AD NUMBER
AD852601
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited. Document partially illegible.**
FROM: **Distribution authorized to U.S. Gov't. agencies and their contractors; Critical Technology; MAY 1969. Other requests shall be referred to Air Force Armament Laboratory, ATWG, Eglin AFB, FL 32542. Document partially illegible. This document contains export-controlled technical data.**
AUTHORITY
afatl ltr, 4 oct 1972

AFATL-TR-69-42

AD852601

Analytic and Experimental Interior Ballistics of Closed Breech Guns

by

Otto K. Heiney, 1st Lt, USAFR

MAY 1969

This document is subject to special export controls, and each transmittal to foreign nationals or foreign governments may be made only with prior approval of the Air Force Armament Laboratory (ATWG), Eglin Air Force Base, Florida 32542.

AIR FORCE ARMAMENT LABORATORY

AIR FORCE SYSTEMS COMMAND • UNITED STATES AIR FORCE

EGLIN AIR FORCE BASE, FLORIDA

96

ANALYTIC AND EXPERIMENTAL INTERIOR BALLISTICS
OF CLOSED BREECH GUNS

by

Otto K. Heiney, 1st Lt, USAFR

FOREWORD

This report has been generated under the interior ballistic analysis portion of Project 62405094 2560. It is an extension of a propellant actuated device interior ballistic formulism developed at the Jet Propulsion Laboratory (reference 1) at Pasadena, California, under NAS 7-100. The report was written by 1st Lt O. K. Heiney, USAFR, attached to the Air Force Armament Laboratory [AFATL (ATWG)] for an annual active duty tour. Assistance of the personnel of both AFATL (ATBA) and the Armament Development and Test Center [ADTC (ADTVF-2)] with the formulation and execution of the computer program is gratefully acknowledged.

Information in this report is embargoed under the Department of State International Traffic in Arms Regulations. This report may be released to foreign governments by departments or agencies of the U. S. Government subject to approval of the Air Force Armament Laboratory (ATWG), Eglin Air Force Base, Florida, or higher authority within the Department of the Air Force. Private individuals or firms require a Department of State export license.

This technical report is approved.

CHARLES K. ARPKE, Lt Colonel, USAF
Acting Chief, Weapons Division

ABSTRACT

A closed breech incremental interior ballistic formulism is presented along with a Fortran 4 computer program which utilizes the system. Typical input and output data, both plotted and tabular, are included. A unique characteristic of the system is that it avoids the inaccuracies associated with approximate analytic propellant regression expressions in that regression rates are determined by a tabular routine. Various pressure gradient expressions are investigated. Correlation of the mathematical model and computer predictions to experimental device firings are presented. A shock-driven deflagration effect which may be initiated during the ignition transient is described and a postulated correlation parameter defined.

(The reverse of this page is blank.)

CONTENTS

ILLUSTRATIONS AND TABLES

ILLUSTRATIONS AND TABLES (CONTINUED)

NOMENCLATURE

A = Bore Area
a = Acceleration
C = Arbitrary Constant
C_v = Constant Volume Gas Specific Heat
C_w = Charge Weight
E_G = Kinetic Energy of Propellant Gas
F = Force
F_p = Impetus of Propellant
g = Acceleration Due to Gravity
m_A = Pseudo Mass of Propelled Device
m_p = Mass of Propelled Device
M = Mach Number
N_B = Propellant Burned
P_{AV} = Average Plenum Pressure
P_o = Total Pressure
P_s = Shot Base Pressure
r = Regression Rate of Propellant
R = Gas Constant
S_B = Burning Surface of Propellant
T = Gas Temperature
T_o = Isochoric Flame Temperature of Propellant
V = Shot Velocity
v_c = Initial Chamber Volume
v = Gas Velocity
X = Distance from Shot Base to X_o
X_o = Initial Shot Reference
x = Arbitrary Reference Behind Shot
β = Heat Loss Factor
γ = Specific Heat Ratio of Propellant Gas
δ = Density Distribution Factor
η = Covolume of Propellant Gases
ρ = Average Density of Gas
ρ_p = Density of Propellant
ρ_0 = Breech Gas Density
ρ_s = Density of Gas at Projectile
ϕ = Pressure Gradient Factor
ω_0 = Initial Propellant Web
Δ = Burning Surface Factor

(The reverse of this page is blank.)

SECTION I

INTRODUCTION

The basic interior ballistic problem of any closed breech gun system is to determine the energy release and corresponding pressure generated by the burning of propellant in a variable volume. From the energy balance and the equation of state, the pressure-time or pressure-travel as well as muzzle velocity and piezometric efficiency of the system is established, thus providing the complete ballistic solution.

The results of the analysis, Section II, are essentially contained in equations (9) and (26) which are in an incremental form specifically tailored for machine computation. Program listing and typical results are presented in Section III.

The analysis in Section II considers first the energy balance of the system in paragraph A, Section II. In paragraph B, Section II, the kinetic energy in the propellant gas is determined. Also investigated are various expressions for the pressure gradient from the breech to the moving shot. In paragraph C, Section II, the constant burning surface of single perforate propellant is demonstrated and a tabular regression routine defined.

Section IV illustrates the comparison of the presented model to experimentally measured pressure histories of device firings. The experimental set-up is described, and a shock-driven deflagration phenomenon that was encountered is defined.

SECTION II

ANALYSIS

ENERGY BALANCE

The Noble-Abel equation of state is:

$$P(V - \eta) = nRT \qquad (1)$$

Where η is the "covolume" of the propellant and has the units of volume/mass which arises due to the fact that the combustion products are not perfect gases.

The central property of the propellant is its "impetus," F_p, which is qualitatively similar to the c* of rocket propellants.

$$F_p = RT_o \qquad (2)$$

Where T_o is the isochoric flame temperature of the propellant gases and F_p has units of specific energy (ft-lb/lb).

The energy equation, following the techniques in reference 2, for the system will be

$E_1 = E_2 + E_3 + E_4$, where

E_1 = energy put in system from propellant combustion
E_2 = translational energy of piston
E_3 = heat loss to walls
E_4 = kinetic energy of unburned propellant and propellant gases
A = cross section of bore
v_c = initial chamber volume
X = distance from X_o to piston base.

The instantaneous free chamber volume is a function of the initial chamber volume plus the barrel volume exposed by shot motion minus volume occupied by unburnt propellant and combustion gases. Combining equations (1) and (2) then gives

$$P\left[(v_c + AX) - \frac{(C_w - N_b)}{\rho_p} - \eta N_b\right] = \frac{N_b F_p T}{T_o} \qquad (3)$$

Thermal and chemical energy released by propellant will be

$$E_1 = N_b C_v (T_o - T) \quad (4)$$

Translational energy of the piston will be

$$E_2 = 1/2\ m_p\ V^2$$

The heat loss of the gases is proportional to the distance traveled, which (following reference 3) is roughly proportional to the square of the velocity. We can, to a good approximation, say that

$$E_3 = 1/2\ \beta m_A\ V^2$$

Using the expression developed in paragraph B, below, for the kinetic energy contained in the accelerating gas and unburned propellant, we may write

$$E_4 = 1/2\ \frac{C_w V^2}{g\delta}$$

We may define

$$m_A = m_p + \frac{C_w}{\delta g}$$

Then

$$E_2 + E_3 + E_4 = (1 + \beta)(1/2) m_A\ V^2 \quad (5)$$

Defining γ by equation (6)

$$(\gamma - 1) = \frac{R}{C_v} = F_p / C_v T_o \quad (6)$$

Then from equations (4), (5), and (6)

$$N_b F_p (1 - T/T_o) = 1/2\ (\gamma - 1)\ (1 + \beta)\ m_A\ V^2 \quad (7)$$

The temperature ratio is eliminated by the introduction of the equation of state to give the fundamental ballistic equation

$$N_b F_p - (\gamma - 1)(1 + \beta) \frac{m_A}{2} V^2 = P_{AV} \left[(v_c + AX) - \frac{(C_w - N_b)}{\rho_p} - \eta N_b \right] \quad (8)$$

or as a differential form of equation (8) is more convenient for incremental computation, differentiating, and taking differential chamber volume changes due to charge regression as second order; this is

$$\frac{dP_{AV}}{dt} \left[(v_c + AX) - \frac{(C_w - N_b)}{\rho_p} - \eta N_b \right] = \frac{dN_b}{dt} F_p - (\gamma - 1)(1 + \beta) m_A \frac{dV}{dt} \frac{dx}{dt} - P_{AV} A \frac{dx}{dt} \quad (9)$$

Equation (9) provides the basis for the complete incremental interior ballistic solution; however, two additional functions are necessary to provide required relationship in the above formulation.

The first is projectile velocity as a function of average chamber pressure, or $V = f(P_s, t, m_p)$

This relation is determined in paragraph B below. The second expression required is a value for the surface exposed to burning as a function of web fraction burned.

$$N_t = f(P_{AV}, t)$$

which is covered in paragraph C below.

PRESSURE GRADIENT AND GAS KINETIC ENERGY

The determination of the pressure gradient in the barrel is central to the ballistic solution, as the velocity of the shot is a function of the pressure at the shot while equation (9) gives a value for P_{AV}. The density distribution in the gas is also required to give a value for the gas kinetic energy. The density and pressure variations are determined for an average temperature in the combustion chamber of T_0 and also for an average temperature of 7/10 T_0. This problem was first studied by La'Grange and his approach introduces the analysis.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v) = 0 \quad (10)$$

and assuming constant density

$$\frac{\partial \rho}{\partial x} = 0$$

results in equation (10) being separable with the result.

$$\frac{1}{\rho}\frac{\partial \rho}{\partial t} = -\frac{\partial v}{\partial x} = C \qquad (11)$$

Equation (11) is integrated with the boundary conditions

BD 1. $X = X_o = 0, \; v = 0$

BD 2. $X = X \quad , \; v = V = \frac{dx}{dt}$

$$\int_o^V dv = C \int_o^X dx$$

$$v = Cx \qquad (12)$$

at boundary 2

$$C = \frac{1}{X}\frac{dX}{dt}$$

then

$$v = \frac{x}{X}\frac{dX}{dt} \qquad (13)$$

It is thus seen the constant density assumption of La'Grange will directly result in a linear velocity profile for the gases, equation (13). Constant density is then a sufficient condition for velocity linearity, though not necessarily a necessary condition.

The kinetic energy in the gas using the above approach is then

$$E_G = 1/2 \int_o^X A\rho v^2 \, dx = \frac{A\rho}{2} V^2 \int_o^X \frac{x^2}{X^2} dx = (1/2)\,(1/3)\, A\rho X V^2$$

but

$$A\rho X = \frac{C_w}{g}$$

then

$$E_G = (1/2)\,(1/3)\,\frac{C_w V^2}{g} = 1/2\,\frac{C_w V^2}{\delta g} \tag{14}$$

where

$\delta = 3$ for the La'Grange solution.

The factor δ was introduced by Hirschfelder (reference 3) in his extension of the work of Kent (reference 4) who allowed the gas density to vary and solved for δ as a function of the charge to projectile mass ratio.

Solutions of the form $\delta = f\,(C_w/m_p g)$

are useful for the approximate closed form ballistics of Hirschfelder but are of less utility for incremental computer solvable interior ballistic system discussed here. The results of La'Grange ($\delta = 3$) essentially state that the energy in the accelerating gas is equivalent to 1/3 of the gas mass traveling at shot velocity. This is a good approximation at velocities where the gas density is almost constant. It falls apart, as would be expected, at velocities where the density is no longer uniform.

For incremental computations, δ is most effectively formulated as a function of shot velocity. To do this, it is first necessary to describe the density variation behind the projectile as a function of shot velocity. It is then assumed that a linear velocity gradient exists behind the shot and also that isentropic flow relations may be used during an interval to describe the flow behind the shot.

