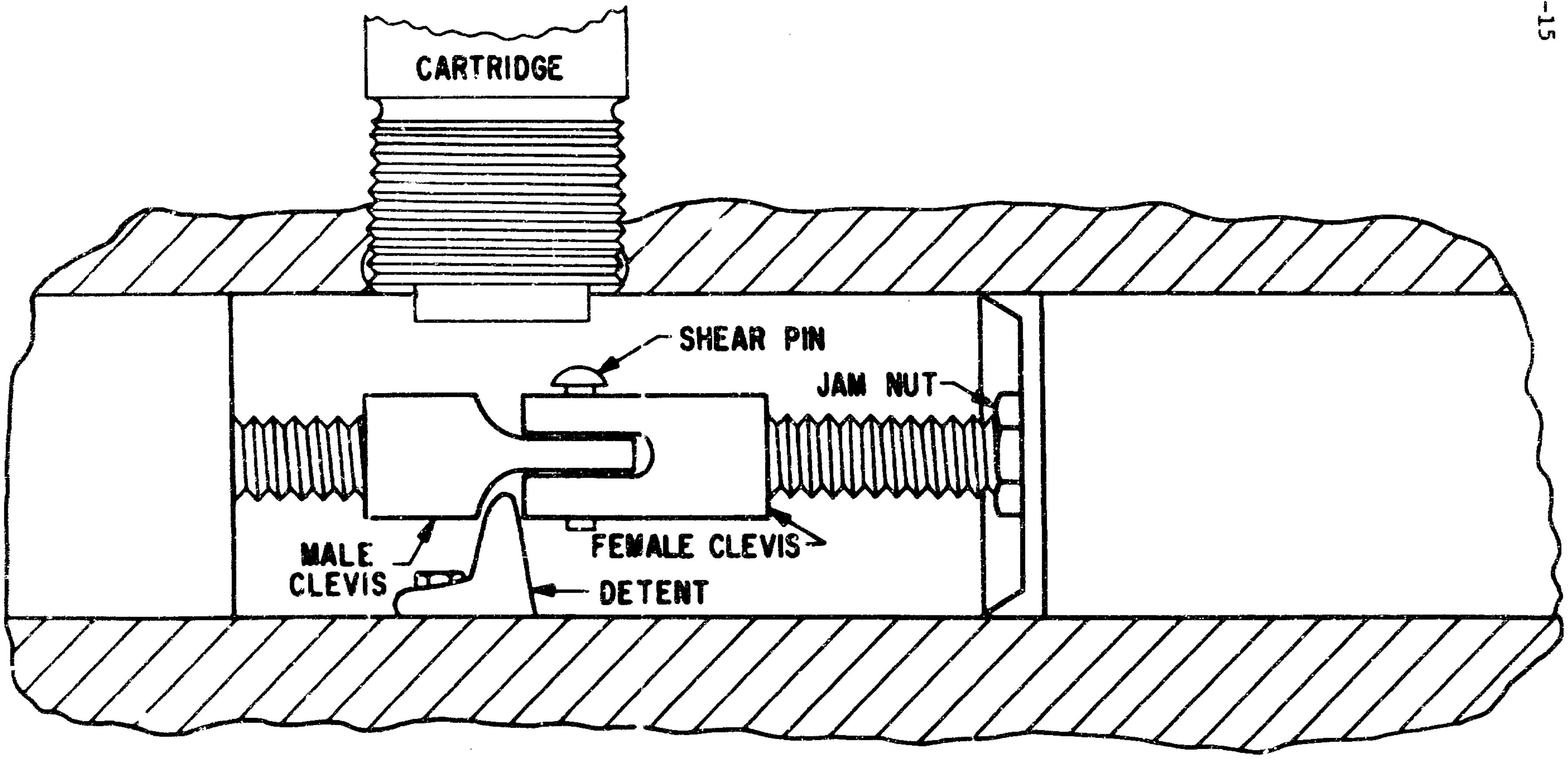


Figure 4. Propellant-Burning Chamber

SECTION II

THEORY

The proposed Davis Gun System with a counterweight containing constant area ducts resembles a recoilless rifle with the recoilless rifle nozzle analogous to the counterweight. In the basic interior ballistic theory of recoilless rifles developed by J. Corner and used by the United States Army in design of recoilless rifles (Ref. 1), it is assumed that the gas resulting from burning propellant originates in a large reservoir. This means that the conditions in the reservoir do not change appreciably in the time required for an element of gas to pass through the nozzle. The flow then is said to be quasi-steady; that is, it is assumed that the equations for steady flow apply at each instant of time and may be applied to the nonsteady flow in the recoilless rifle. Corner also assumes one-dimensional flow along the longitudinal axis of the nozzle. This means that the condition of the gas is a function only of this one coordinate, and is uniform across each normal cross section. Another assumption considered by Corner is adiabatic gas flow because of the short time from propellant ignition to projectile muzzle exit. The above assumptions are considered valid in the theoretical analysis of the Davis Gun System.

The energy equation for the ideal situation of adiabatic, one-dimensional, steady flow of a perfect gas is

$$h_o = h + V^2/2g_cJ \tag{1}$$

The continuity equation for constant area ducts is

$$\dot{m}/A = \rho V = \text{constant} = G \tag{2}$$

Equation (2) is solved for V. This expression for V is substituted into equation (1), the result is

$$h_o = h + G^2/2g_cJ\rho^2$$

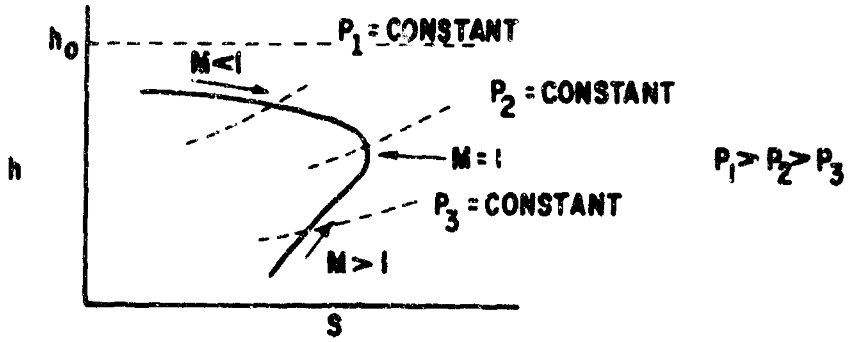
Since the cross sectional area of the ducts through the counterweight is small enough so that frictional effects cannot be neglected, the gas flow through the ducts is irreversible. From this fact, the Second Law of Thermodynamics gives

$$dS > \delta Q/T \qquad \text{(Irreversible)}$$
$$Q = 0 \qquad \text{(Adiabatic)}$$
$$dS > 0$$

The equation of state of the gas can be written in the form

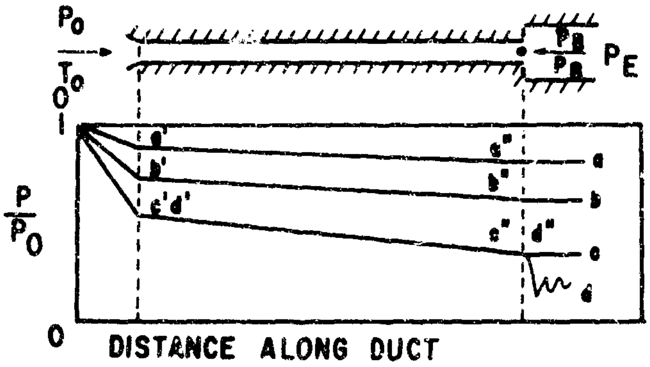
$$h = h(s,\rho)$$
$$s = s(P,\rho)$$

By taking the energy equation and the continuity equation, and the equation of state, adiabatic, one-dimensional, steady flow of an ideal gas through constant area ducts with friction is represented by a loci of states on an enthalpy-entropy diagram.



This loci of states is called a Fanno Line. From the equations above and basic thermodynamic definitions, such as Mach number, friction factor, ratios of important properties can be developed through algebraic manipulations and differentiation (Ref. 2). These ratios consist of P/P^*, V/V^*, T/T^*. ρ/ρ^*, P_o/P_o^*, F/F^*, as a function of the Mach number and the particular gas, where the * values occur at Mach 1. From these ratios, the top portion of the Fanno Line represents $M < 1$; the bottom portion shows $M > 1$. Both subsonic and supersonic flows have $M = 1$ as a limit. These ratios are solved for values of k and M, and placed in tables, such as the Fanno Line Tables in Keenan and Kaye, Gas Tables (Ref. 3). In the computer program analysis, values from these tables are used for $I = 1.2$.

In this particular Davis Gun System, where the combustion chamber is a reservoir (chamber pressure and temperature at stagnation), the gas entering the duct in the counterweight is subsonic. Thus the subsonic portion of the Fanno Line explains what happens to the gas as it flows down the duct; the pressure decreases as the Mach number increases. The Mach number of the gas at duct exit is controlled by the pressure just after the exit of the duct. If the duct entrance in the counterweight is assumed a frictionless converging nozzle, the following reference system is constructed:



If $P_0 = P_B$, there is no flow through the duct. As P_B decreases, the flow rate and the pressure drops in the nozzle increase until the maximum pressure drop and flow rate occur, when $M_E = 1$. Further reductions in P_B cannot produce further increases in flow rate, because M_E cannot become greater than 1. Thus the flow pattern within the duct for condition d is identical with that for condition c, and the flow is choked (Ref. 4).

In the analysis of Fanno Line Flow, a friction number, $4f\ L_{max}/D$, is developed corresponding to each Mach number, where

f = friction coefficient

D = diameter of the duct

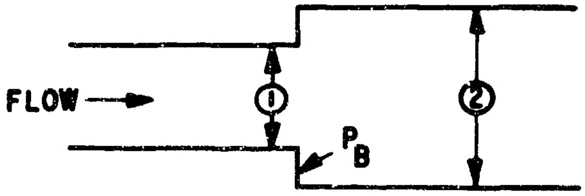
L_{max} = required length for the flow in the duct to reach M = 1

By knowing the friction number of the duct and $M_E = 1$ at duct exit, the conditions at duct exit are found by referring to the Fanno Line Tables, if the entrance conditions are known.

In the present Davis Gun System, the pressure in the chamber reaches a maximum of 1900 psi for a primary projectile muzzle velocity of 370 ft/sec in 3 milliseconds, 1/10 the total time from propellant ignition to projectile exit.

Thus, while the chamber pressure is 1900 psi, P_B is approximately ambient. From the Fanno Tables, a possible ratio of P_0/P_B for $M_E = 1$ is 10. P_B would have to increase to 200 psi before the flow becomes unchoked. Sometime during the counterweight travel, P_0 decreases enough, and P_B increases enough for $M_E < 1$, but for the computer analysis choked flow is assumed.

Because the muzzle pressure must never exceed 250 psi at anytime during the launching, there is not only interest in the pressure behind the counterweight, but also in front of the counterweight. A. R. Shouman and J. L. Massey (Ref. 4) developed compressible-gas equations, and verified these equations experimentally, assuming one-dimensional, adiabatic flow for abrupt area changes. These equations are applied to the gas flowing from the counterweight ducts to the bore area in front of the counterweight. If the reference system below is used,



P_1 is known, and $M_1 = 1$; therefore, M_2 can be found from the following quadratic equation:

$$M_2^2 = \frac{1 - 2KC^2 \pm [1 - 2(K + 1)\ C^2]^{1/2}}{2K^2C^2 - K + 1}$$

where

$$C = \frac{M_1 \left[1 + \left(\frac{K-1}{2}\right) M_1^2\right]^{1/2}}{1 + KM_1^2 + \frac{P_B}{P_1}\left(\frac{A_2}{A_1} - 1\right)}$$

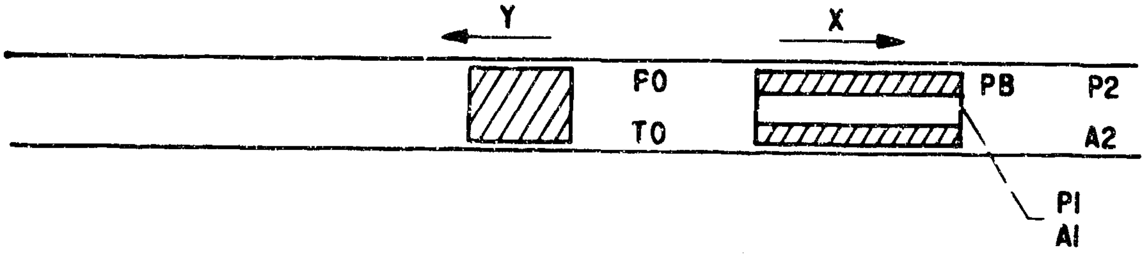
Once M_2 is known, P_2 can be determined from the following equation:

$$\frac{P_2}{P_1} = \frac{A_1 M_1}{A_2 M_2}\left[\frac{1 + \left(\frac{K-1}{2}\right) M_1^2}{1 + \left(\frac{K-1}{2}\right) M_2^2}\right]^{1/2}$$

As stated in the conclusions of Shouman and Massey's paper, the average pressure at the base of the abrupt area change cannot be determined analytically. It is assumed in this particular case that P_B is approximately equal to P_2, because of the large area ratio, A_2/A_1.