This requires that the flow during the short interval considered be looked upon as "quasi-isentropic." From reference 5, the density ratio is then

$$\rho/\rho_0 = \left(1 + \frac{\gamma - 1}{2}\,\frac{v^2}{gRT}\right)^{-1/\gamma - 1} \tag{15}$$

The question then arises as to what temperature should be used to define the speed of sound in the environment of the burning gases. An upper bound for this temperature would be the isochoric flame temperature of the gases T_0; a reasonable lower bound would be 7/10 T_0. The analysis is then conducted with the above values as bounds.

The results of equation (15) are plotted on Figure 1 for a $\gamma = 1.222$ and an $RT_0 = 375{,}000$ ft-lb/lb.

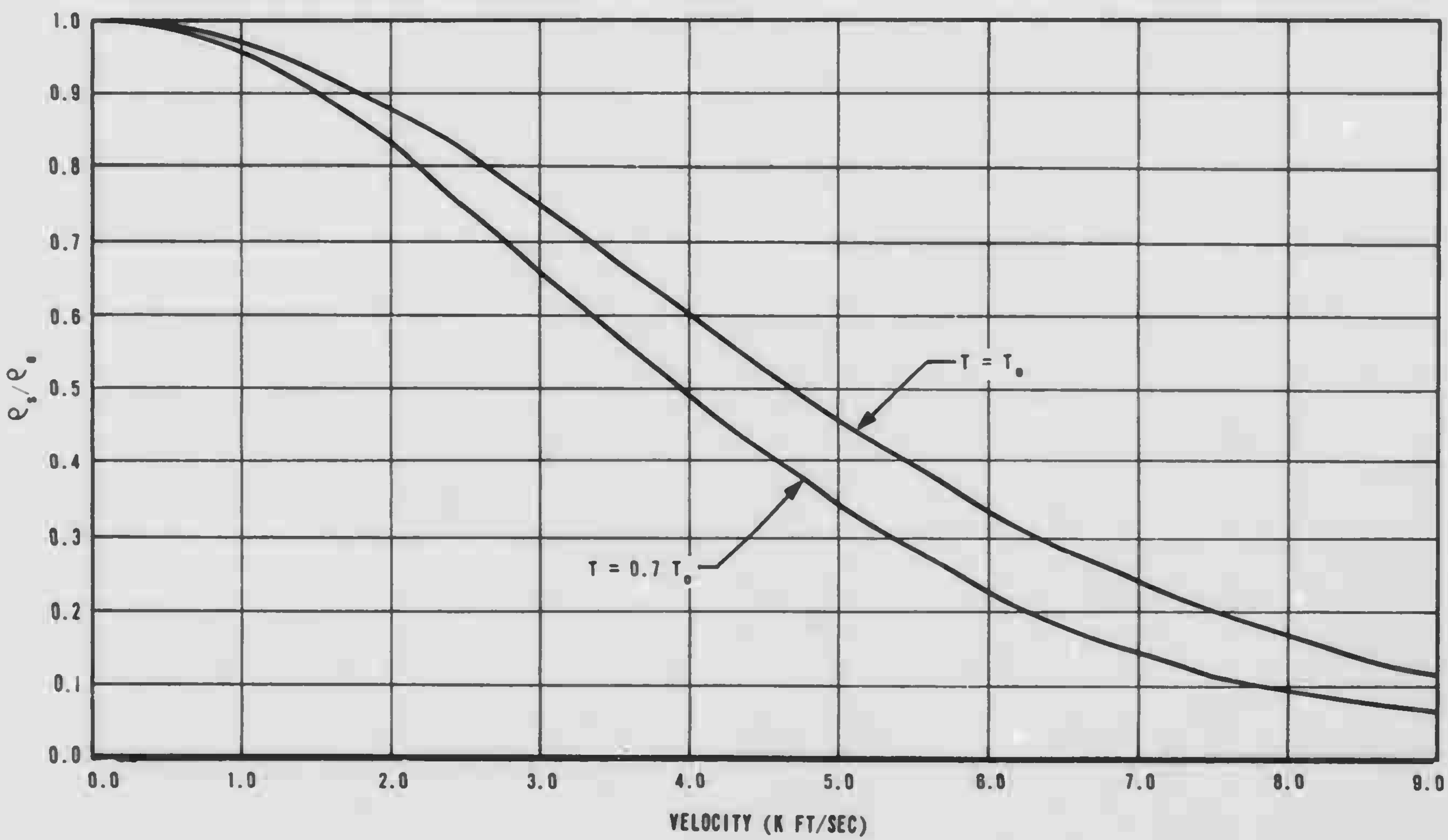


Figure 1. Density Gradient as Function of Shot Velocity.

The energy increment in a small control volume of gas will then be

$$E_I = 1/2 \; \rho_N \; V_N^2 \; A\Delta X_N$$

$$E_G = \frac{A\rho_o}{2} \sum \frac{\rho_N}{\rho_o} V_N^2 \; \Delta X_N = 1/2 \; \frac{C_w}{g\delta} \; V^2 \qquad (16)$$

The value of δ, for a given velocity, is determined by performing the numerical summation of equation (16) on a digital computer. The results of this procedure are plotted on Figure 2. As would be expected at low velocities, the value of δ approaches 3.0. The results of δ as a function of velocity is then fed into the main ballistic program as data and allows for the computation of the value of the kinetic energy of the gas.

PRESSURE GRADIENT

The necessity of relating $P_s = f\,(P_{AV})$ has been explained above. The approach used here is to relate P_s to P_o by two independent methods and then empirically determine a P_{AV} to P_s relationship. A value for the ratio of P_s/P_o may be obtained by means of the "quasi-isentropic" assumption used for densities above.

$$P/P_o = \left(1 + \frac{\gamma - 1}{2} \frac{V^2}{gRT}\right)^{-\gamma/\gamma-1} \qquad (17)$$

The results of this relation are plotted on Figures 3 and 4 for the temperatures $T = T_o$ & $T = .7T_o$ respectively.

Another approach to the pressure gradient solution would be to assume a constant temperature process. In which case Euler's equation and the equation of state will give:

$$P = \rho RT \qquad (18)$$

$$vdv = -\frac{dp}{\rho} \qquad (19)$$

combining equations (18) and (19) and integrating

$$\int_o^v vdv = -\int_{P_o}^{P_s} \frac{RT}{P} dP$$

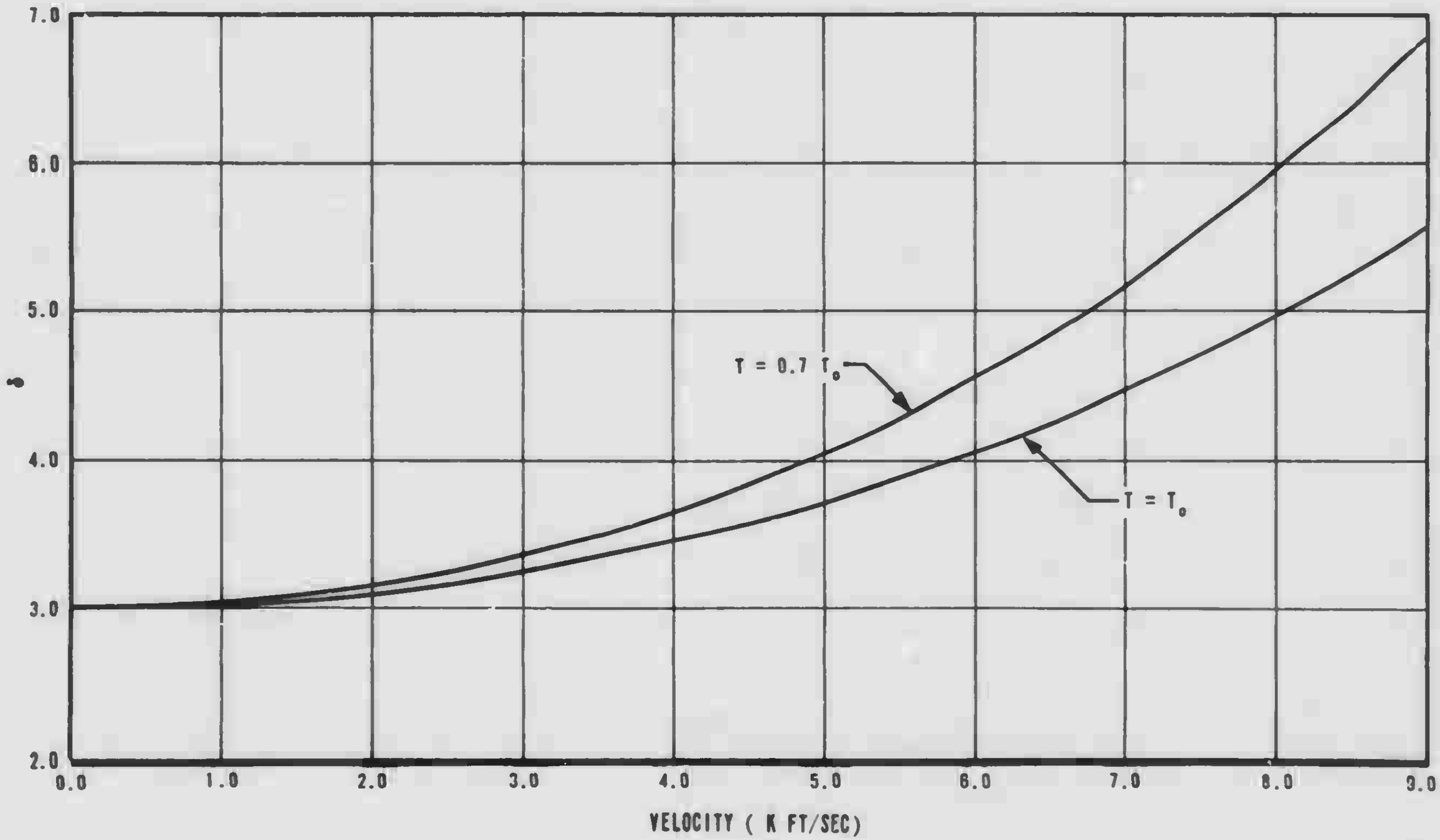


Figure 2. δ Value as Function of Projectile Velocity.

$$\frac{V^2}{2} = -RT \ln (P_s - P_o) \qquad (20)$$

The results of equation (20) are also plotted on Figures 3 and 4. The constant temperature equation predicts a lower shot pressure than the quasi-isentropic relation. To relate P_s to P_{AV} then, a heuristically reasonable approach would be to assume that a relation of the form

$$P_s/P_{AV} = \left(1 + \frac{\gamma - 1}{2\phi} \frac{v^2}{gRT}\right)^{-\gamma/\gamma-1} \qquad (21)$$

with $\phi > 1$ would be satisfactory. To investigate this possibility, it is necessary to develop a value for P_{AV} which has only the gas acceleration energy accounted for. This is done as follows:

$$P_o v_c - \frac{mv^2}{2\delta} = P_{AV} v_c$$

$$P_{AV}/P_o = 1 - \frac{V^2}{2\delta\, gF_p(T/T_o)} \qquad (22)$$

Using the expression developed for $\delta = f(v)$ with $\phi = 1.5$ the combined results of equations (21) and (22) will give a value for P_s/P_o which is again plotted on Figures 3 and 4. It is seen that this value of ϕ gives consistent results for both temperature extremes. It is used in the interior ballistic formulism to relate the average pressures generated by equation (9) to the pressure at the base of the shot required for the equation of motion, as shown below.

$$V = V_o + at \qquad (23)$$

$$a = \frac{P_s A}{m_p} \qquad (24)$$

$$P_s = \left[1 + \frac{\gamma-1}{2\phi} M^2\right]^{-\gamma/\gamma-1} P_{AV} \qquad (25)$$

then

$$V = V_o + \frac{A\, P_{AV}}{m_p} \left[1 + \frac{(\gamma-1)}{3} \frac{V^2}{g\gamma F_p}\right]^{-\gamma/\gamma-1} \qquad (26)$$

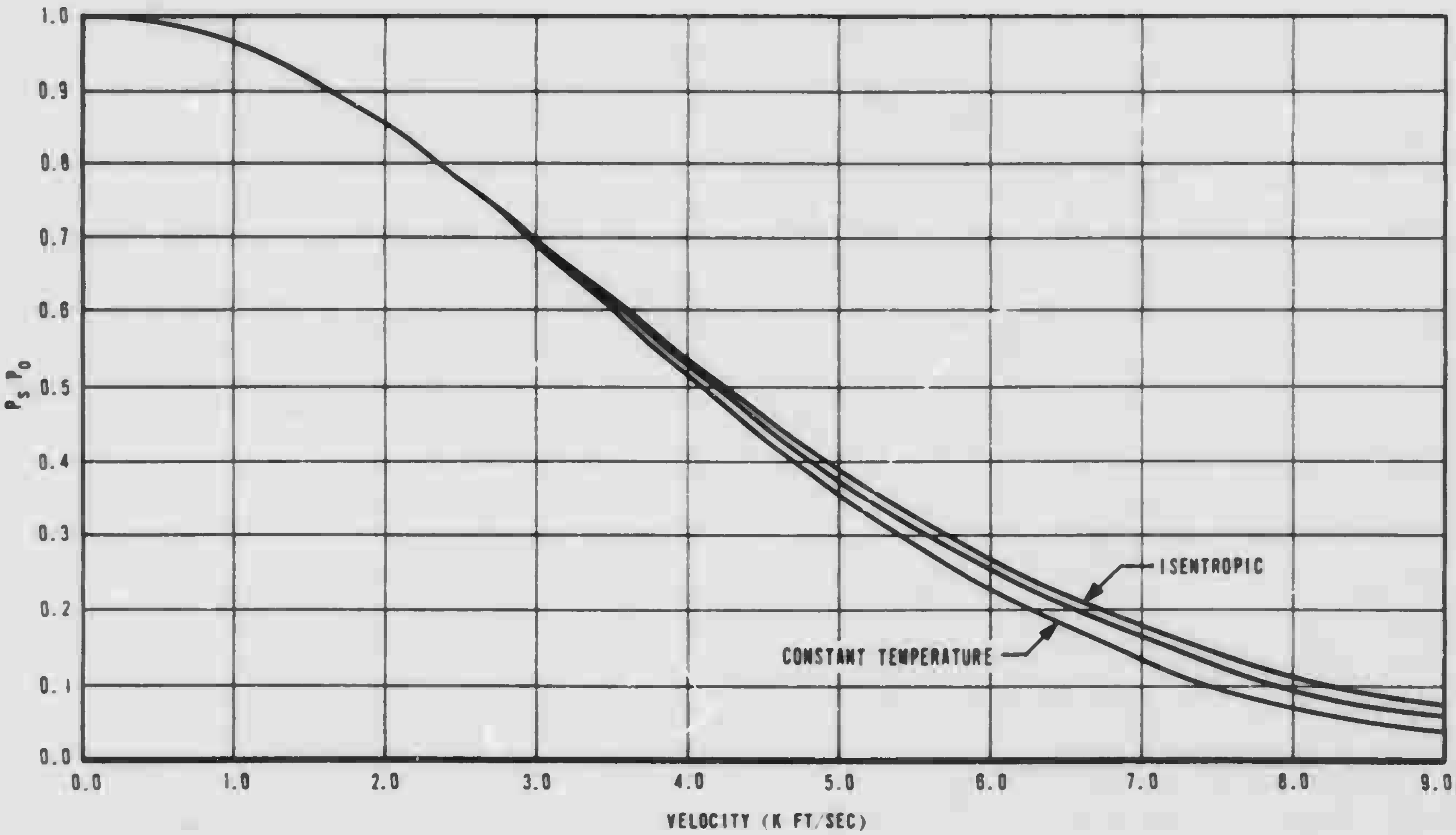


Figure 3. Shot Pressure to Static Pressure Ratio, $T = T_o$.

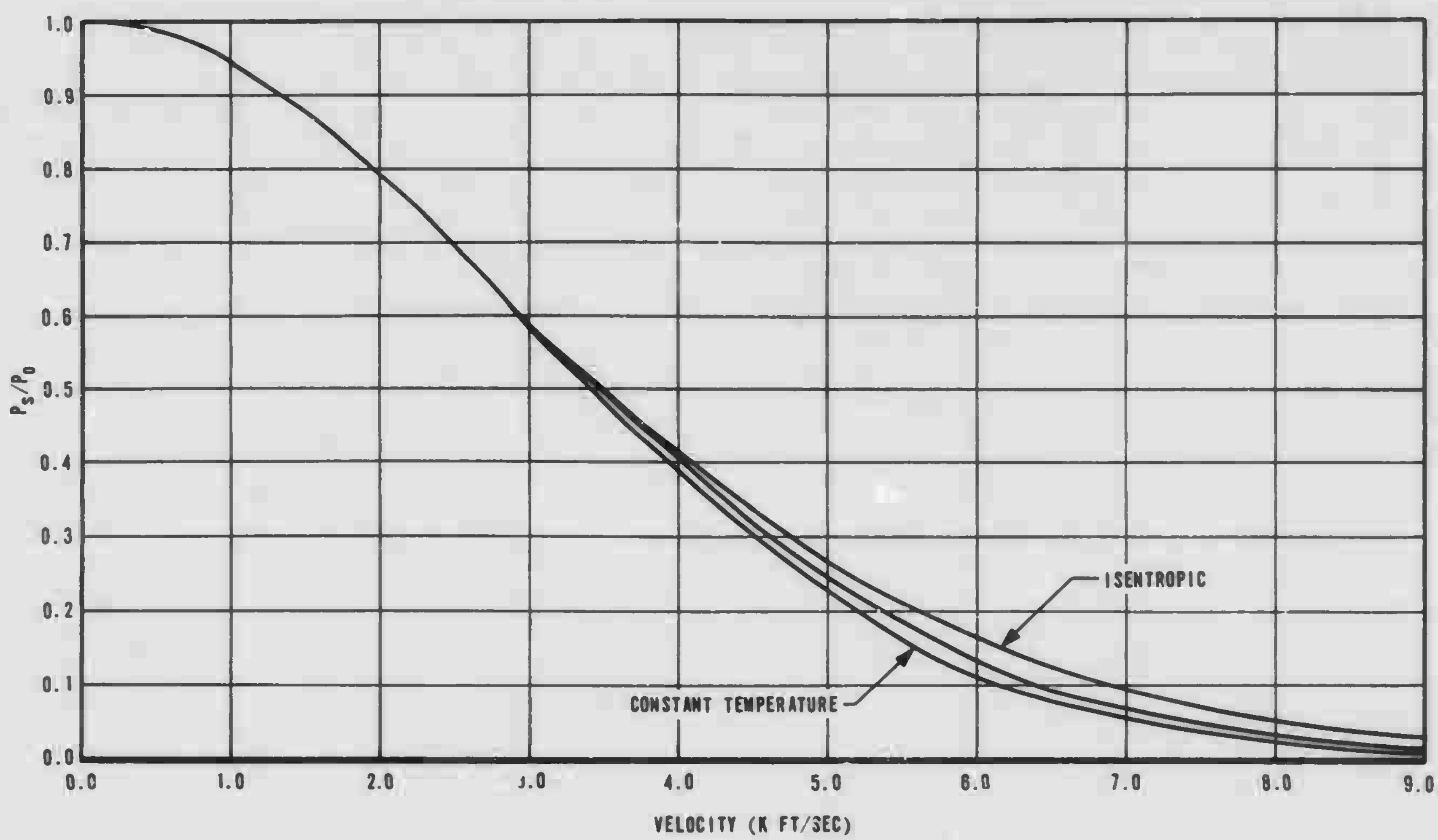


Figure 4. Shot Pressure to Static Pressure Ratio, $T = .7T_o$

Equation (26) thus provides the necessary relationship to solve for the projectile motion once the average chamber pressure is shown. The final information required is an expression for the total rates of combustion.

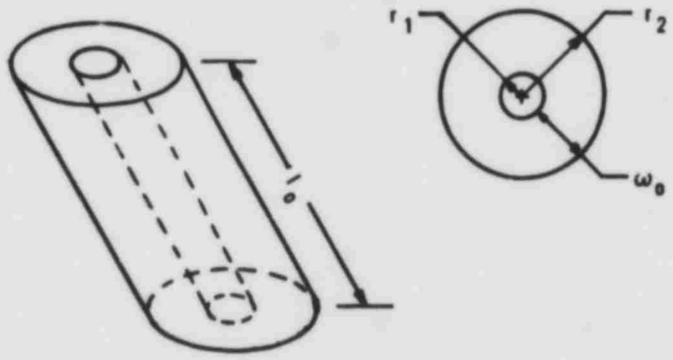
GAS PRODUCTION

The time rate of gas production is simply written as

$$\frac{dN_B}{dt} = r\ S_B\ \rho_p$$

In most prior interior ballistic formulisms the approximation $r = BP^n$ with constant N has been made. Frequently, for closed form solutions, the often questionable assumption that N = 1 is made. For a numeric solution, however, no approximations are required. Burning rates as a function of pressure, for currently used propellants, are tabulated in reference 7. These values are read into the program as data, and a tabular interpolation routine in the program determines the correct burning rate. Thus all recourse to Vielle's law has been avoided.

The surface of burning of single perforate propellants is very nearly constant as shown below. For other forms, such as cord, disk, and multiperforate, various empirical "form" functions exist to evaluate burning surface as a function of unburned web. These functions are covered in detail in references 3, 6, and 8.



$$\omega_o = r_{2,o} - r_{1,o} \quad \text{for a propellant with} \quad \frac{\omega_o}{l_o} << 1.$$

Burning surface for each grain will be

$$S_{I,o} = 2l_o\ \pi\ (r_2 + r_1)$$

after a burning increment of Δr

$$S_{I,t} = 2\, l_o \pi \left([r_2 - \Delta r] + [r_1 + \Delta r] \right) = 2\, l_o \pi (r_2 + r_1)$$

thus at all times the burning surface is constant.

Volume of grain $= l_o \pi (r_2^2 - r_1^2)$

N' = Number of grains/unit mass

Then the burning surface/unit mass of the propellant will be

$$\frac{S_B}{C_w} = \frac{S_I N'}{\rho_p V_o N'} = \frac{2\, l_o \pi (r_2 + r_1)}{\rho_p\, l_o\, \pi (r_2 - r_1)(r_2 + r_1)} = \frac{2}{\rho_p\, \omega_o}$$

or

$$S_B = \frac{2}{\rho_p\, \omega_o} C_w \qquad (27)$$

Thus equations (9), (26), and (27) plus burning rate data provide the relationships necessary to solve for peak pressure, muzzle velocity and complete pressure-time, pressure-travel, and velocity-travel of any type of closed breech weapon.

SECTION III

COMPUTER PROGRAM

INPUT DATA AND USAGE

The input data for the program is in two parts. The first is the burning rate and impetus data for the propellant and may remain unchanged as long as one type of propellant is used. The second type card delineates the exact parameters for one given case and will change for each case. Propellant data are determined from the tables in references 7 and 9.

PROPELLANT CARDS.

1st CARD

Columns	Data	Decimal Point	Units
1-8	Impetus of Propellant	7	Ft-Lb/Lb
12-16	Specific Heat Ratio of Gases	13	Dimensionless
20-24	Density of Propellant	20	Lb/In.^{2}
28-31	Covolume of Gases	30	In.^{3}/Lb
33-36	Propellant Type	Alpha Meric	

2nd AND 3rd CARDS

20 reference pressures - 10 per card from 500 to 200,000 psia.

4th AND 5th CARDS

20 burning rates taken from reference 7 at pressures listed above.

6th AND 7th CARDS

20 reference velocities taken from 0 to 12,000 ft/sec.

8th AND 9th CARDS

Density distribution factor appropriate to propellant used and corresponding to velocity listed above. Values can be extracted from Figure 2.

PROBLEM CARDS.