1. COMPUTER PROGRAM

The following is a reference system of symbols for the computer program.



Constants:

AY	Base area of primary projectile	3.14 in^2
AD	Cross section area of one duct	0.000045 ft^2
MY	Mass of primary projectile	0.124 slug
MX	Mass of counterweight	0.372 slug
K	Ratio of specific heats	1.22[1]
T	Time interval	0.001 sec
VCL	Initial chamber volume	15.7 in^3
R	Propellant gas constant	1932 ft-lbf/slug R[1]

Input Variables:

PC	Maximum chamber pressure	lbf/in^2
PO	Chamber pressure	lbf/in^2
AX	Base area of counterweight	in^2
E	PO/P1 for choked flow	
D	Number of ducts	
MASS	Initial mass of propellant gas	slug
C1	PB/P1	
TC	Maximum chamber temperature	R
TO	Chamber temperature	R
AC	A2/A1	

Calculated Values

YA	Acceleration of primary projectile	ft/sec^2
YD	Distance traveled by primary projectile	ft
YV	Velocity of primary projectile	ft/sec
XA	Acceleration of counterweight	ft/sec^2
XD	Distance traveled by counterweight	ft
XV	Velocity of counterweight	ft/sec
DMASS	Mass of gas exiting ducts	slug
MACH2	Mach number of gas in front of the counterweight	
P2	Pressure of gas in front of the counterweight	lbf/in^2

The computer program begins with an assumed maximum chamber pressure, PC, and ambient pressure, PB, in front of the projectile. It is assumed that the chamber pressure is constant over a millisecond, so that both the primary projectile and counterweight undergo a constant acceleration. Velocity and distance traveled are calculated over the time interval.

$YA = (AY \times PO)/MY$

$YD = .5 \times YA \times T^2 + YV \times T + YD$

$YV = (YA \times T) + YV$

$XA = (AX \times (PO - PB))/MX$

$XD = .5 \times XA \times T^2 + XV \times T + XD$

$XV = (XA \times T) + XV$

With the total distance traveled by both projectiles known, a new volume between the projectiles can be calculated.

$VOL = 12 \times (XD + YD) \times AY + VOL$

Starting with the continuity equation, the following rearrangements are made:

$$\frac{\Delta m}{\Delta T} = \rho VA = \frac{P}{RT} VA = \frac{PVA}{\sqrt{KRT}} \sqrt{\frac{K}{R}} \sqrt{\frac{T_o}{T}} \frac{1}{\sqrt{T_o}} = \sqrt{\frac{K}{R}} \frac{P}{\sqrt{T_o}} M \sqrt{1 + \frac{K-1}{2} M^2}$$

If choked flow is assumed, the continuity equation is

$$DMASS = \sqrt{\frac{K}{R}} \sqrt{1 + \frac{K-1}{2}} \frac{P1 \times AD \times T \times D}{\sqrt{T_o}}$$

The following relationship is known,

$$P1 = \frac{PO}{E}$$

and substituting it into the DMASS equation, the continuity equation becomes

$$DMASS = \sqrt{\frac{K}{R}}\sqrt{1 + \frac{K-1}{2}}\,\frac{PO \times AD \times T \times D}{E \times \sqrt{TO}}$$

Assuming the relationship between TO and PO is isentropic in the chamber, the following equation results:

$$DMASS = \sqrt{\frac{K}{R}}\sqrt{1 + \frac{K-1}{2}}\,\frac{AD \times T \times D \times PC^{\frac{K-1}{2K}}}{E \times \sqrt{TC}}\,(PO)^{\frac{K+1}{2K}}$$

where TC is the initial temperature in the chamber.

The last DMASS equation calculates the mass of gas escaping through the ducts over the time interval. With both the new chamber volume, and the mass of the gas remaining in the chamber calculated, and the isentropic relationship between TO and PO, a new PO is calculated for the next time interval by the following equation:

$$PO = \left[12\,\frac{R \times MASS \times TC}{VOL \times PC^{(K-1)/K}}\right]^{K} \qquad (1)$$

Using the equations developed by Shouman and Massey, and assuming PB/P1 = 0.75, the Mach number of the gas in front of the projectile, MACH2, and pressure, P2, can be calculated for the interval. A new time interval then begins, assuming the new PO calculated in equation (1).

2. COMPUTER ANALYSIS

In reviewing the input variables of the computer program, some input variables are not independent, but depend on another input variable. Actually, three input variables exist. With C1 = PB/P1 = 0.75, and the same mass of propellant, MASS = 0.000684 slug, to be used for the initial analysis, only the maximum chamber pressure, PO, the number of ducts, D, and the ratio, E = PO/P1, are variables. If PC is assumed, TC is known. If D is assumed, AX and AC = A2/A1 are fixed. E is a function of $4f\,L_{max}/D$ of the duct, the true variable is f, which is a function of the material from which the duct is made. The initial analysis shows the basic relation among these three variables.

Since in the present system a maximum chamber pressure of 1900 psi produces the primary projectile velocity of 370 ft/sec and the maximum muzzle pressure of 250 psi, 1900 psi is assumed as the maximum chamber pressure. E = 5.25, which corresponds to f = 0.02, is assumed, and the number of ducts is varied. In the second series, D = 3 is assumed, and f is varied. The results of these computer runs are shown in figures 5 and 6.

From this initial investigation, the following observations are made:

a. The maximum chamber pressure must be increased to obtain a primary projectile muzzle velocity of 370 ft/sec.

b. The maximum pressure in front of the counterweight decreases as the friction coefficient increases and as the number of ducts decreases.

c. In the present system, the projectiles exit in approximately 30 milliseconds from propellant ignition, and it takes the primary projectile 16 milliseconds to reach the maximum velocity in this new system, according to the computer. If this is the case, there is no pressure behind the counterweight at muzzle exit.

From the initial computer investigation, it becomes apparent that a maximum chamber pressure must be found that causes a muzzle velocity of 370 ft/sec. In the second investigation, D = 6, E = 5.25, and PO is increased until the primary projectile muzzle velocity is greater than 370 ft/sec.

Maximum chamber pressure (psi)	Primary muzzle velocity (ft/sec)
2200	315
2600	359
2800	382

The question now becomes--What is the maximum pressure in front of the counterweight when the chamber pressure is 2800 psi? From the initial computer investigation, the maximum pressure in front of the counterweight decreases as the number of ducts decreases; therefore, only two ducts are used in the following computer analysis. The coefficient of friction is varied to discover the particular coefficients which keep the maximum pressure in front of the counterweight below 250 psi. This computer analysis is presented in figures 7 and 8.

It appears that the coefficient of friction must be greater than 0.07 for the maximum pressure in front of the counterweight to be less than 250 psi.

In summary, a counterweight with two ducts, and at least a friction coefficient of 0.07 (E = 8.75), should reduce the maximum muzzle pressure below 250 psi, when enough propellant is added to obtain a maximum chamber pressure of 2800 psi. This should accelerate the primary projectile to at least a muzzle velocity of 370 ft/sec.