Columns	Data	Decimal Point	Units
1-7	Bore Area	4	$In.^2$
8-14	Chamber Volume	11	$In.^3$
15-21	Projectile Weight	19	Lb
22-28	Barrel Length	27	In.
29-35	Propellant Web	31	In.
36-42	Heat Loss	40	Dimensionless
43-49	Charge Weight	44	Lb
50-56	Shot Start Press	56	$Lb/In.^2$

As many problem cards as desired may be loaded after the data for a given propellant and will be handled sequentially by the program. Data in the above format is illustrated in Table I.

RESULTS

Typical output is illustrated in Figures 5 and 6 and Tables II and III. Output includes time from propellant ignition, chamber pressure, shot base pressure, projectile velocity, chamber pressure slope, and distance traveled for a typical 25mm. The two sample cases are identical except for a decrease in charge weight in the latter. Subsequent to the case run, additional computations of extrapolated muzzle velocity to the specified barrel length, ballistic efficiency, and piezometric efficiency are also made. Following each printed output is the pressure-travel plot generated by the computer, which is also a standard output. It should be noted that the program is currently set up to run single perforate uninhibited propellant. For other forms, a proper form function, as mentioned above, must be inserted in the program. The heat loss factor, β, has a value of between .3 to .4 for a 25mm and will be somewhat larger for smaller bores and less for larger bore weapons.

COMPUTER PROGRAM

The FORTRAN Program listing used is given as Table IV. Run time on the 7094 computer is quite short (about .05 second per case). The program number is 958, and it is being maintained by ADTC (ADTVF-2).

TABLE I. PROGRAM INPUT: TYPI

	1–10	11–20	21–30	31–
Typical Propellant Cards	346180.	1.252 .	0603 29.	69 M-1
	300.	500. 7	00. 1000	. 15
	6000.	8000. 10	000. 20000	. 300
	.13	.2	.28 .3	8 .
	1.72	2.20	2.70 4.6	6.
	0.	500. 1	000. 1500	. 200
	5000.	5500. 6	000. 6500	. 700
	3.	3.	3.05 3.1	3.
	4.05	4.3	4.55 4.8	5 5.
Case Data Cards	.761 5	. 74 .3	97 69.	.022
	.761 5	. 74 .3	97 69.	.022

…UT: TYPICAL PROPELLANT AND CASE DATA CARDS.

M-10					
1500.	2000.	2500.	3000.	4000.	5000.
30000.	40000.	50000.	70000.	100000.	200000.
.52	.68	.81	.96	1.2	1.45
6.7	8.3	9.6	12.2	15.8	25.
2000.	2500.	3000.	3500.	4000.	4500.
7000.	7500.	8000.	8500.	9000.	12000.
3.18	3.25	3.38	3.50	3.70	3.85
5.2	5.55	5.95	6.40	7.00	12.0
22 .	3 .20	4000.			
22 .	3 .18	4000.			

TABLE II. COMPUTER PRINTOUT OF 20MM PERFORMANCE 0.015 WEB.

SHOT WT.	CHARGE	WFM	H.LENGTH	CMB VOL	BORE AREA
.40	.200	.0220	69.0	5.74	.76

PROPELLANT USED IN DEVICE IS M-10

TIME	CHAMB PRES	TRAVEL	PROP BURNED	PRES SLOPE	VELOCITY	BS PRES
.0000	4000.0	.001	.0027	37466827.5	6.17	4000.0
.0000	4936.7	.004	.0060	44723334.8	13.78	4936.7
.0001	6054.8	.009	.0099	53923001.5	23.11	6054.7
.0001	7402.8	.018	.0146	63735680.1	34.52	7402.7
.0001	8996.2	.031	.0202	75458912.4	48.39	8995.9
.0001	10882.7	.048	.0267	87596429.3	65.17	10881.9
.0002	13072.6	.070	.0341	99010671.9	85.32	13070.9
.0002	15547.9	.099	.0427	111229256.8	109.28	15544.5
.0002	18328.6	.136	.0524	124020755.7	137.53	18322.1
.0002	21429.1	.183	.0635	137938537.0	170.55	21417.0
.0003	24877.6	.239	.0763	152968938.1	208.87	24855.9
.0003	28701.8	.309	.0909	167549085.0	253.06	28664.4
.0003	32840.5	.392	.1072	176296540.3	303.66	32827.6
.0003	37297.9	.492	.1251	179851798.3	361.01	37195.2
.0004	41794.2	.610	.1445	177555371.8	425.19	41631.6
.0004	46213.1	.748	.1652	167942188.3	496.08	45983.8
.0004	50431.7	.908	.1871	153298853.6	573.26	50061.8
.0004	54264.2	1.093	.2102	134076228.8	656.09	53733.5
.0005	57616.1	1.303	.2343	111180355.0	743.78	56879.4
.0005	60345.6	1.540	.2592	85908750.3	835.37	59405.4
.0005	62543.3	1.805	.2847	59766233.0	929.80	61253.2
.0005	64037.4	2.098	.3107	34247727.2	1026.00	62405.8
.0006	64843.6	2.420	.3369	10637852.3	1122.95	62887.1
.0006	65159.6	2.772	.3632	-10126502.8	1219.70	62755.0
.0006	64906.4	3.152	.3894	-27508989.0	1315.42	62092.0
.0006	64218.7	3.561	.4154	-41348734.5	1409.45	60993.7
.0007	63185.0	3.997	.4411	-51783295.0	1501.27	59558.5
.0007	61890.4	4.461	.4665	-59150429.2	1590.50	57879.3
.0007	60411.6	4.951	.4914	-63879372.3	1676.89	56038.3
.0007	58814.6	5.467	.5158	-66465412.9	1760.30	54105.2
.0008	57153.0	6.007	.5397	-67365417.6	1840.68	52135.2
.0008	55468.9	6.571	.5632	-66986763.1	1918.02	50170.8
.0008	53794.2	7.157	.5861	-65674414.0	1992.40	48243.3
.0008	52152.3	7.766	.6085	-63709183.9	2063.89	46374.6
.0009	50559.6	8.395	.6305	-61315026.5	2132.62	44579.1
.0009	49026.7	9.045	.6521	-58659080.6	2198.70	42865.5
.0009	47560.3	9.714	.6732	-55868375.1	2262.28	41238.3
.0009	46163.6	10.402	.6938	-53036011.8	2323.48	39698.7
.0010	44837.7	11.108	.7141	-50228279.9	2382.44	38245.8
.0010	43582.0	11.831	.7341	-47490913.4	2439.29	36877.2
.0010	42399.7	12.571	.7536	-44854162.1	2494.16	35589.3
.0010	41273.3	13.327	.7729	-42336798.0	2547.16	34378.2
.0011	40214.9	14.099	.7918	-39942959.8	2598.40	33239.6
.0011	39216.4	14.886	.8104	-37636121.4	2647.99	32169.2
.0011	38270.4	15.688	.8286	-35874577.8	2696.03	31159.4
.0011	37373.6	16.503	.8465	-34016712.2	2742.60	30205.8
.0012	36523.1	17.333	.8641	-32231274.3	2787.77	29305.0
.0012	35716.6	18.176	.8814	-30606694.1	2831.64	28453.8
.0012	34951.4	19.032	.8985	-29049746.5	2874.26	27648.8
.0012	34225.2	19.900	.9152	-27586372.1	2915.72	26887.0

.0011	34216.3	14.886	.8104	-37836121.4	2647.99	32169.2
.0011	34270.4	15.688	.8286	-35874977.8	2696.03	31159.4
.0011	37373.6	16.503	.8465	-34016718.2	2742.60	30205.8
.0012	36523.1	17.333	.8641	-32261274.3	2787.77	29305.0
.0012	35716.6	18.176	.8814	-30606694.1	2831.64	28453.8
.0012	34451.4	19.032	.8985	-29049746.5	2874.26	27648.8
.0012	34225.2	19.900	.9152	-27586372.1	2915.72	26887.0
.0013	33535.5	20.781	.9317	-26212013.9	2956.05	26165.7
.0013	32880.2	21.674	.9480	-24921858.7	2995.34	25482.1
.0013	32257.2	22.578	.9640	-23711010.3	3033.62	24833.7
.0013	31666.4	23.494	.9799	-22574981.6	3070.96	24218.2
.0014	31100.0	24.421	.9955	-21508658.8	3107.39	23633.4
.0014	30562.3	25.358	1.0109	-20507440.1	3142.97	23077.3
.0014	30049.6	26.306	1.0109	-45125915.0	3177.73	22548.0
.0014	28421.5	27.264	1.0109	-42079247.1	3210.98	21567.3
.0015	27869.5	28.233	1.0109	-39307761.8	3242.83	20658.7
.0015	26888.8	29.210	1.0109	-36781676.8	3273.38	19815.2
.0015	25967.3	30.198	1.0109	-34474815.8	3302.72	19030.6
.0015	25105.4	31.191	1.0109	-32364149.2	3330.93	18299.5
.0016	24296.1	32.195	1.0109	-30429391.5	3358.09	17617.0
.0016	23535.6	33.206	1.0109	-28652649.5	3384.26	16978.6
.0016	22819.2	34.225	1.0109	-27018116.0	3409.51	16380.7
.0016	22143.8	35.252	1.0109	-25511803.9	3433.90	15819.7
.0017	21506.0	36.285	1.0109	-24121315.8	3457.48	15292.5
.0017	20903.0	37.326	1.0109	-22835643.9	3480.29	14796.4
.0017	20332.1	38.373	1.0109	-21644997.4	3502.38	14328.9
.0017	19790.4	39.427	1.0109	-20540575.0	3523.79	13887.7
.0018	19277.4	40.488	1.0109	-19514094.1	3544.56	13470.7
.0018	18789.6	41.554	1.0109	-18559266.0	3564.72	13076.3
.0018	18325.6	42.626	1.0109	-17669837.6	3584.30	12702.7
.0018	17883.4	43.705	1.0109	-16840198.1	3603.34	12348.3
.0019	17462.8	44.788	1.0109	-16065304.5	3621.85	12011.9
.0019	17061.2	45.878	1.0109	-15340616.5	3639.88	11692.1
.0019	16677.7	46.972	1.0109	-14662039.4	3657.43	11387.9
.0019	16311.1	48.072	1.0109	-14025874.4	3674.54	11098.2
.0020	15960.5	49.177	1.0109	-13428774.7	3691.23	10821.9
.0020	15624.8	50.287	1.0109	-12867707.7	3707.50	10558.3
.0020	15303.1	51.401	1.0109	-12339921.0	3723.39	10306.6
.0020	14994.6	52.521	1.0109	-11842912.5	3738.91	10065.9
.0021	14698.5	53.645	1.0109	-11374404.7	3754.07	9835.6
.0021	14414.2	54.773	1.0109	-10932321.5	3768.90	9615.2
.0021	14140.4	55.906	1.0109	-10514767.4	3783.40	9403.9
.0021	13878.0	57.043	1.0109	-10120009.8	3797.58	9201.3
.0022	13625.0	58.184	1.0109	-9746462.7	3811.47	9006.8
.0022	13381.3	59.330	1.0169	-9392672.2	3825.06	8820.0
.0022	13146.5	60.479	1.0109	-9057304.3	3838.38	8640.5
.0022	12920.1	61.633	1.0109	-8739133.1	3851.44	8467.9
.0023	12701.6	62.790	1.0109	-8437030.6	3864.24	8301.8
.0023	12490.7	63.951	1.0109	-8149958.1	3876.79	8141.8
.0023	12286.9	65.116	1.0109	-7876957.4	3889.10	7987.7
.0023	12090.0	66.285	1.0109	-7617144.3	3901.19	7839.0
.0024	11899.6	67.457	1.0109	-7369701.3	3913.05	7695.7
.0024	11715.3	68.633	1.0109	-7133872.1	3924.70	7557.3
.0024	11537.0	69.812	1.0109	-6908956.3	3936.15	7423.6