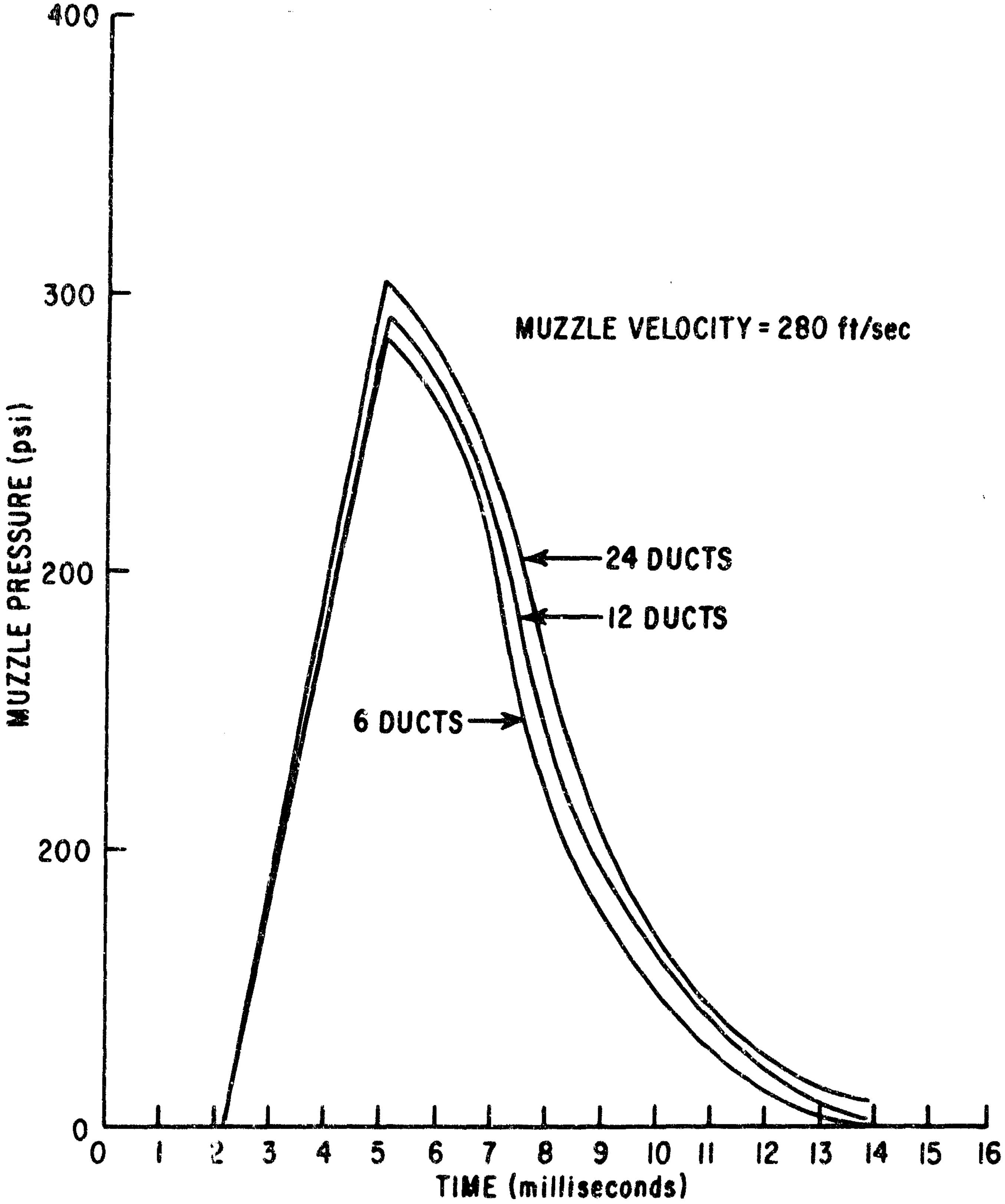


Figure 5. Effect of Duct Variation on Muzzle Pressure

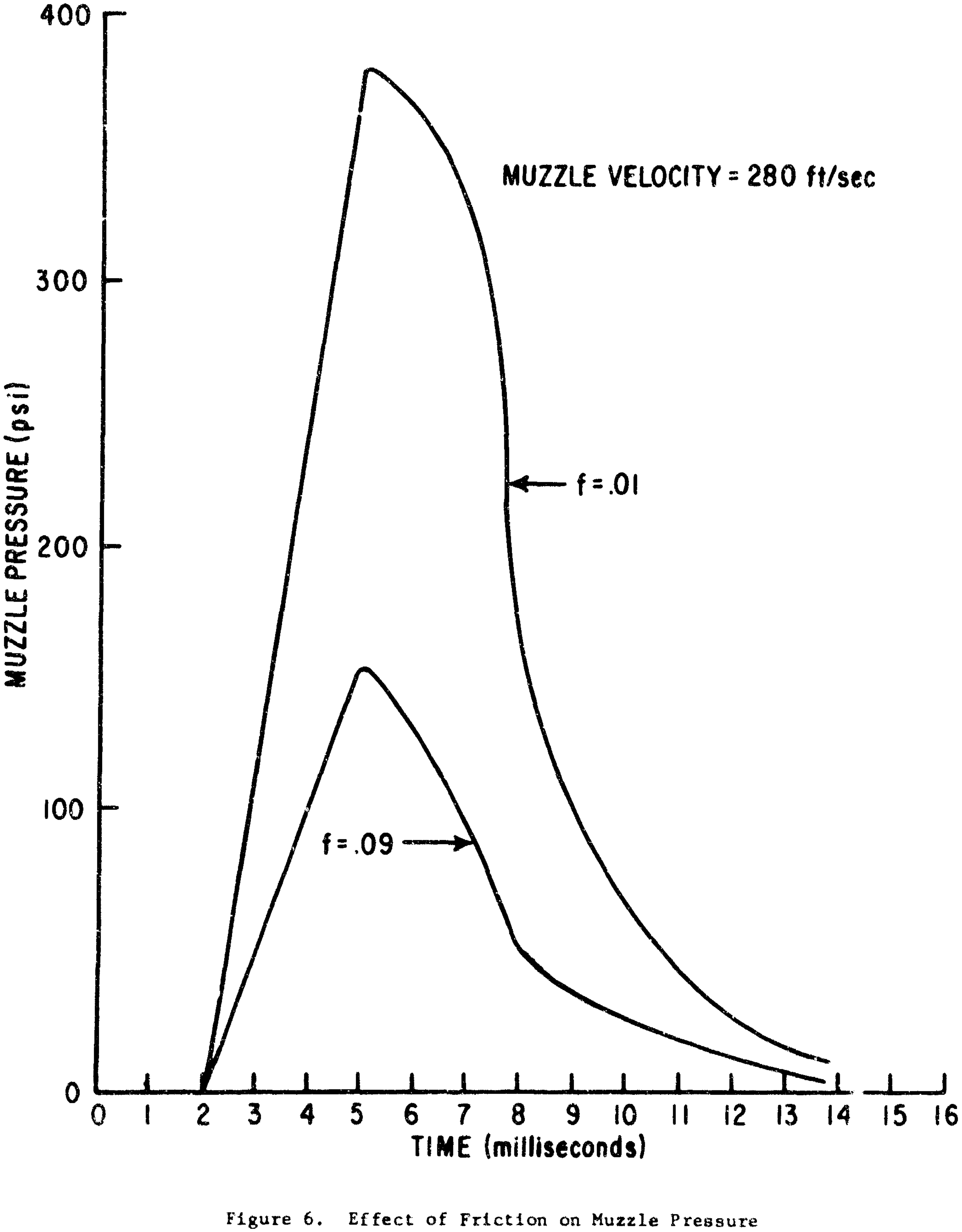


Figure 6. Effect of Friction on Muzzle Pressure

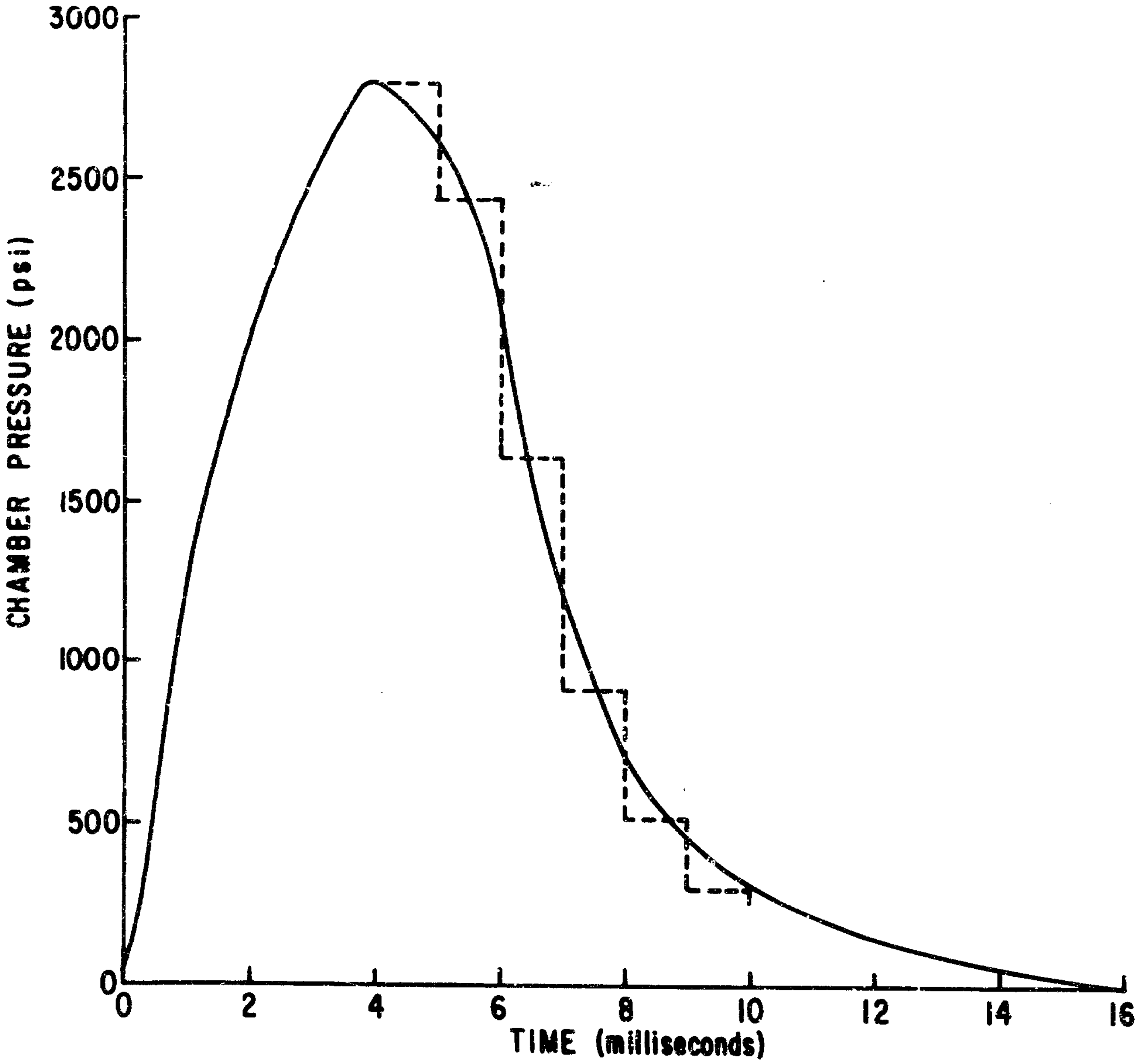


Figure 7. Predicted Chamber Pressure Curve for 370 ft/sec Primary Projectile Muzzle Velocity

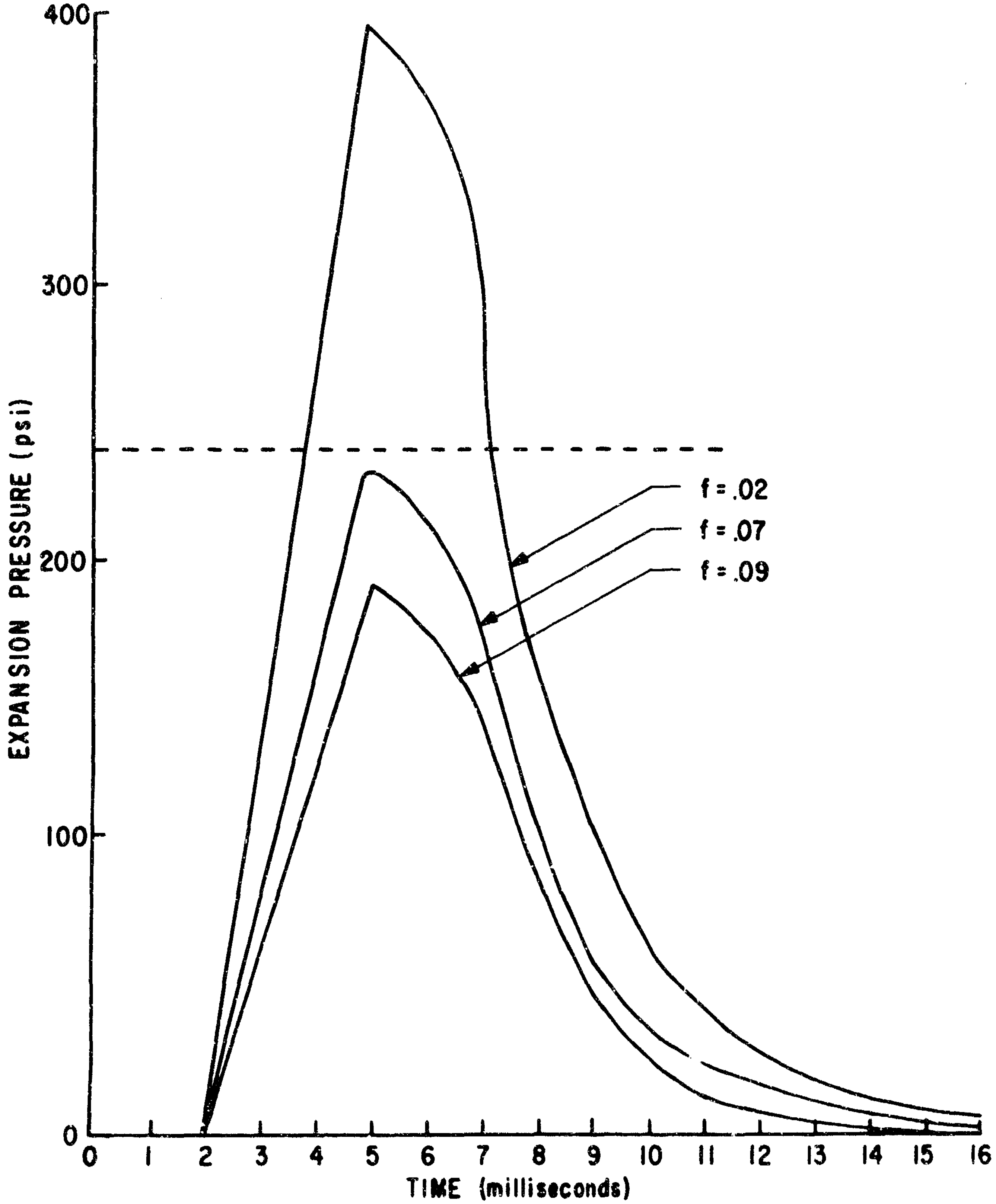


Figure 8. Friction Coefficient Comparison for PC = 2800 psi

SECTION III

EXPERIMENTATION

The purpose of the experimentation is to actually solve the problem of maximum muzzle pressure by using the theory and the computer analysis as guidelines.

1. TEST FACILITY AND INSTRUMENTATION

The test firings for the study were performed in an Air Force explosive-test facility at Kirtland Air Force Base, New Mexico. In the facility, the launch tube is suspended approximately 3 feet above the floor by two chains from a support structure (figure 9). When fired from the launcher, the projectiles slam into catchers approximately 8 feet from the muzzles. These catchers are old bomb nose-sections strapped to a trailer and weighted with sandbags. The catchers consist of aluminum honeycomb, and lead and steel plates. This system enables the same set of projectiles to be used throughout the test series (figure 10).

The necessary data recorded for each firing consist of the primary projectile muzzle velocity, and time histories of the chamber pressure and counterweight muzzle pressure. The primary projectile muzzle velocity is obtained near the muzzle by recording the time it takes the projectile to travel 1 foot. This is done by attaching to the end flange a rigid plastic support which holds two pieces fo chalk in the path of the projectile. The first piece of chalk is placed 4 inches from the muzzle. The second piece is placed 1 foot from the first. A stripe of current-carrying paint is applied lengthwise down and across one base of each piece of chalk. While in the plastic support, each piece of chalk is connected in a separate electrical circuit with a battery and time counter. When the projectile breaks the second chalk piece, after 1 foot of travel, the voltage drop stops the counter, and the time for 1 foot of projectile travel is recorded (figure 11).

The chamber pressure and counterweight muzzle pressure are sensed by piezoelectric crystal transducers, and are transmitted to a recorder which traces a pressure magnitude versus time graph. Both transducers are placed in the wall of the launch tube with the muzzle transducer placed 4 inches from the muzzle (figures 12 and 13). Both transducer systems are calibrated by a hydroelectric pump.

2. COUNTERWEIGHT DESIGN

The new counterweight is designed to obtain the largest value of $4f\ L_{max}/D$ with the materials available, and within the practical limits of the launcher and instrumentation. The total stroke of the counterweight is 34 inches, and the placement of the muzzle pressure transducer is 30 inches from the beginning of the stroke. The counterweight is 20 inches long, so that the pressure of the escaping gas can be sensed by the muzzle transducer before the counterweight passes the transducer (figure 14). After the test series, a graphical integration of the chamber pressure versus time trace is performed to show the relative position of the counterweight with respect to the transducer at the time when the muzzle pressure is first recorded. The smallest inside diameter tubes available are 3/32 inch with an outside diameter of 3/16 inch. The counterweight is constructed with 48 of these tubes as constant area ducts. This is done by machining two end caps to accept these tubes, and by covering the tubes with a steel cylinder, 2 inches O.D. The steel cylinder that covers the tube mates with the caps in such a way that the stainless steel tubes loosely fit in the end caps so that on projectile impact the tubes will not buckle. The rear end cap of the counterweight is center drilled to accept the female clevis attachment This entire assembly weighed 12 pounds after lead had been added between the tubes (figure 15).

3. ACTUAL TESTS

The first step in testing is to observe the effect of the number of ducts on muzzle pressure and muzzle velocity, keeping the other parameters as they are in the present system. The number of ducts is varied by placing 3/32-inch shaft diameter rivits, 1/4-inch long, in the duct entrances. Tests at 48 ducts, 36 ducts, 24 ducts, 12 ducts, 6 ducts, and 3 ducts are performed. The results are presented in figure 16, and in the following table form:

Ducts	Maximum muzzle pressure (psi)	Maximum chamber pressure (psi)	Muzzle velocity (ft/sec)
48	Not measurable	666	86
	Not measurable	587	67
36	53	1066	149
24	110	1410	256

Ducts	Maximum muzzle pressure (psi)	Maximum chamber pressure (psi)	Muzzle velocity (ft/sec)
12	181	1546	294
6	205	1786	340
	203	1760	341
3	229	1866	348

From these results, both the muzzle velocity and muzzle pressure increase as the number of ducts decrease, but nowhere does the muzzle velocity equal 370 ft/sec.