PIEZOMETRIC PRESSURE IS 21734.75

MUZZLE VELOCITY IS 3928.3 FEET PER SECOND

PIEZOMETRIC EFFICIENCY IS 33.4 PERCENT

CORRECTED PIEZOMETRIC EFFICIENCY IS 37.9 PERCENT

BALLISTIC EFFICIENCY IS 34.7 PERCENT

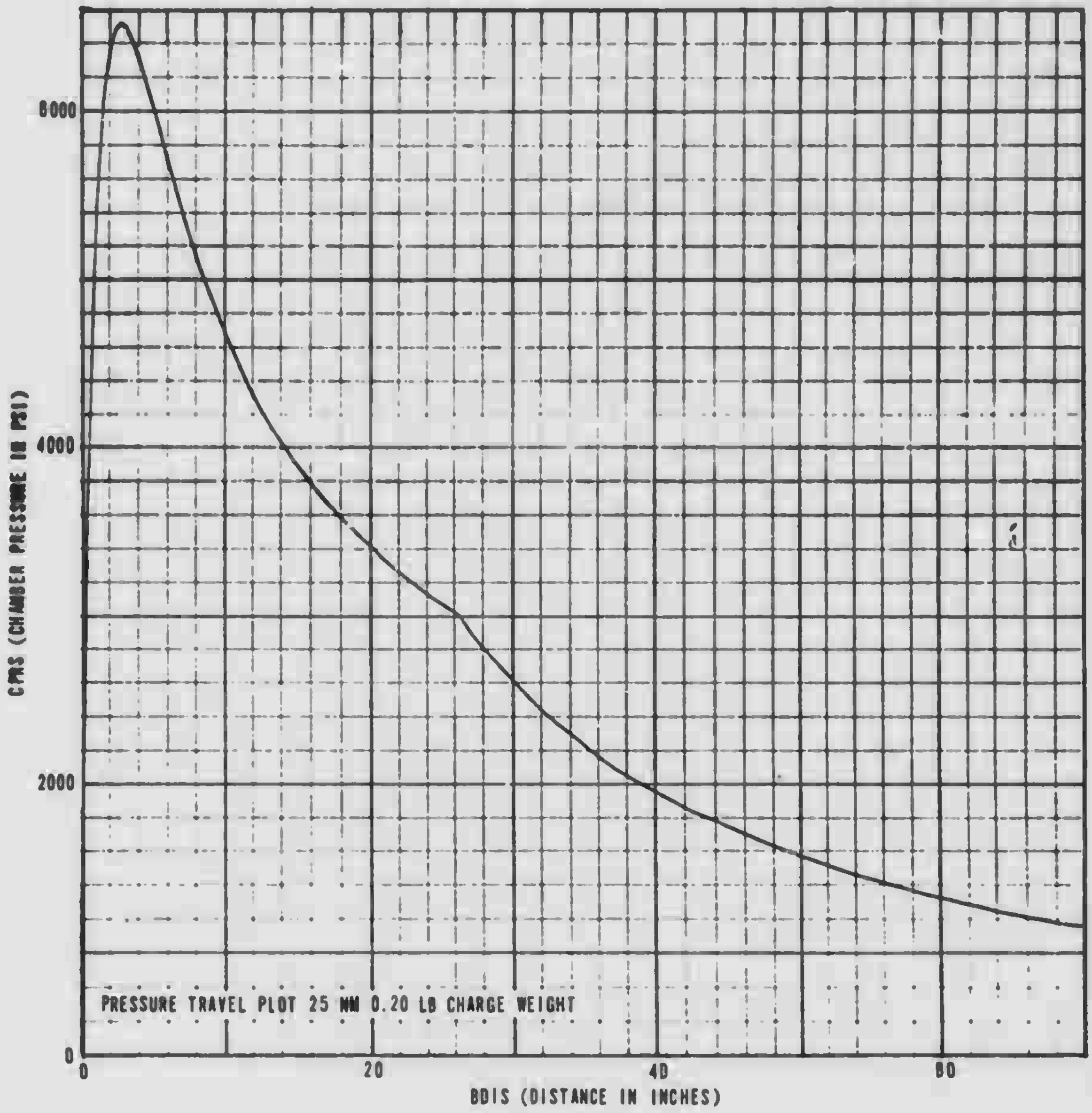


Figure 5. Graph of 20mm Performance 0.015 Web.

 (The reverse of this page is blank.)

TABLE III. COMPUTER PRINTOUT OF 20MM PERFORMANCE 0.020 WEB.

SHOT WT.	CHARGE	WEB	B.LENGTH	CHB VOL	BORE AREA
.40	.180	.0220	69.0	5.74	.76

PROPELLANT USED IN DEVICE IS M-10

A

TIME	CHAMB PRES	TRAVEL	PROP BURNED	PRES SLOPE	VELOCITY	BS PRES
.0000	4000.0	.001	.0027	29640546.3	6.17	4000.0
.0000	4741.0	.004	.0059	34139304.6	13.48	4741.0
.0001	5594.5	.009	.0095	39557022.5	22.10	5594.5
.0001	6583.4	.017	.0138	45465753.5	32.25	6583.3
.0001	7720.1	.029	.0186	51788485.4	44.15	7719.8
.0001	9016.8	.044	.0242	59074131.1	58.05	9014.3
.0002	10491.6	.064	.0305	66498321.2	74.22	10490.6
.0002	12154.1	.089	.0376	72872565.5	92.95	12152.1
.0002	13975.9	.120	.0455	79411508.7	114.49	13972.3
.0002	15961.2	.158	.0542	85970003.4	139.09	15954.9
.0003	18110.4	.204	.0638	92360045.9	167.00	18100.0
.0003	20419.4	.259	.0745	98556620.7	198.45	20402.4
.0003	22883.4	.324	.0863	105099001.4	233.69	22856.4
.0003	25510.8	.400	.0994	110832996.5	272.95	25469.2
.0004	28281.7	.488	.1138	115404895.7	316.45	28216.7
.0004	31186.8	.590	.1294	117065760.1	364.36	31073.5
.0004	34093.4	.707	.1461	114717553.1	416.71	33958.3
.0004	36961.4	.841	.1639	110128894.4	473.40	36769.9
.0005	39714.6	.992	.1827	103277387.3	534.21	39449.3
.0005	42296.5	1.162	.2022	92795849.9	598.86	41937.1
.0005	44616.4	1.352	.2224	80477086.9	666.91	44140.6
.0005	46628.3	1.563	.2433	66976117.0	737.85	46012.5
.0006	48302.7	1.795	.2646	52837290.0	811.11	47523.3
.0006	49623.7	2.050	.2863	38621883.1	886.13	48657.9
.0006	50589.2	2.327	.3083	24854665.1	962.31	49416.8
.0006	51210.6	2.627	.3305	11979920.5	1039.11	49814.5
.0007	51510.1	2.950	.3527	333017.8	1116.00	49877.2
.0007	51518.4	3.297	.3750	-9870462.7	1192.53	49640.2
.0007	51271.7	3.666	.3972	-18529847.0	1268.29	49143.9
.0007	50808.4	4.057	.4192	-25643059.4	1342.95	48431.4
.0008	50167.3	4.471	.4411	-31284109.7	1416.25	47544.8
.0008	49385.2	4.907	.4627	-35579106.8	1487.98	46524.4
.0008	48495.8	5.364	.4841	-38684249.1	1557.98	45406.0
.0008	47528.6	5.841	.5052	-40761914.1	1626.15	44221.3
.0009	46509.6	6.339	.5260	-41984575.4	1692.44	42997.1
.0009	45460.0	6.857	.5465	-42509956.2	1756.81	41755.5
.0009	44397.2	7.393	.5666	-42478766.8	1819.27	40513.9
.0009	43335.3	7.948	.5865	-42013847.4	1879.83	39286.3
.0010	42284.9	8.521	.6060	-41218803.8	1938.54	38083.1
.0010	41254.5	9.111	.6252	-40180924.8	1995.45	36911.9
.0010	40249.9	9.718	.6442	-38970827.1	2050.60	35778.0
.0010	39275.7	10.341	.6628	-37809060.2	2104.08	34685.2
.0011	38330.4	10.980	.6810	-36602359.1	2155.93	33631.7
.0011	37415.4	11.634	.6990	-35328732.4	2206.21	32618.3
.0011	36532.2	12.303	.7166	-34019064.8	2255.00	31645.7
.0011	35681.7	12.987	.7339	-32697370.3	2302.35	30714.1
.0012	34864.2	13.686	.7509	-31382032.2	2348.32	29823.1
.0012	34079.7	14.394	.7676	-30086870.3	2392.99	28971.8
.0012	33327.5	15.120	.7840	-28822040.7	2436.40	28159.2
.0012	32607.0	15.857	.8002	-27594785.8	2478.62	27383.9
.0013	31917.1	16.607	.8161	-26410050.2	2519.69	26644.4
.0013	31256.9	17.369	.8318	-25269548.5	2559.68	25939.1
.0013	30625.1	18.143	.8472	-24175207.3	2598.63	25266.6
.0013	30020.7	18.928	.8625	-23129531.4	2636.60	24625.1

(The

.0012	34804.2	13.685	.7509	-31382032.7	[illegible]	[illegible]
.0012	34079.7	14.396	.7676	-30086870.3	2392.99	28971.8
.0012	33327.5	15.120	.7840	-28822040.7	2436.40	28154.2
.0012	32617.0	15.857	.8002	-27594785.8	2476.62	27383.9
.0013	31917.1	16.607	.8161	-26410050.2	2519.69	26644.4
.0013	31256.4	17.369	.8318	-25269548.5	2559.68	25939.1
.0013	30625.1	18.143	.8472	-24175267.3	2598.63	25266.6
.0013	30020.7	18.928	.8625	-23124531.4	2636.60	24625.1
.0014	29442.5	19.725	.8774	-22252694.4	2673.62	24013.3
.0014	28886.2	20.532	.8921	-21411411.8	2709.73	23420.9
.0014	28350.4	21.350	.9066	-20601758.3	2744.98	22865.0
.0014	27845.8	22.179	.9208	-19824036.6	2779.40	22326.3
.0015	27360.2	23.018	.9347	-19078141.0	2813.03	21809.8
.0015	26883.3	23.857	.9485	-18363653.9	2845.89	21314.4
.0015	26404.2	24.725	.9620	-17679923.4	2878.01	20839.2
.0015	25982.2	25.593	.9753	-17026125.4	2909.44	20383.2
.0016	25536.5	26.471	.9884	-16401314.0	2940.18	19945.4
.0016	25126.5	27.357	1.0013	-15804460.4	2970.28	19524.9
.0016	24731.4	28.253	1.0013	-32581343.4	2999.76	19120.9
.0016	23916.4	29.157	1.0013	-30691354.3	3028.13	18348.9
.0017	23149.6	30.070	1.0013	-28946863.2	3055.45	17722.5
.0017	22425.4	30.990	1.0013	-27334430.7	3081.79	17087.7
.0017	21742.6	31.919	1.0013	-25842146.4	3107.22	16441.3
.0017	21096.5	32.854	1.0013	-24459286.1	3131.77	15930.2
.0018	20485.0	33.798	1.0013	-23176143.6	3155.52	15401.6
.0018	19905.6	34.748	1.0013	-21984164.9	3178.49	14903.0
.0018	19356.0	35.705	1.0013	-20875373.2	3200.74	14432.1
.0018	18834.1	36.668	1.0013	-19842728.6	3222.31	13986.9
.0019	18338.1	37.638	1.0013	-18879847.6	3243.22	13565.5
.0019	17866.1	38.614	1.0013	-17980956.0	3263.52	13166.1
.0019	17416.5	39.596	1.0013	-17140829.4	3283.23	12787.2
.0019	16988.0	40.584	1.0013	-16354735.5	3302.39	12427.4
.0020	16579.1	41.577	1.0013	-15618383.5	3321.02	12085.4
.0020	16188.7	42.576	1.0013	-14927878.1	3339.15	11759.9
.0020	15815.5	43.581	1.0013	-14279679.3	3356.80	11450.0
.0020	15458.5	44.590	1.0013	-13670505.8	3374.00	11154.5
.0021	15116.7	45.605	1.0013	-13097603.5	3390.76	10872.6
.0021	14789.3	46.625	1.0013	-12558116.2	3407.11	10603.4
.0021	14475.3	47.649	1.0013	-12049660.5	3423.06	10346.0
.0021	14174.1	48.678	1.0013	-11570002.6	3438.63	10099.9
.0022	13884.6	49.712	1.0013	-11117098.5	3453.83	9864.3
.0022	13606.4	50.751	1.0013	-10689075.2	3468.69	9638.6
.0022	13339.7	51.793	1.0013	-10284214.7	3483.22	9422.2
.0022	13082.6	52.841	1.0013	-9900939.6	3497.42	9214.6
.0023	12835.1	53.892	1.0013	-9537799.6	3511.32	9015.3
.0023	12596.6	54.947	1.0013	-9193312.7	3524.93	8823.8
.0023	12366.8	56.007	1.0013	-8866382.2	3538.25	8639.8
.0023	12145.1	57.070	1.0013	-8555907.7	3551.29	8462.7
.0024	11931.2	58.137	1.0013	-8260840.5	3564.08	8292.3
.0024	11724.7	59.209	1.0013	-7980211.6	3576.61	8128.2
.0024	11525.2	60.283	1.0013	-7713125.1	3588.89	7970.0
.0024	11332.4	61.362	1.0013	-7458750.9	3600.95	7817.5
.0025	11145.9	62.444	1.0013	-7216320.0	3612.77	7670.4
.0025	10965.5	63.530	1.0013	-6985119.2	3624.38	7528.4
.0025	10790.9	64.619	1.0013	-6754486.1	3635.77	7391.3
.0025	10621.8	65.711	1.0013	-6553805.3	3646.96	7258.8
.0026	10457.9	66.807	1.0013	-6352504.3	3657.96	7130.7
.0026	10299.1	67.906	1.0013	-6160050.2	3668.76	7006.8
.0026	10145.1	69.008	1.0013	-5975946.2	3679.37	6886.9

PIEZOMETRIC PRESSURE IS 19071.38

MUZZLE VELOCITY IS 3679.3 FEET PER SECOND

PIEZOMETRIC EFFICIENCY IS 47.0 PERCENT

CORRECTED PIEZOMETRIC EFFICIENCY IS 41.7 PERCENT

BALLISTIC EFFICIENCY IS 33.8 PERCENT

(The reverse of this page is blank.)

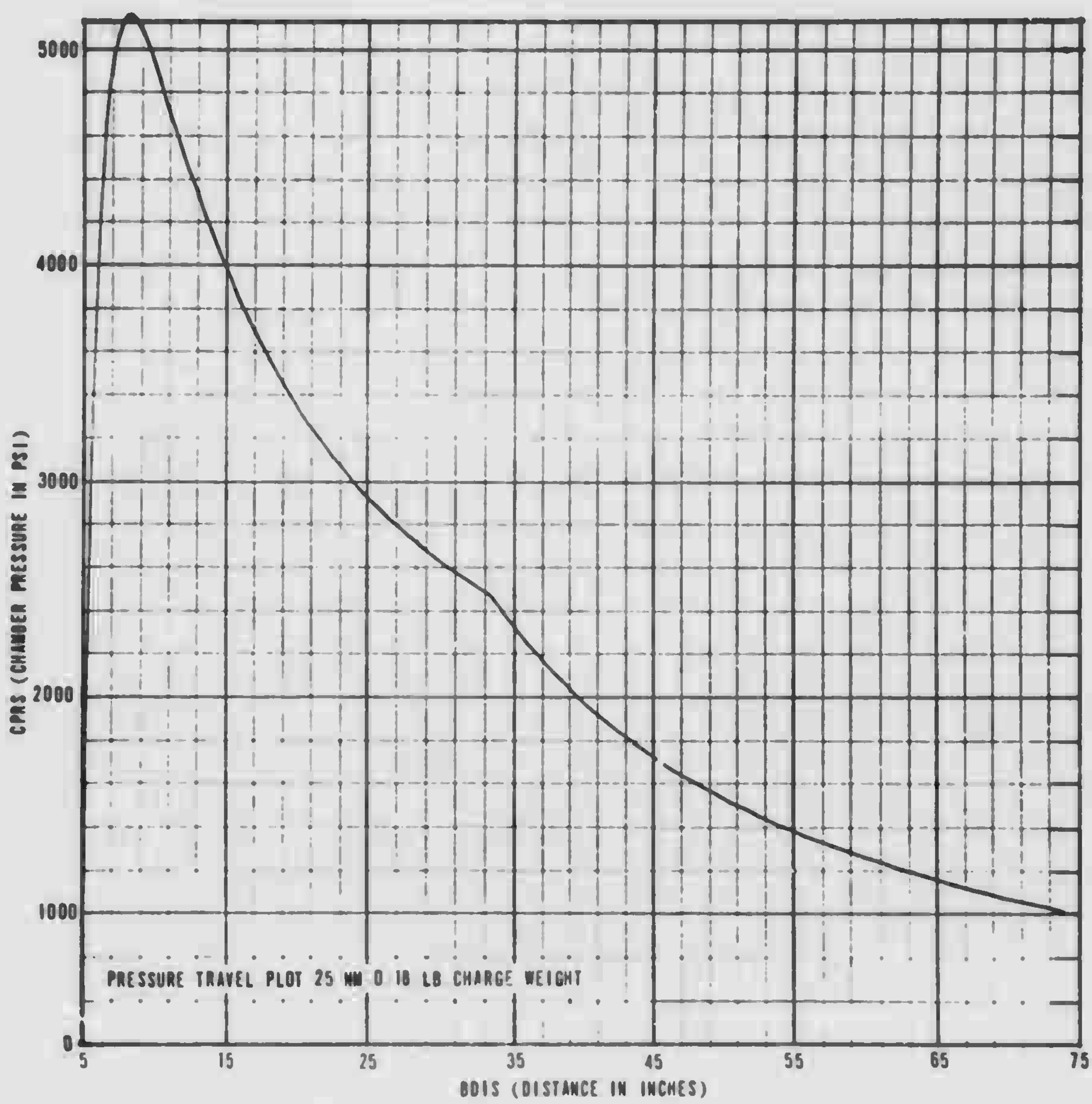


Figure 6. Graph of 20mm Performance 0.020 Web.

TABLE IV. INTERIOR BALLISTIC PROGRAM FORTRAN 4 LISTING.

```
PROGRAM    P095H     FORTRAN EXTENDED V 1.0              28/03/69            15.19.47.
              PROGRAM P095H(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,FILMPL)    P095800 00001
        $JOB          F99 SADLER, J   11102543V1 H958-2 095AG1 00109    9    P0958   00003
        $*  O/P H9  PLOT                                                     P0958   00004
        $EXECUTE        IHJOH                                                P0958   00005
        $IAJOH          MAP                                                  P0958   00006
        $IHETC 95H                                                           P0958   00007
              COMMON/   /PCPRS(1000),PHDIS(1000),RUN,PTOP,NPTS               P0958   00008
              DIMENSION PSY(20),VEE(20)                                      P0958   00009
              DIMENSION PRS(20),RATE(20),TYPE(8)                             P0958   00010
              READ(5,3)FIMP,GAMA,RHO,CVL,(TYPE(N),N=1,4)                     P0958   00011
            3 FORMAT(F8.1,F8.3,F8.4,F8.2,4A2)                                P0958   00012
              READ(5,4)PRS                                                   P0958   00013
            4 FORMAT(10F8.1)                                                 P0958   00014
              READ(5,5)RATE                                                  P0958   00015
            5 FORMAT(10F8.3)                                                 P0958   00016
              READ(5,24)VEE                                                  P0958   00017
           24 FORMAT(10F8.1)                                                 P0958   00018
              READ(5,26)PSY                                                  P0958   00019
           26 FORMAT(10F8.3)                                                 P0958   00020
              PIT=1.5                                                        P0958   00021
              TAD=GAMA/(GAMA-1.)                                             P0958   00022
            6 READ(5,7)AREA,CVOL,SHOT,RUN,WEB,BETA,CHG,SCPRS                 P0958   00023
            7 FORMAT(F7.3,F7.3,F7.3,F7.1,F7.4,F7.2,F7.3,F8.1)                P0958   00024
              NPTS=0                                                         P0958   00025
              HP=0.                                                          P0958   00026
              VEL=0.                                                         P0958   00027
              RARE=2.*CHG/(RHO*WEB)                                          P0958   00028
              WRITE(6,8)                                                     P0958   00029
            8 FORMAT(1H1,61H  SHOT WT.   CHARGE      WEB    B.LENGTH   CHB VOL  P0958   00030
             1HORE AREA//)                                                   P0958   00031
              WRITE(6,9)SHOT,CHG,WEB,RUN,CVOL,AREA                           P0958   00032
            9 FORMAT(F10.2,F10.3,F10.4,F10.1,F10.2,F10.2///)                 P0958   00033
              WRITE(6,35)(TYPE(N),N=1,4)                                     P0958   00034
           35 FORMAT(32H  PROPELLANT USED IN DEVICE IS  ,4A2,///)            P0958   00035
              WRITE(6,27)                                                    P0958   00036
           27 FORMAT(101H          TIME        CHAMB PRES        TRAVEL     PRO P0958   00037
             1P BURNED   PRES SLOPE        VELOCITY   BS PRES//)             P0958   00038
              HP=0.0                                                         P0958   00039
              VEL2=0.                                                        P0958   00040
```

```
      BDTS=0.0                                                          P0958    00041
      PTOP=3000.                                                        P0958    00042
      CPRS=SCPRS                                                        P0958    00043
      GAMB=(1.+BETA)*(GAMA-1.)                                          P0958    00044
      DO 39 J=1,750,1                                                   P0958    00045
   74 JA=1                                                              P0958    00046
   78 IF(CPRS-PRS(JA))77,76,75                                          P0958    00047
   75 JA=JA+1                                                           P0958    00048
      GO TO 78                                                          P0958    00049
   76 R=RATE(JA)                                                        P0958    00050
      GO TO 10                                                          P0958    00051
   77 DIT=PRS(JA)-PRS(JA-1)                                             P0958    00052
      DAT=RATE(JA)-RATE(JA-1)                                           P0958    00053
      PIG=CPRS-PRS(JA-1)                                                P0958    00054
      DIM=((PIG/DIT)*DAT)                                               P0958    00055
      R=RATE(JA-1)+DIM                                                  P0958    00056
   10 IF (BP-CHG)11,80,80                                               P0958    00057
   80 DNDT=0                                                            P0958    00058
      GO TO 12                                                          P0958    00059
   11 DNDT=R*RHO*BARE                                                   P0958    00060
      BP=BP+(DNDT*.000025)                                              P0958    00061
   12 VEL1=VEL2                                                         P0958    00062
      RTM=(VEL2*VEL2)/(GAMA*32.17*FIMP*PIT)                             P0958    00063
      ROOT=1./(1.+(((GAMA-1.)/2.)*RTM))                                 P0958    00064
      TUT=ROOT**TAU                                                     P0958    00065
      PREX=CPRS*TUT                                                     P0958    00066
      KO=1                                                              P0958    00067
   50 IF(VEE(KO)-VEL2)51,52,53                                          P0958    00068
   51 KO=KO+1                                                           P0958    00069
      GO TO 50                                                          P0958    00070
   52 PFAC=PSY(KO)                                                      P0958    00071
      GO TO 59                                                          P0958    00072
   53 HAG=(VEL2-VEE(KO-1))/(VEE(KO)-VEE(KO-1))                          P0958    00073
      PFAC=((PSY(KO)-PSY(KO-1))*HAG)+PSY(KO-1)                          P0958    00074
   59 EFM=(SHOT+(CHG/PFAC))/32.17                                       P0958    00075
      ACEL=PREX*AREA*32.17/SHOT                                         P0958    00076
      VEL2=VEL1+(ACEL*.000025)                                          P0958    00077
      ACOL=(ACEL*.000025)/2.                                            P0958    00078
      BINC=(VEL1*.000025)+(ACOL*.000025)                                P0958    00079
      BDTS=BDIS+(BINC*12.)                                              P0958    00080
   13 AVOL=CVOL+(BDIS*AREA)                                             P0958    00081
      DLDT=VEL2                                                         P0958    00082
      UBW=(CHG-BP)/RHO                                                  P0958    00083
      COVL=CVL*BP                                                       P0958    00084
      DPDT=((DNDT*FIMP*12.)-((GAMB*EFM*ACEL*VEL2*12.)+(AREA*PREX*VEL1*12 P0958    00085
     1.)))/(AVOL-(UBW+COVL))                                            P0958    00086
      DOPE=J                                                            P0958    00087
      TIME=DOPE*.000025                                                 P0958    00088
      FPU=BP/CHG                                                        P0958    00089
      IF(CPRS.GT.PTOP) PTOP=CPRS                                        P0958    00090
   15 WRITE(6,17)TIME,CPRS,BDIS,FPU,DPDT,DLDT,PREX                      P0958    00091
```

```
      IF(CPRS.GT.PTOP) PTOP=CPRS                                        P0958    00090
   15 WRITE(6,17)TIME,CPRS,BDIS,FPU,DPDT,DLDT,PREX                      P0958    00091
   17 FORMAT(F15.4,F15.1,F15.3,F15.4,F15.1,F15.2,F10.1)                 P0958    00092
      NPTS=NPTS+1                                                       P0958    00093
      PCPRS(NPTS)=CPRS                                                  P0958    00094
      PBDIS(NPTS)=BDIS                                                  P0958    00095
      CPRS=CPRS+(DPDT*.000025)                                          P0958    00096
      IF(BDIS.GE.RUN) GO TO 79                                          P0958    00097
   39 CONTINUE                                                          P0958    00098
   79 DELV=VEL2-VEL1                                                    P0958    00099
      ORUN=BDIS-RUN                                                     P0958    00100
      ADV=(1.-(ORUN/(BINC*12.)))*DELV                                   P0958    00101
      VM=VEL1+ADV                                                       P0958    00102
      AO=(VM*VM/RUN)*SHOT*12./(AREA*64.4)                               P0958    00103
      WRITE(6,40)AO                                                     P0958    00104
   40 FORMAT(//25H PIEZOMETRIC PRESSURE IS ,F9.2,//)                    P0958    00105
      WRITE(6,41)VM                                                     P0958    00106
   41 FORMAT(/19H MUZZLE VELOCITY IS,F8.1,16H FEET PER SECOND/)         P0958    00107
      AR=AO/PTOP                                                        P0958    00108
      AF=AR*100.                                                        P0958    00109
      WRITE(6,42)AF                                                     P0958    00110
   42 FORMAT(//26H PIEZOMETRIC EFFICIENCY IS,F7.1,8H PERCENT)           P0958    00111
      AB=(AF*EFM*32.17)/SHOT                                            P0958    00112
      FKE=(VM*VM*SHOT)/(2.*32.17)                                       P0958    00113
      TE=CHG*FIMP/(GAMA-1.)                                             P0958    00114
      BE=FKE/TE*100.                                                    P0958    00115
      WRITE(6,44)AB                                                     P0958    00116
   44 FORMAT(//36H CORRECTED PIEZOMETRIC EFFICIENCY IS,F7.1,8H PERCENT) P0958    00117
      WRITE(6,43)BE                                                     P0958    00118
   43 FORMAT(//24H BALLISTIC EFFICIENCY IS,F8.1,8H PERCENT)             P0958    00119
      CALL BPLOT                                                        P0958    00120
      GO TO 6                                                           P0958    00121
      END                                                               P0958    00122
$IBFTC BPLOT                                                            P0958    00123
      SUBROUTINE BPLOT                                                  P0958    00124
      COMMON/   /PCPRS(1000),PBDIS(1000),RUN,PTOP,NPTS                  P0958    00125
      L=0                                                               P0958    00126
      XL=PBDIS(1)                                                       P0958    00127
      XR=PBDIS(NPTS)                                                    P0958    00128
      YB=PCPRS(1)                                                       P0958    00129
      YT=PTOP                                                           P0958    00130
      CALL DXDYV(1,XL,XR,DX,N,I,NX,20.0,IERR)                           P0958    00131
      CALL DXDYV(2,YB,YT,DY,M,J,NY,20.0,IERR)                           P0958    00132
      I=-I                                                              P0958    00133
      J=-J                                                              P0958    00134
      CALL GRIDIV(L,XL,XR,YB,YT,DX,DY,N,M,I,J,NX,NY)                    P0958    00135
      CALL PRINTV(-4,4HBDIS,500,10)                                     P0958    00136
      CALL APRNTV(0,-14,-4,4HCPRS,10,500)                               P0958    00137
C     CALL APLOTV(NPTS,PT(1),PR1(1),1,1,1,55,IERR)                      P0958    00138
C     CALL APLOTV(NPTS,PT(1),PR2(1),1,1,1,38,IERR)                      P0958    00139
      IX1=NXV(PBDIS(1))                                                 P0958    00140
      IY1=NYV(PCPRS(1))                                                 P0958    00141
      DO 300 IKK=2,NPTS                                                 P0958    00142
      IX2=NXV(PBDIS(IKK))                                               P0958    00143
      IY2=NYV(PCPRS(IKK))                                               P0958    00144
      CALL LINEV(IX1,IY1,IX2,IY2)                                       P0958    00145
      IX1=IX2                                                           P0958    00146
      IY1=IY2                                                           P0958    00147
  300 CONTINUE                                                          P0958    00148
      RETURN                                                            P0958    00149
      END                                                               P0958    00150
```