To decrease the muzzle pressure, the effective diameter of the ducts must be reduced. The reduction increases the Fanno friction number, $4f\ L_{max}/D$, and hence, should reduce the muzzle pressure. The effective diameter reduction is mechanically done by bending in half a 36-inch long, 1/8-inch diameter welding rod, and placing each end into a duct. The loop formed behind the counterweight by the bent welding rod catches the acceleration stop (detent). As the counterweight moves down the tube away from the acceleration stop, the welding rod is being pulled from the ducts. The rod is long enough, so that when the counterweight reaches the muzzle pressure transducer, the welding rod is still in the ducts. Two tests are performed with this new modification, one with six ducts, three bent rods; the other with two ducts, one bent rod. These results follow:

Ducts	Maximum muzzle pressure (psi)	Maximum chamber pressure (psi)	Muzzle velocity (ft/sec)
6MOD	160	1760	346
2MOD	181	1786	357

In these tests a considerable drop in muzzle pressure is realized, but with the muzzle velocity and maximum chamber pressure remaining constant. It appears that the efficiency of propellant burning is not affected by the difference of six to two ducts with the modification.

The final step in the solution is to raise the muzzle velocity to at least 370 ft/sec, and still maintain less than 250 psi muzzle pressure. To raise the muzzle velocity, more propellant is added to the cartridge. With two ducts modified, 11 grams are burned; with six ducts modified, 12 grams are burned. The results follow:

Propellant (gm)	Ducts	Maximum muzzle pressure (psi)	Maximum chamber pressure (psi)	Muzzle velocity (ft/sec)
11	2MOD	165	2266	380
		154	2260	377
12	6MOD	200	---	388

On the last test, the chamber pressure system did not record. By use of the modified duct system and propellant addition, the muzzle pressure is decreased without decreasing muzzle velocity.

An analysis of the information gathered during the tests and a comparison with the computer analysis are made to decide if the results are consistent before recommendations and conclusions are made about the system.

The muzzle and chamber pressure versus time traces are presented for the test in which the modified counterweight with two ducts and 11 grams of propellant are used. A graphical integration of the chamber pressure versus time trace is performed to obtain the position of the counterweight when

a. The muzzle pressure is first measured,

b. The muzzle pressure is a maximum,

c. The transducer is covered by the projectile, and

d. The muzzle transducer begins to measure the pressure behind the counterweight.

The mathematics of the graphical integration is in Appendix II; the results are presented in figures 19 and 20 along with experimental pressure time traces (figures 17 and 19).

In comparing the distance-time graph, and the muzzle and chamber pressure-time trace, one observes

a. From the muzzle pressure-time trace, the maximum muzzle pressure is measured at 0.009 second after propellant ignition. From the distance-time graph, while this maximum muzzle pressure is recorded, the counterweight has moved 6 inches; therefore, the maximum muzzle pressure is front of the counterweight.

b. From the distance-time trace, the muzzle transducer is covered by the counterweight from 0.013 second to 0.025 second. From the muzzle pressure-time trace during this interval, the muzzle pressure remains almost constant.

c. From the distance-time trace, the muzzle transducer begins to measure the pressure behind the counterweight at 0.025 second. From the muzzle pressure-time trace, this is about the time when the slope of the muzzle pressure curve changes.

The second part of the investigation of the actual tests is a comparison of the computer analysis with the actual tests. In the first test series, where the launcher was fired to observe the effect of the number of ducts on muzzle pressure and velocity, no comparison is made because the tests actually measured the efficiency of burning of the propellant in different initial volumes; the computer program did not consider propellant burning. The different initial volumes are caused by a different number of ducts. In the next series of tests, reducing the effective diameter of the duct increased the Fanno friction number, $4f\ L_{max}/D$, and reduced the muzzle pressure. This principle is dictated by the theory developed in Section II.

In the next series of tests, adding propellant to obtain a higher velocity produced the actual solution. With two ducts modified and 11 grams of propellant, a maximum chamber pressure of 2200 psi produced a primary velocity greater than 370 ft/sec and a muzzle pressure less than 250 psi. In the computer analysis, the predicted solution would be a maximum chamber pressure of 2800 psi, a muzzle pressure less than 250 psi, and a primary velocity greater than 370 ft/sec, and a friction coefficient of 0.07. To explain why this occurs, another computer series is made with the maximum chamber pressure of 2200 psi and 11 grams of propellant. The results of this computer analysis and the actual results are compared on the same graphs (figures 21 and 22).

The computer program shows the sensitivity of the design variables in relation with other variables and the system. The computer program does not predict exactly the actual primary projectile muzzle velocity, and pressure curves. It can be conjectured that one reason for this discrepancy is the assumption in the computer program that the flow through the duct is always choked. In the choked conditions, $M = 1$ at duct exit and the maximum mass flow through the ducts occurs for the particular changing chamber conditions. As it was mentioned in Section II, when the pressure in front of the counterweight increases enough, and the chamber pressure decreases enough, $M < 1$, and the mass flow is not maximum. At any particular time when $M < 1$, the actual chamber pressure is greater than predicted because less mass escapes from the chamber than predicted by the computer.

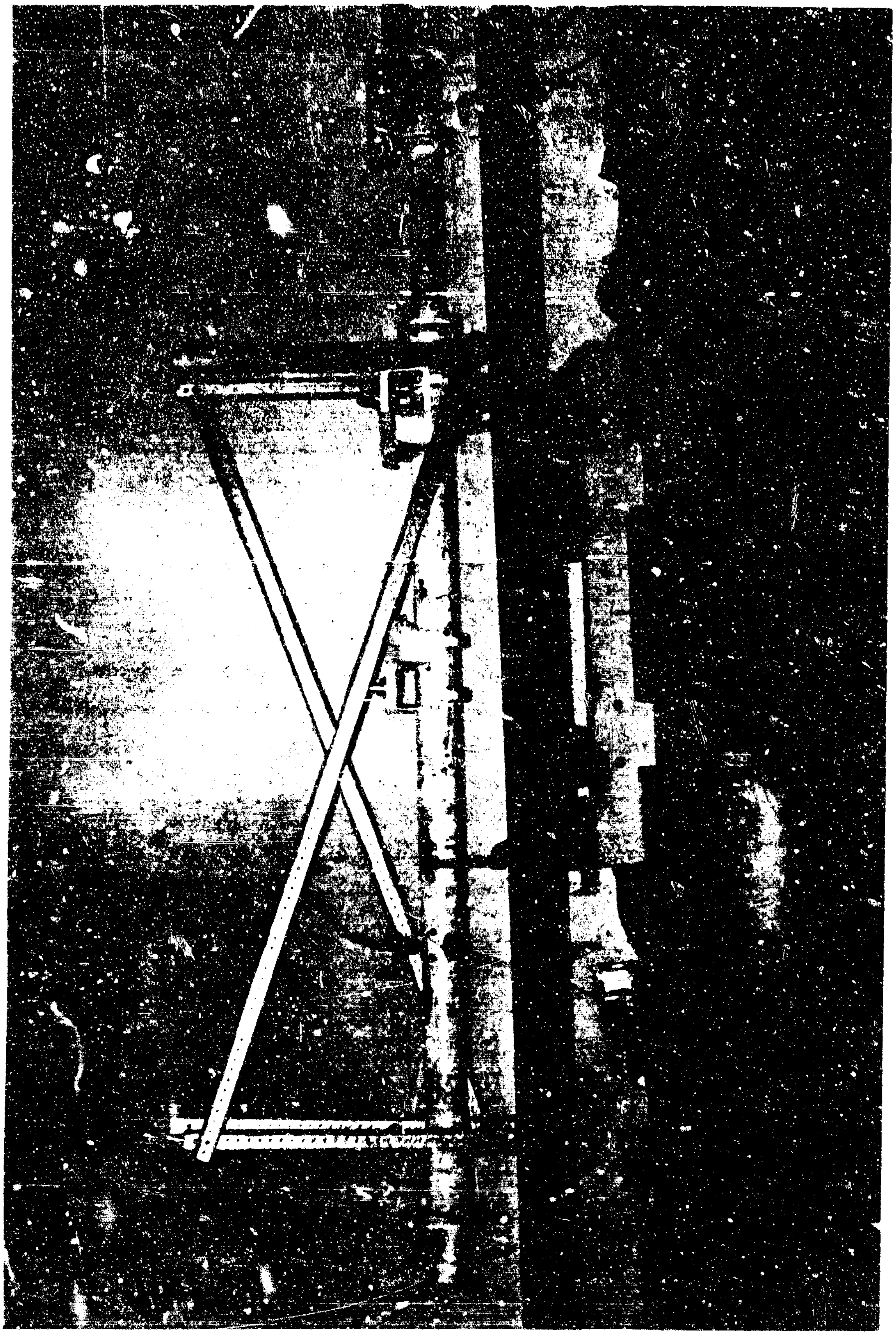


Figure 9. Davis Gun and Support Structure

Figure 10. Projectile Catcher

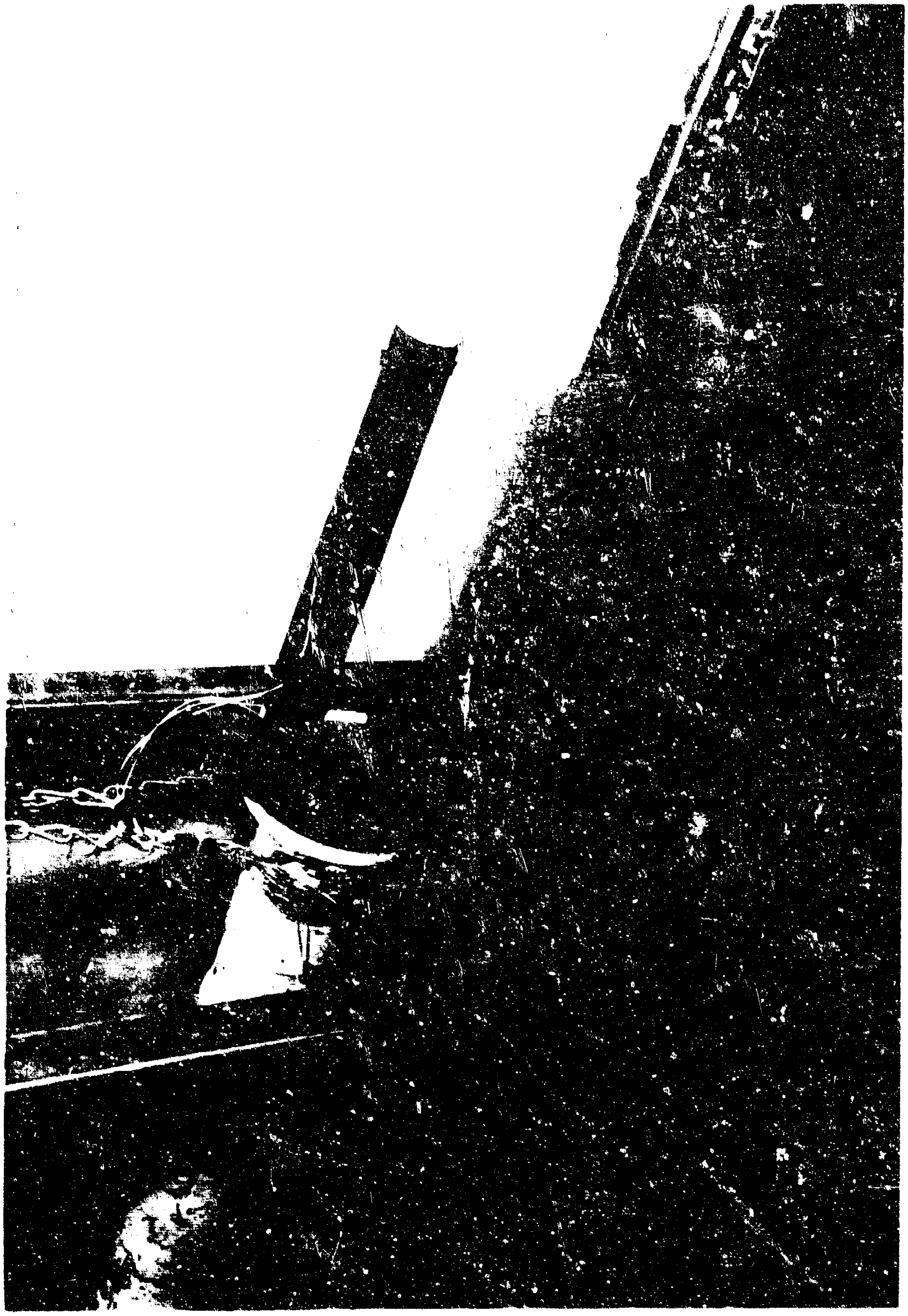


Figure 11. Velocity Measuring Device

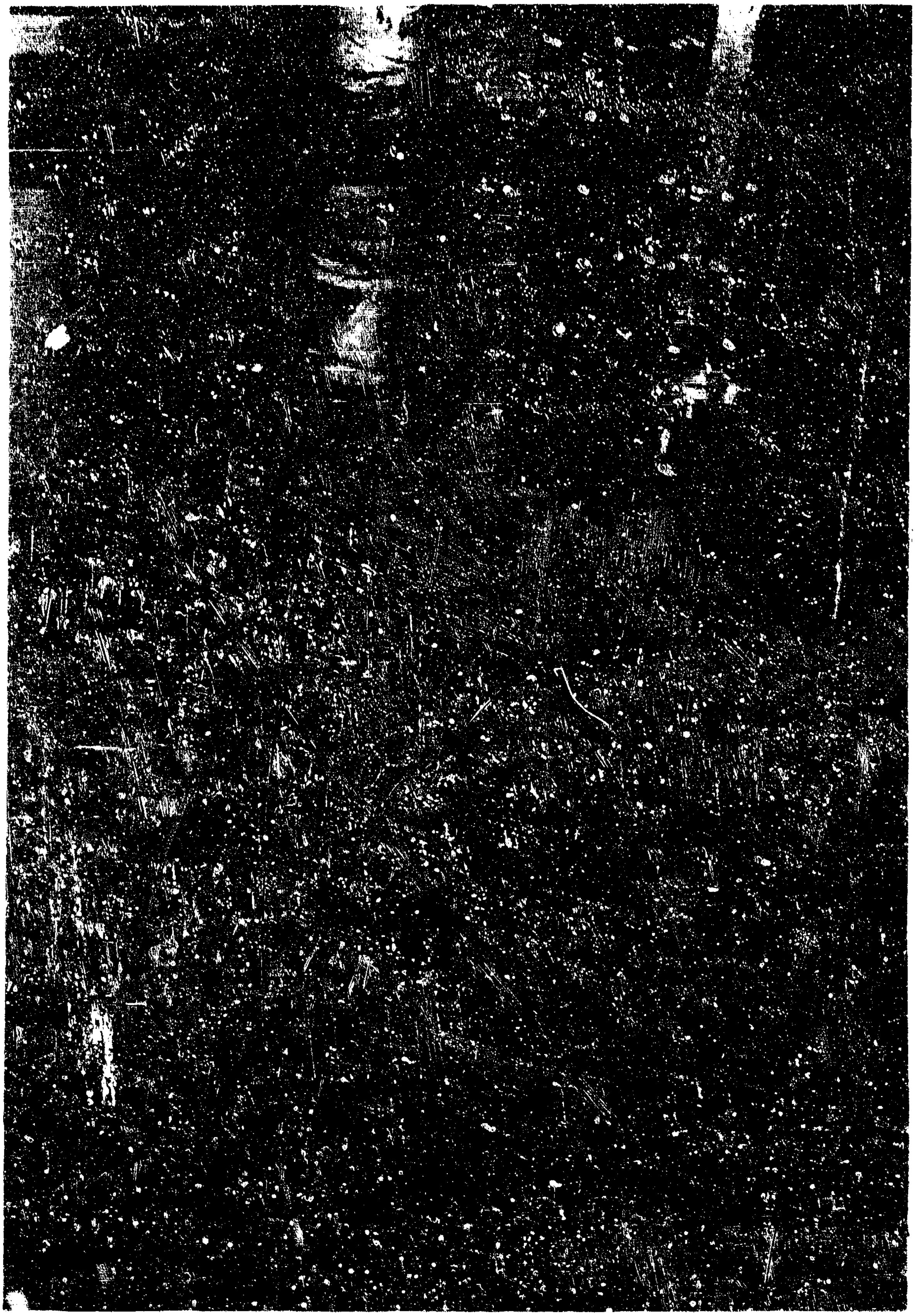


Figure 12. Transducer Placement-Muzzle

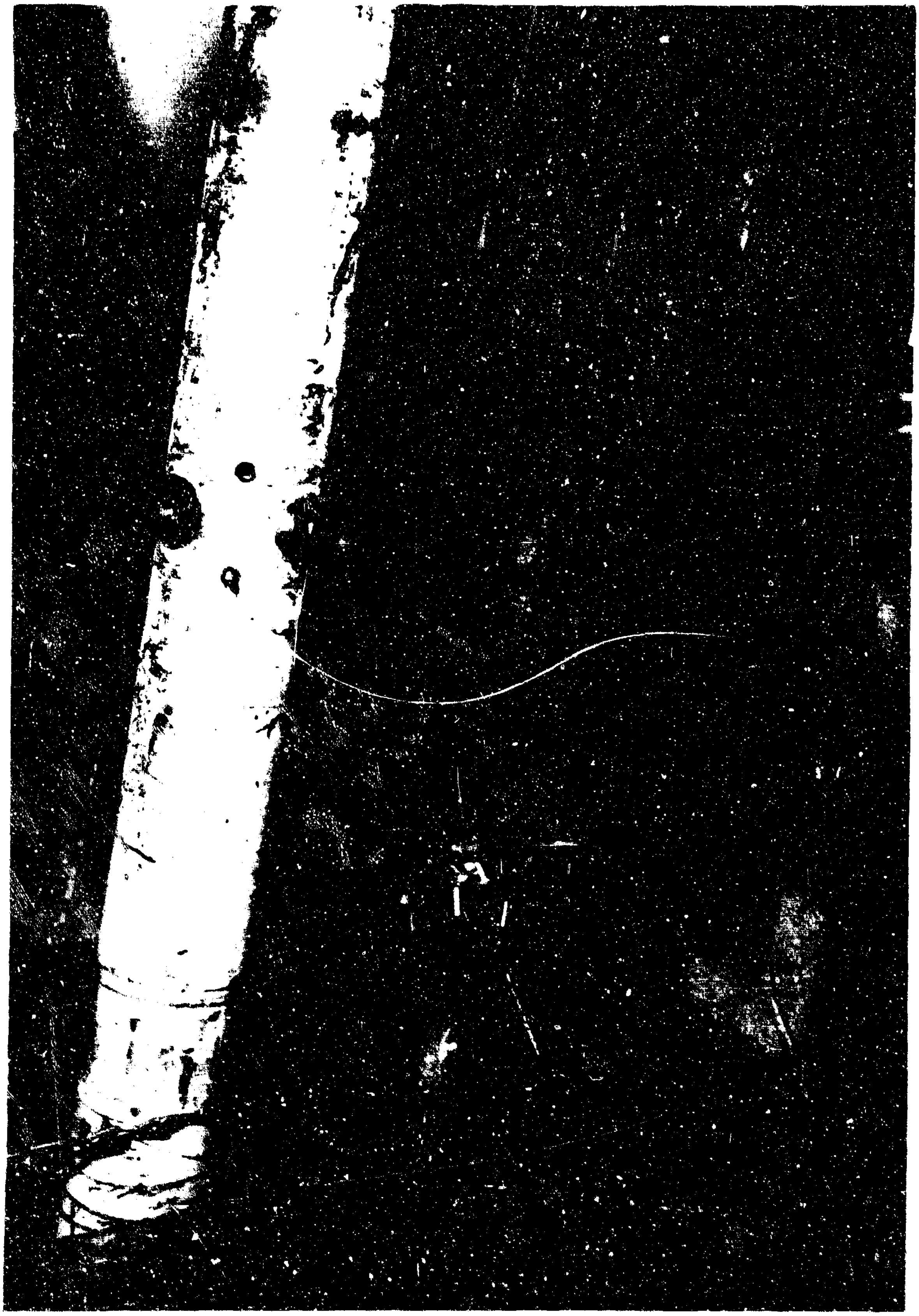


Figure 13. Transducer Placement-Chamber

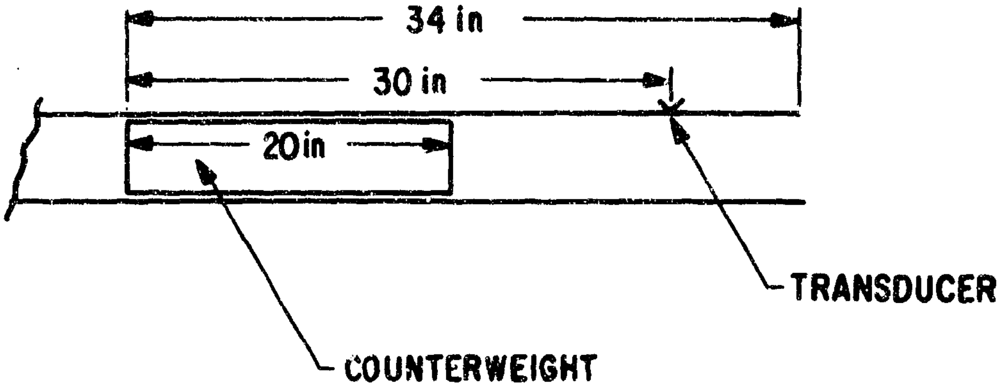


Figure 14. Transducer Counterweight Reference

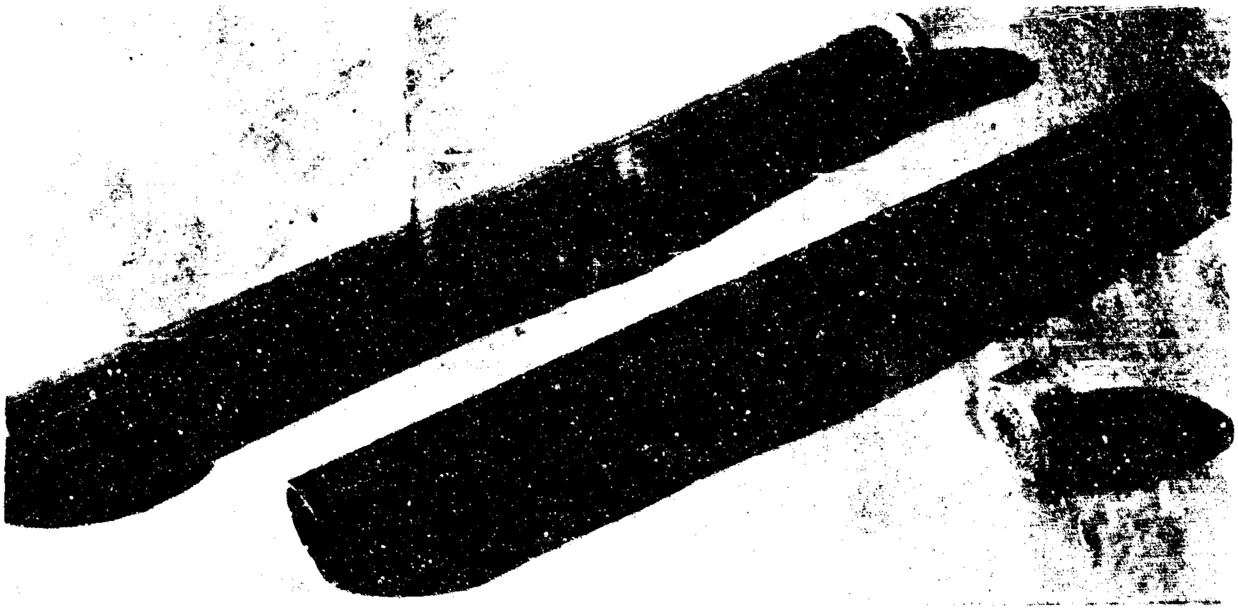


Figure 15. Newly Designed Counterweight

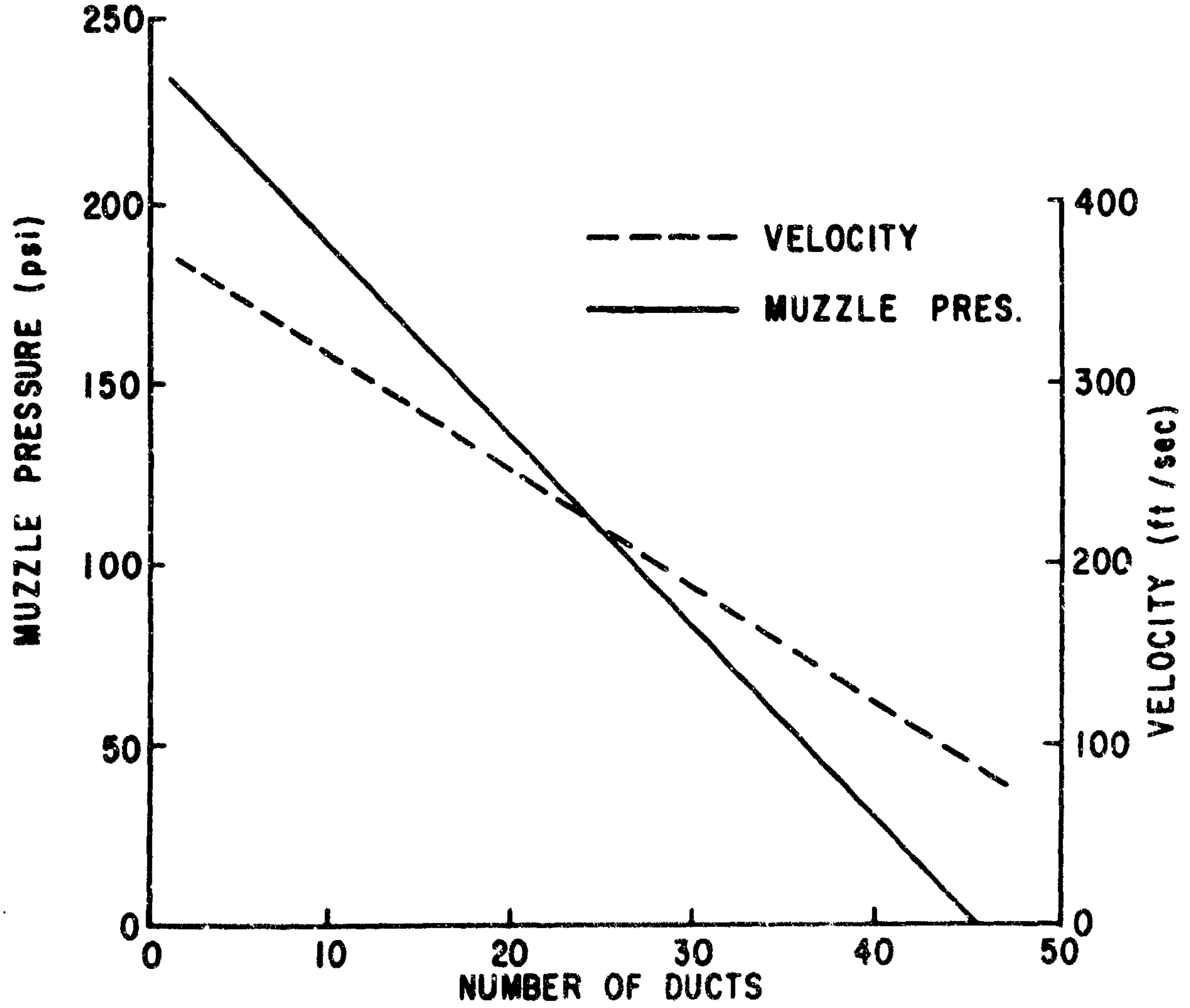


Figure 16. Duct Variation Sensitivity

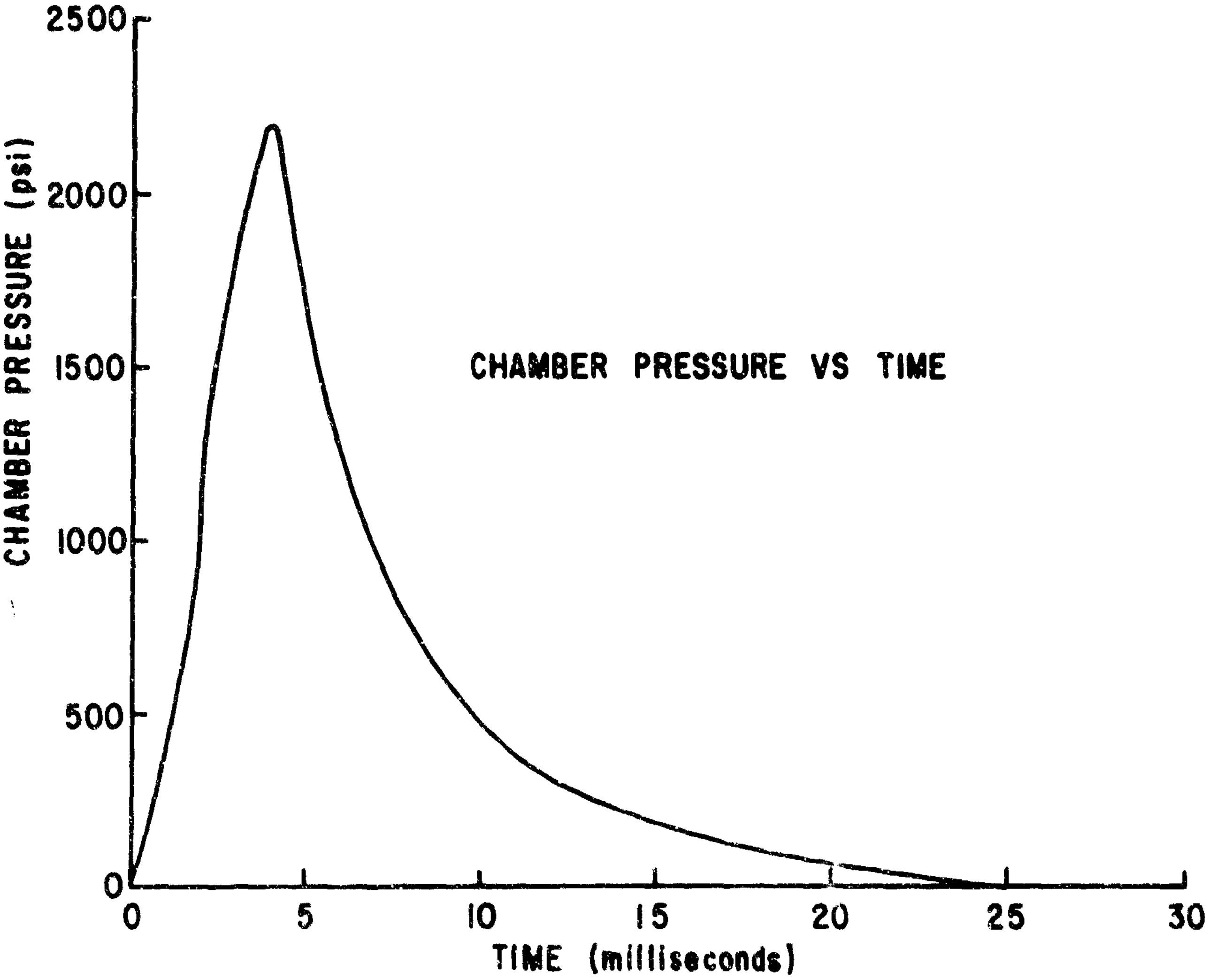


Figure 17. Experimental Solution of the Chamber Pressure Curve

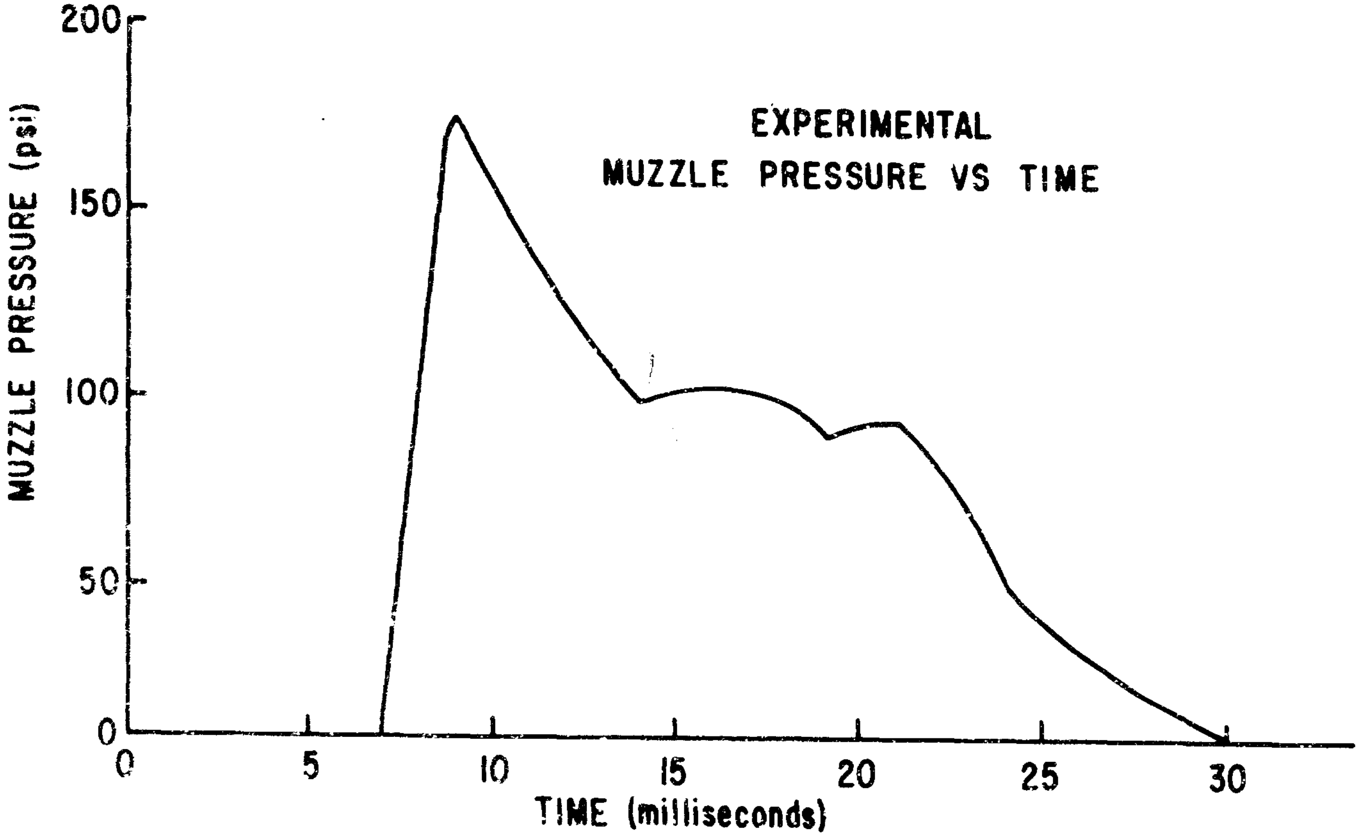


Figure 18. Experimental Solution of the Muzzle Pressure Curve

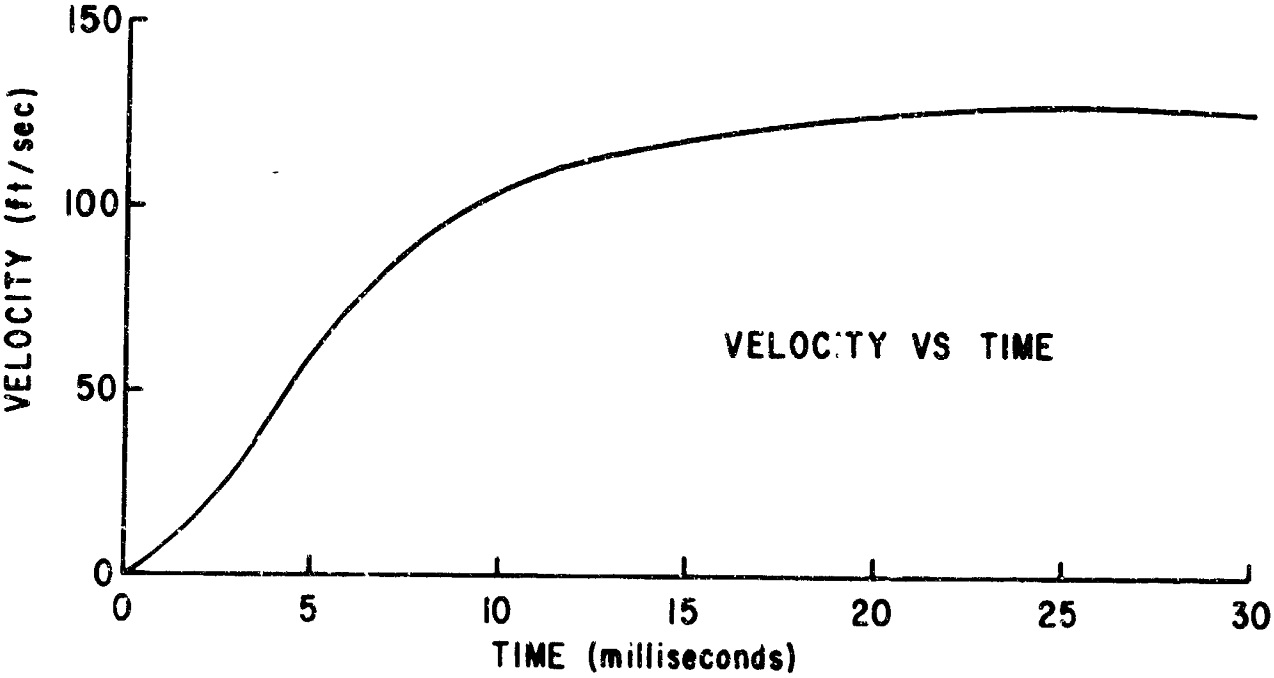


Figure 19. Graphical Integration of the Chamber Pressure Curve

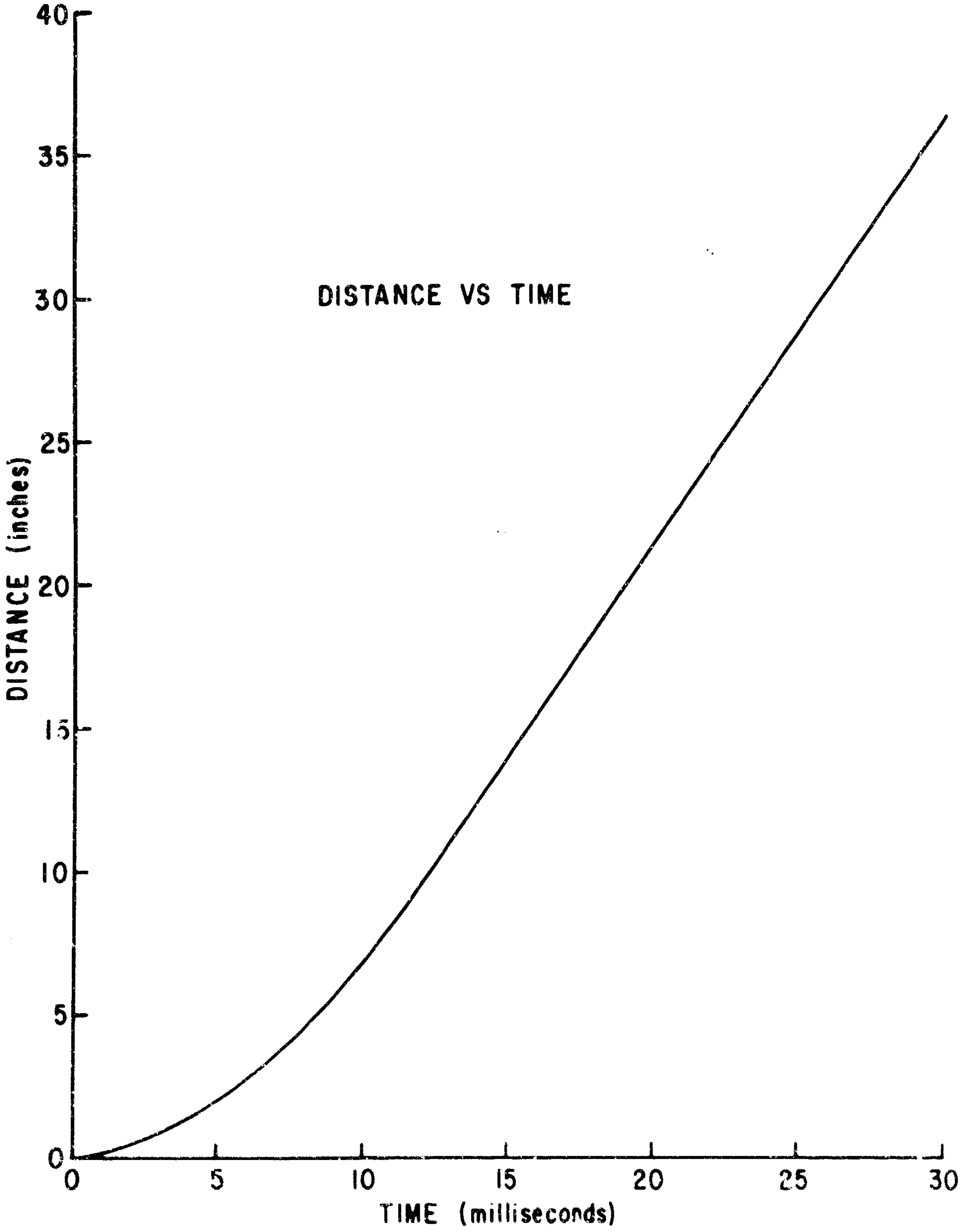


Figure 20. Graphical Integration of the Velocity Curve

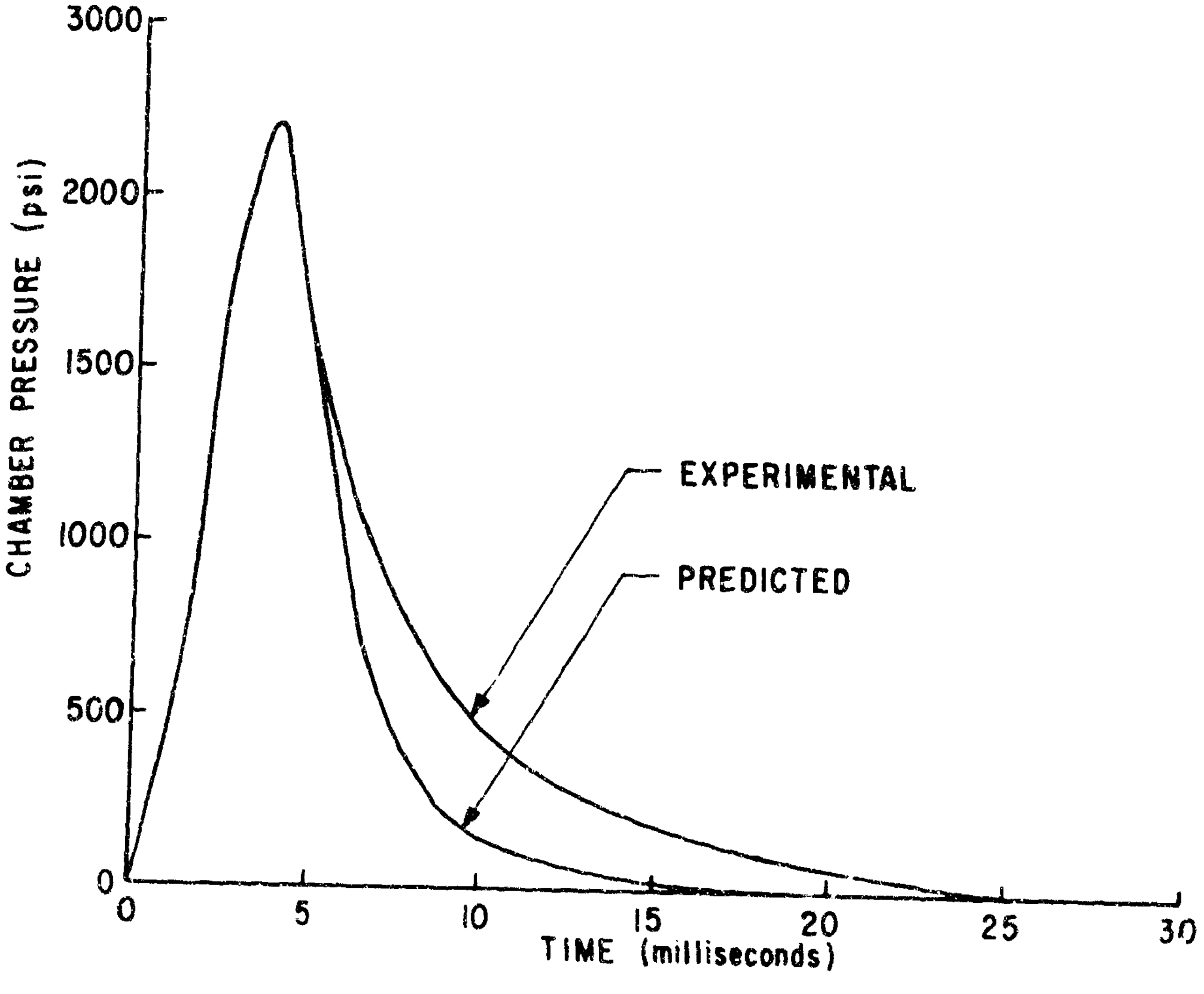


Figure 21. Experimental versus Predicted Chamber Pressure Curve

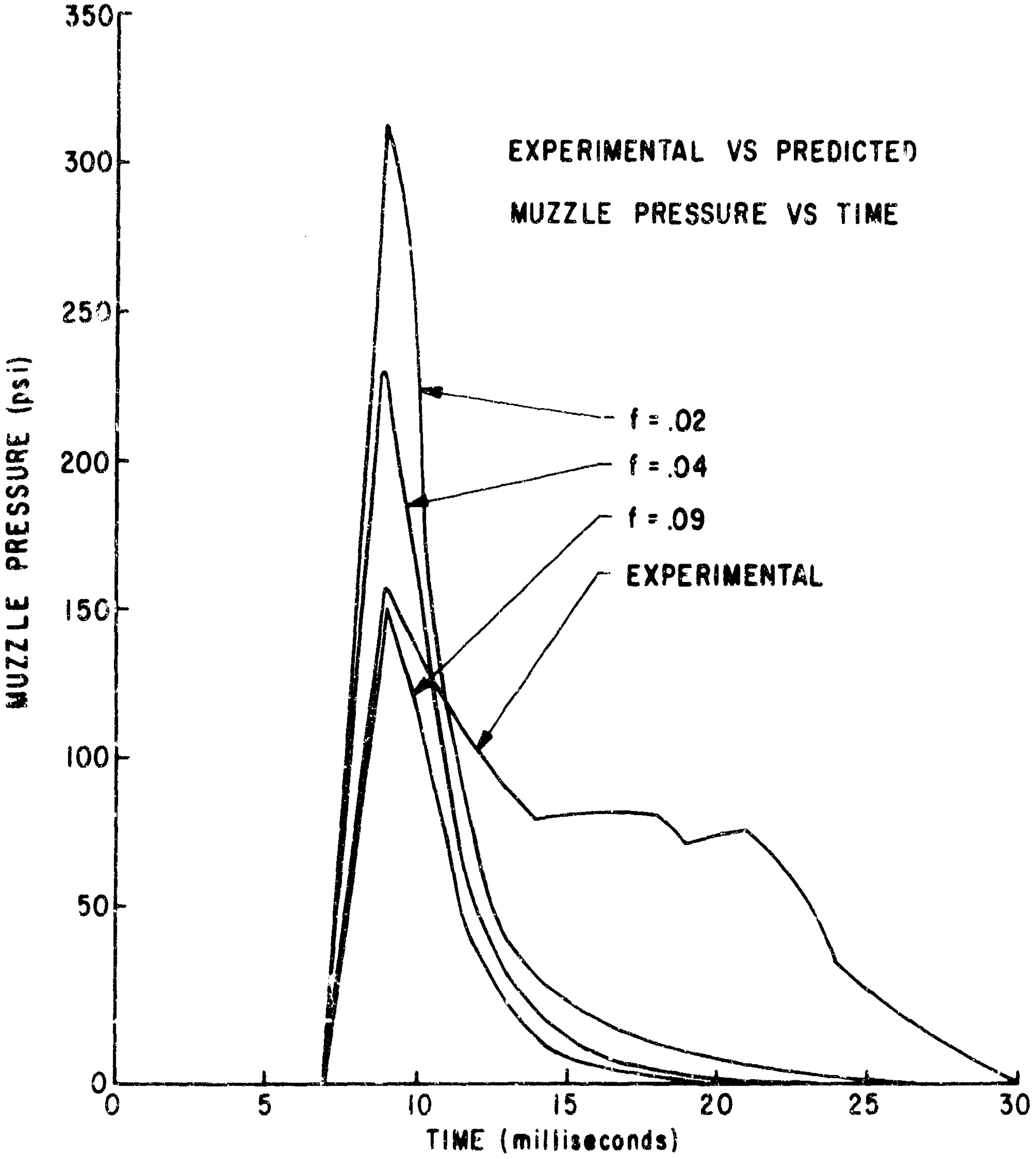


Figure 22. Experimental versus Predicted Muzzle Pressure Curve

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

It can be concluded that