(The reverse of this page is blank.)

SECTION IV

EXPERIMENTAL RESULTS

NORMAL DEFLAGRATION

The validity of the preceding analysis is easily assessed by measuring the pressure-time history and muzzle velocity of a given device and correlating the results with those predicted by the theory. This experimental effort was conducted at the Jet Propulsion Laboratory of the California Institute of Technology under NASA sponsorship. The device which was used for this purpose is shown in Figure 7.

Figure 7. Device to Measure Pressure-Time History and Muzzle Velocity.

Pressures were measured in the chamber and at two additional points down the barrel by means of high-pressure Kistler piezometric pressure transducers feeding Kistler charge amplifiers and recorded on persistent phosphor Techtronix oscilloscopes. Muzzle velocities were measured by means of break screens connected to Hewlett-Packard digital clocks.

The launch tube was of smooth bore configuration and for maximum flexibility was constructed with a uniform bore diameter rather than with an expanded chamber; this design allows an infinitely variable chamber volume. Ignition and propellant loading techniques are shown in Figure 8.

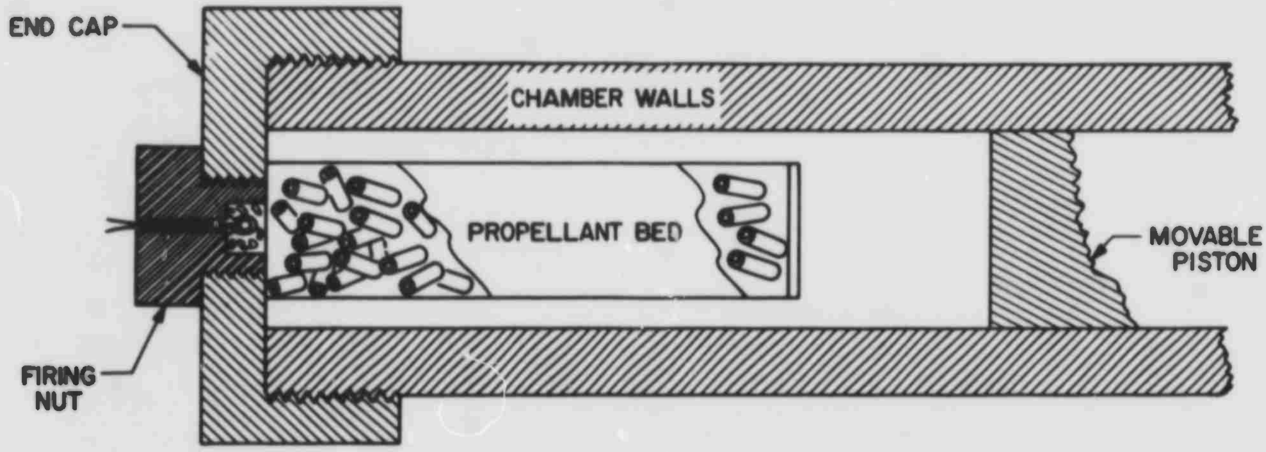


Figure 8. Ignition and Propellant Loading Techniques.

The initial chamber volume is determined by the location of the piston base while the loading volume is a function of the diameter and length of the phenolic sleeve into which the propellant is initially packed. The ignitor used consists of a firing nut containing an Atlas electric match surrounded by 300 mg of black powder. This type igniter gives a short-duration flame of high intensity with little brisance. When the tubular propellant grains are not too tightly packed, the effect of the phenolic loading sleeve may be neglected except insofar as the volume it displaces is concerned.

Firings demonstrating proper deflagration and typical correlation with the above referenced theory are illustrated in Figures 9, 10, and

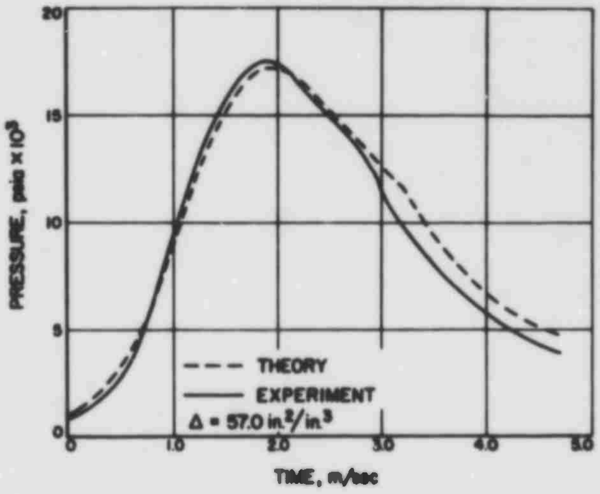


Figure 9. Pressure Time Plot With $\Delta = 57.0$ in.^{2}/in.^{3}.

11. A qualitative delineation of the phenomena occurring in Figure 9, for example, would be as follows:

1. t = 0 to t = 1.0 m/sec: Very slow increase in chamber volume as the result of an almost negligible projectile velocity, hence very rapid pressure increase due to energy release by propellant in almost constant chamber volume.

2. t = 1.0 m/sec to t = 1.9 m/sec: Projectile velocity increasing and, thus, exposed chamber volume increasing more rapidly. Excess energy input decreasing as function of incremental volume to be pressurized.

3. Peak pressure (t = 1.9) to propellant burnout (t = 2.9 experimentally, 3.2 analytically): Plenum volume increasing more rapidly than energy input. Sharp break in curve slope due to propellant burnout.

4. Subsequent to burnout, a very rapid pressure decrease occurs as a result of the expansion of the gases, heat loss to tube, and further energy imparted to projectile.

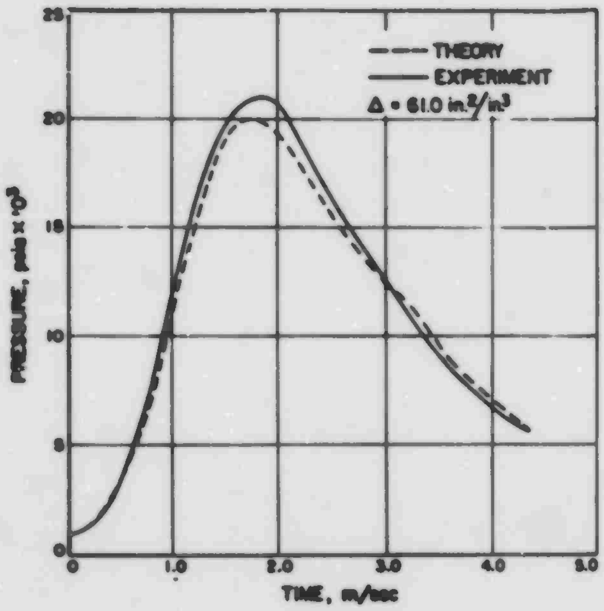


Figure 10. Pressure Time Plot With $\Delta = 61.0$ in.^{2}/in.^{3}.