a. Constant area ducts through the counterweight can reduce the maximum pressure at the counterweight muzzle of the Davis Gun without reducing the muzzle velocity of the primary projectile.

b. For a fixed duct length through the counterweight, the maximum pressure at the counterweight muzzle can be reduced by decreasing the effective area of the duct and increasing the friction in the duct.

It is recommended that more work be done in correlating the computer program with experimental data. The computer program might be written to take into account unchoked flow.

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APPENDIX I

COMPUTER RUNS

```
$JOB LEWANDOWSKI,KP=29,TIME=1
        REAL MY, MX, K, MASS, MACH2,N
        AY=3.14
        PO=2200.0
        PC=2200.0
        MY=.124
        YV=0.0
        T=.001
        YD=0.0
        AX=3.13
        MX=.372
        PB=15.0
        XV=0.0
        XD=0.0
        VOL=15.70
        K=1.22
        R=1932.0
        E=5.25
        D=2.0
        AD=.0000448
        MASS=.000752
        C1=.75
        TO=2180.0
        AC=228.0
        N=0.0
        WRITE(6,20)
 20     FORMAT(1H1,6H TIME ,2X,14H CHAMBER PRES ,2X,11H EXIT PRES ,2X,11H
       X BACK PRES ,2X,16H EXPANSION PRES ,2X,13H MACH NUMBER ,2X,10H PRIM
       X VEL )
 1      N=N+.001
        IF(N.GT. .030) GO TO 100
        YA= (AY*PO)/MY
        YD=.5*YA*(T**2.0)+YV*T+YD
        YV=(YA*T)+YV
        XA=(AX*(PO-PB))/MX
        XD=.5*XA*(T**2.0)+XV*T+XD
        XV=XA*T+XV
        VOL=(XD+YD)*(AY)*12.0+VOL
        DMASS=((((K/R)*(1.0+((K-1.0)/2.0)))**.5)*((D*AD*T*(PC**((K-1.0)/2.
       X0*K)))/(E*TO**.5))*(PO**((1.0+K)/2.0*K)))
        MASS=MASS-DMASS
        P1=PO/E
        PB=C1*P1
        PO=(((12.0*R*MASS*TO)/((VOL)*(PC**((K-1.0)/K))))**K)
        C=((1.0+((K-1.0)/2.0))**.5)/((1.0+K)+(PB/P1)*(AC-1.0))
        MACH2=((((1.0-2.0*K*(C**2.0))-((1.0-2.0*(K+1.0)*(C**2.0))**.5))/(2.
       X0*(K**2.0)*(C**2.0)-K+1.0))**.5
        P2=((P1/(AC*MACH2))*(((1.0+((K-1.0)/2.0))/((1.0+(((K-1.0)/2.0))*(M
       XACH2**2.0)))))**.5))
        WRITE(6,21)N,PO,P1,PB,P2,MACH2,YV
 21     FORMAT(1H0,F5.3,8X,F5.0,10X,F4.0,8X,F4.0,10X,F5.0,11X,F6.4,8X,F4.0
       X)
        GO TO 1
 100    CALL EXIT
        END

$ENTRY
```

PO = 1900 psi E = 5.25 D = 6.0

TIME	CHAMBER PRES	EXIT PRES	BACK PRES	EXPANSION PRES	MACH NUMBER	PRIM VEL
0.001	1735.	362.	271.	278.	0.0181	48.
0.002	1289.	331.	248.	254.	0.0181	92.
0.003	811.	246.	184.	189.	0.0181	125.
0.004	485.	154.	116.	119.	0.0181	145.
0.005	297.	92.	69.	71.	0.0181	158.
0.006	190.	56.	42.	43.	0.0181	165.
0.007	128.	36.	27.	28.	0.0181	170.
0.008	90.	24.	18.	19.	0.0181	173.
0.009	66.	17.	13.	13.	0.0181	175.
0.010	49.	12.	9.	10.	0.0181	177.
0.011	38.	9.	7.	7.	0.0181	178.
0.012	30.	7.	5.	6.	0.0181	179.
0.013	24.	6.	4.	4.	0.0181	180.
0.014	20.	5.	3.	4.	0.0181	181.
0.015	17.	4.	3.	3.	0.0181	181.
0.016	14.	3.	2.	2.	0.0181	182.

PO = 1900 psi   E = 5.25   D = 12.0

TIME	CHAMBER PRES	EXIT PRES	BACK PRES	EXPANSION PRES	MACH NUMBER	PRIM VEL
0.001	1736.	362.	271.	285.	0.0353	48.
0.002	1290.	331.	248.	260.	0.0353	92.
0.003	812.	246.	184.	194.	0.0353	125.
0.004	486.	155.	116.	122.	0.0353	145.
0.005	297.	93.	69.	73.	0.0353	158.
0.006	191.	57.	42.	45.	0.0353	165.
0.007	128.	36.	27.	29.	0.0353	170.
0.008	90.	24.	18.	19.	0.0353	173.
0.009	66.	17.	13.	14.	0.0353	175.
0.010	49.	13.	9.	10.	0.0353	177.
0.011	38.	9.	7.	7.	0.0353	178.
0.012	30.	7.	5.	6.	0.0353	179.
0.013	24.	6.	4.	5.	0.0353	180.
0.014	20.	5.	3.	4.	0.0353	181.
0.015	17.	4.	3.	3.	0.0353	181.
0.016	14.	3.	2.	2.	0.0353	182.

PO = 1900 psi E = 5.25 D = 24.0

TIME	CHAMBER PRES	EXIT PRES	BACK PRES	EXPANSION PRES	MACH NUMBER	PRIM VEL
0.001	1737.	362.	271.	298.	0.0674	48.
0.002	1293.	331.	248.	272.	0.0674	92.
0.003	815.	246.	185.	203.	0.0674	125.
0.004	488.	155.	116.	128.	0.0674	145.
0.005	299.	93.	70.	77.	0.0674	158.
0.006	192.	57.	43.	47.	0.0674	165.
0.007	129.	36.	27.	30.	0.0674	170.
0.008	91.	25.	18.	20.	0.0674	174.
0.009	66.	17.	13.	14.	0.0674	176.
0.010	50.	13.	9.	10.	0.0674	177.
0.011	38.	9.	7.	8.	0.0674	179.
0.012	30.	7.	5.	6.	0.0674	180.
0.013	24.	6.	4.	5.	0.0674	180.
0.014	20.	5.	3.	4.	0.0674	181.
0.015	17.	4.	3.	3.	0.0674	182.
0.016	14.	3.	2.	3.	0.0674	182.

PO = 1900 psi E = 3.92 D = 3.0

TIME	CHAMBER PRES	EXIT PRES	BACK PRES	EXPANSION PRES	MACH NUMBER	PRIM VEL
0.001	1735.	485.	364.	369.	0.0091	48.
0.002	1289.	443.	332.	337.	0.0091	92.
0.003	812.	329.	247.	250.	0.0091	125.
0.004	487.	207.	155.	158.	0.0091	145.
0.005	298.	124.	93.	94.	0.0091	158.
0.006	191.	76.	57.	58.	0.0091	165.
0.007	129.	49.	37.	37.	0.0091	170.
0.008	91.	33.	25.	25.	0.0091	173.
0.009	66.	23.	17.	18.	0.0091	176.
0.010	50.	17.	13.	13.	0.0091	177.
0.011	38.	13.	10.	10.	0.0091	178.
0.012	30.	10.	7.	7.	0.0091	179.
0.013	25.	8.	6.	6.	0.0091	180.
0.014	20.	6.	5.	5.	0.0091	181.
0.015	17.	5.	4.	4.	0.0091	181.
0.016	14.	4.	3.	3.	0.0091	182.

```
              PO = 1900 psi       E = 10.5        D = 3.0
  TIME     CHAMBER PRES     EXIT PRES     BACK PRES   EXPANSION PRES     MACH NUMBER     PRIM VEL

 0.001          1735.          181.          136.           138.           0.0091          48.
 0.002          1287.          165.          124.           126.           0.0091          92.
 0.003           807.          123.           92.            93.           0.0091         125.
 0.004           481.           77.           58.            58.           0.0091         145.
 0.005           293.           46.           34.            35.           0.0091         157.
 0.006           189.           28.           21.            21.           0.0091         165.
 0.007           126.           18.           13.            14.           0.0091         169.
 0.008            88.           12.            9.             9.           0.0091         173.
 0.009            65.            8.            6.             6.           0.0091         175.
 0.010            49.            6.            5.             5.           0.0091         176.
 0.011            37.            5.            3.             4.           0.0091         178.
 0.012            30.            4.            3.             3.           0.0091         179.
 0.013            24.            3.            2.             2.           0.0091         179.
 0.014            20.            2.            2.             2.           0.0091         180.
 0.015            16.            2.            1.             1.           0.0091         181.
 0.016            14.            2.            1.             1.           0.0091         181.
```

PO = 2800 psi E = 5.25 D = 2.0

TIME	CHAMBER PRES	EXIT PRES	BACK PRES	EXPANSION PRES	MACH NUMBER	PRIM VEL
0.001	2460.	533.	400.	404.	0.0061	71.
0.002	1645.	469.	351.	355.	0.0061	133.
0.003	933.	313.	235.	238.	0.0061	175.
0.004	523.	178.	133.	135.	0.0061	198.
0.005	310.	100.	75.	76.	0.0061	212.
0.006	195.	59.	44.	45.	0.0061	220.
0.007	130.	37.	28.	28.	0.0061	224.
0.008	91.	25.	19.	19.	0.0061	228.
0.009	67.	17.	13.	13.	0.0061	230.
0.010	50.	13.	10.	10.	0.0061	232.
0.011	39.	10.	7.	7.	0.0061	233.
0.012	31.	7.	6.	6.	0.0061	234.
0.013	25.	6.	4.	4.	0.0061	235.
0.014	20.	5.	4.	4.	0.0061	235.
0.015	17.	4.	3.	3.	0.0061	236.
0.016	14.	3.	2.	2.	0.0061	236.

PO = 2800 psi E = 10.5 D = 2.0

TIME	CHAMBER PRES	EXIT PRES	BACK PRES	EXPANSION PRES	MACH NUMBER	PRIM VEL
0.001	2460.	267.	200.	202.	0.0061	71.
0.002	1642.	234.	176.	178.	0.0061	133.
0.003	929.	156.	117.	119.	0.0061	175.
0.004	519.	88.	66.	67.	0.0061	198.
0.005	306.	49.	37.	37.	0.0061	211.
0.006	193.	29.	22.	22.	0.0061	219.
0.007	123.	19.	14.	14.	0.0061	224.
0.008	90.	12.	9.	9.	0.0061	227.
0.009	66.	9.	6.	7.	0.0061	230.
0.010	49.	6.	5.	5.	0.0061	231.
0.011	38.	5.	4.	4.	0.0061	233.
0.012	30.	4.	3.	3.	0.0061	233.
0.013	24.	3.	2.	2.	0.0061	234.
0.014	20.	2.	2.	2.	0.0061	235.
0.015	17.	2.	1.	1.	0.0061	235.
0.016	14.	2.	1.	1.	0.0061	236.

PO = 2300 psi E = 5.25 D = 2.0

TIME	CHAMBER PRES	EXIT PRES	BACK PRES	EXPANSION PRES	MACH NUMBER	PRIM VEL
0.001	2228.	419.	314.	318.	0.0061	56.
0.002	1581.	424.	318.	322.	0.0061	112.
0.003	940.	301.	226.	228.	0.0061	152.
0.004	539.	179.	134.	136.	0.0061	176.
0.005	321.	103.	77.	78.	0.0061	190.
0.006	203.	61.	46.	46.	0.0061	198.
0.007	135.	39.	29.	29.	0.0061	203.
0.008	95.	26.	19.	20.	0.0061	206.
0.009	69.	18.	14.	14.	0.0061	209.
0.010	52.	13.	10.	10.	0.0061	210.
0.011	40.	10.	7.	7.	0.0061	212.
0.012	32.	8.	6.	6.	0.0061	213.
0.013	25.	6.	5.	5.	0.0061	214.
0.014	21.	5.	4.	4.	0.0061	214.
0.015	17.	4.	3.	3.	0.0061	215.
0.016	15.	3.	2.	2.	0.0061	215.

PO = 2300 psi B = 7.00 D = 2.0

TIME	CHAMBER PRES	EXIT PRES	BACK PRES	EXPANSION PRES	MACH NUMBER	PRIM VEL
0.001	2228.	314.	236.	238.	0.0061	56.
0.002	1580.	318.	239.	241.	0.0061	112.
0.003	938.	226.	169.	171.	0.0061	152.
0.004	537.	134.	101.	102.	0.0061	176.
0.005	320.	77.	58.	58.	0.0061	139.
0.006	202.	46.	34.	35.	0.0061	198.
0.007	134.	29.	22.	22.	0.0061	203.
0.008	94.	19.	14.	15.	0.0061	206.
0.009	68.	13.	10.	10.	0.0061	208.
0.010	51.	10.	7.	7.	0.0061	210.
0.011	40.	7.	5.	6.	0.0061	212.
0.012	31.	6.	4.	4.	0.0061	213.
0.013	25.	4.	3.	3.	0.0061	213.
0.014	21.	4.	3.	3.	0.0061	214.
0.015	17.	3.	2.	2.	0.0061	214.
0.016	14.	2.	2.	2.	0.0061	215.

PO = 2300 psi E = 10.5 D = 2.0

TIME	CHAMBER PRES	EXIT PRES	BACK PRES	EXPANSION PRES	MACH NUMBER	PRIM VEL
0.001	2228.	210.	157.	159.	0.0061	56.
0.002	1579.	212.	159.	161.	0.0061	112.
0.003	936.	150.	113.	114.	0.0061	152.
0.004	535.	89.	67.	68.	0.0061	176.
0.005	318.	51.	38.	39.	0.0061	189.
0.006	200.	30.	23.	23.	0.0061	197.
0.007	134.	19.	14.	14.	0.0061	202.
0.008	93.	13.	10.	10.	0.0061	206.
0.009	68.	9.	7.	7.	0.0061	208.
0.010	51.	6.	5.	5.	0.0061	210.
0.011	39.	5.	4.	4.	0.0061	211.
0.012	31.	4.	3.	3.	0.0061	212.
0.013	25.	3.	2.	2.	0.0061	213.
0.014	20.	2.	2.	2.	0.0061	214.
0.015	17.	2.	1.	1.	0.0061	214.
0.016	14.	2.	1.	1.	0.0061	215.

APPENDIX II

GRAPHICAL INTEGRATION

Graphical integration of the chamber pressure-time trace gives a velocity-time trace, and graphical integration of the velocity-time trace gives the distance-time trace desired.

Graphical integration of the pressure-time trace:

$$P(t)\ A = d/dt\ (mV)$$

$$dV = A/m\ P(t)\ dt$$

$$V = A/m \int P(t)\ dt$$

$$A/m = 3.14 \times 32.2/12 = 8.45$$

where

$P(t)$ = the pressure as a function of time, psi

A = the base area of the counterweight, in^2

m = the mass of the counterweight, slug

V = the velocity of the counterweight, ft/sec

t = time, sec

Time (sec)	Pressure (psi)	Velocity (ft/sec)
0.000-0.003	0-2200	28
0.003-0.006	2200-1200	72
0.006-0.009	1200- 800	98
0.009-0.012	800- 300	112
0.012-0.030	300- 0	135

Graphical integration of the velocity-time trace:

$$S = \int V(t)\ dt$$

S = the distance traveled by the counterweight.

Time (sec)	Velocity (ft/sec)	Distance (in)
0.000-0.003	0-28	0.51
0.003-0.006	28-72	2.31
0.006-0.009	72-98	5.50
0.009-0.012	98-112	9.50
0.012-0.030	112-135	36.50

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13. ABSTRACT

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This study devises a means of reducing the maximum pressure at the counterweight muzzle of a Davis Gun without reducing the muzzle velocity of the primary projectile. A new counterweight is designed, with constant area ducts placed longitudinally through the counterweight. A proper combination of duct length, duct cross-sectional area, frictional resistance, and the number of ducts, allows the right mass of propelling gas to flow through the counterweight, so that the pressure of the gas fore and aft of the counterweight never reaches the maximum allowable pressure at the muzzle, even when additional propellant is placed in the chamber to keep the primary projectile velocity constant.

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