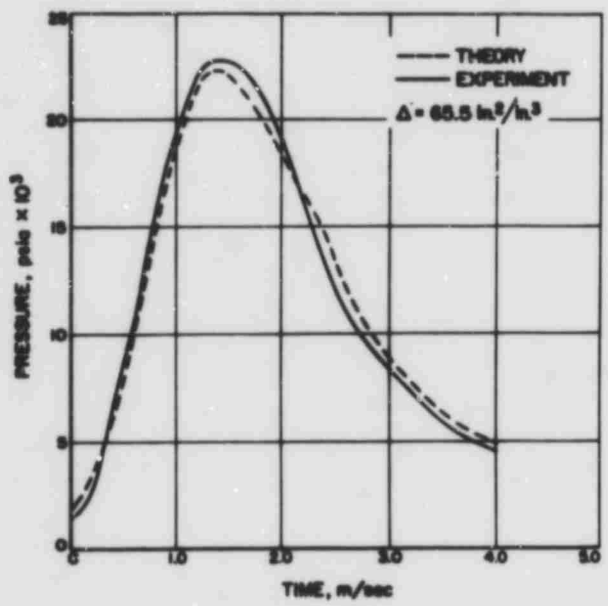


Figure 11. Pressure Time Plot With $\Delta = 65.5$ in.^{2}/in.^{3}.

In these three firings, the primary difference exhibited between the experimental data and the analysis is a result of the following factor: the single-perforate propellant is assumed to burn externally and internally in a radial manner until the total charge is consumed.

In reality, this does not occur. A certain fraction of the grains fragment during combustion, and this increases the exposed burning surface and, in general, leads to slightly higher peak pressures and somewhat earlier web burnout than is analytically predicted. The difference, typically, is of only a few percent in peak pressure and is of such a nature that there is no way to express it analytically.

Figures 9, 10, and 11 show the quite good correlation between theory and experiment which is attainable when the density of loading Δ is kept at less than 75 $in.^2/in.^3$. At loadings above this level, a different mechanism of combustion becomes manifest and could probably be best described as a transition through shock-driven deflagration to virtual charge detonation. The charge characteristics are presented in Table V.

TABLE V. CHARGE CHARACTERISTICS.

Plot References	Charge Weight (gm)	Propellant Web (in.)	Slug Weight (gm)	Δ ($in.^2/in.^3$)	Muzzle Velocity (fps)	
					Predicted	Actual
Figure 9	86.2	0.0164	560	57.0	2,080	2,040
Figure 10	90.0	0.0164	560	61.0	2,220	2,210
Figure 11	110.0	0.0190	508	65.5	2,360	2,300
Figure 12	97.5	0.0164	560	76.7	2,250	2,150
Figure 13	93.0	0.0164	550	80.0	2,190	2,220
Figure 14	105.0	0.0164	560	82.0	2,350	2,700

SHOCK-DRIVEN DEFLAGRATION

It was mentioned previously that the phenolic tube had no effect on the interior ballistic solution. This is not true, however, if the propellant is packed too tightly into the tube. The propellant used was M-10, which is virtually 100 percent nitrocellulose with no nitroglycerine loading and, hence, would be expected to be relatively insensitive to detonation characteristics.

Figures 12, 13, and 14 show this phenomenon of transition from weak shock-driven deflagration to strongly shock-driven deflagration. Figure 15 shows the remains of an end cap when loading was increased to the point where a response similar to complete detonation occurred. No pressure record is available for this firing because the breech pressure transducer was also destroyed. An indirect method of pressure determination may be made by the calculation of the force necessary to shear the normalized 4130 end cap and indicates a peak pressure of at least 450,000 psig.

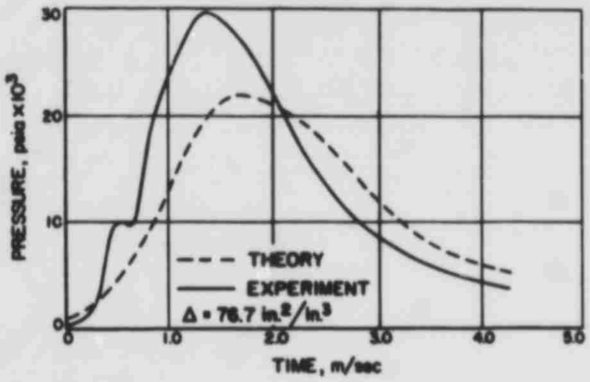


Figure 12. Pressure Time Plot With $\Delta = 76.7$ in.^{2}/in.^{3}.

From the illustrated firings, it is possible to characterize the combustion of the propellant into various regimes as a function of the burning surface per unit of free initial volume. Symbolically, this would be

$$\Delta = S_B/V_{IF}$$

as

$$S_B = 2\, C_w/\rho_p\, w_o$$

then

$$V_{IF} = L\, A_p - C_w/\rho_p$$

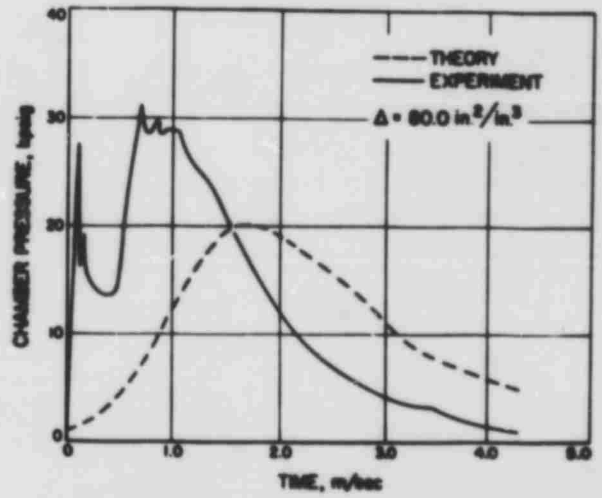


Figure 13. Pressure Time Plot With $\Delta = 80.0$ in.^{2}/in.^{3}.

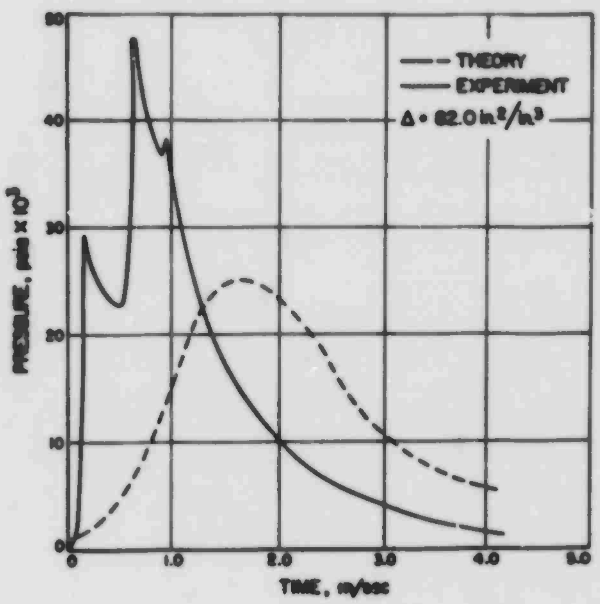


Figure 14. Pressure Time Plot With $\Delta = 82.0$ in.^{2}/in.^{3}.

It was mentioned earlier that, for proper deflagration in this system, Δ must be less than 75 in.^{2}/in.^{3}. In Figure 12, $\Delta = 76.7$ in.^{2}/in.^{3} and it was seen that a slight pressure pulse occurs, then damps out, but drives the peak pressure to a value approximately 30 percent higher than what would have been encountered during proper deflagration.

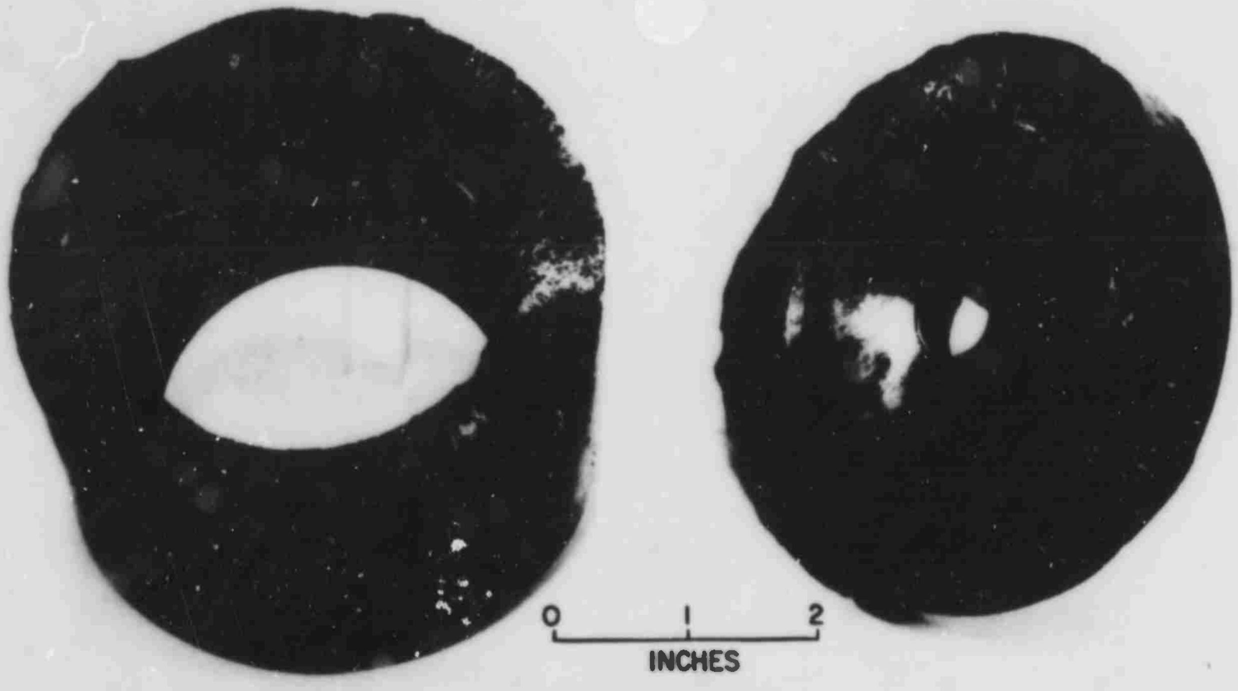


Figure 15. End Cap After Detonative Reaction.

In Figure 13, for which Δ = 80 in.^{2}/in.^{3}, the initial pressure spike is rapid and narrow and quickly decays to be followed by another broader pressure pulse to approximately the same value. Figure 14 shows the pressure-time profile of a loading with a Δ = 82 in.^{2}/in.^{3}.

The initial pressure wave is virtually identical to that exhibited by the previous loading. The second spike, however, is much higher and gives a peak pressure almost 100 percent higher than would be expected if linear regression were the only mechanism at work.

The loading represented by the wreckage shown in Figure 15 was Δ = 86.5 in.^{2}/in.^{3}. A detonation-like reaction phenomenon had occurred, resulting in a pressure probably well above the 450,000 psig mentioned previously. The response could have been a true detonation of the individual propellant grains, which then formed a gaseous blast over-pressure wave to act on the restraining steel. The energy release rate was such that this is the most likely mode of reaction.

The Δ values given for the onset of this highly undesirable mode of reaction would include most fully loaded cartridge cases with thin web propellant. This demonstrates the requirements for either deterring or inhibiting a large fraction of the initial surface area. Good ballistic design, however, requires a tradeoff between reproducible ignition and the formation of these dangerous shock waves in the deflagrating propellant bed.

From the previous results for the system under consideration, the following regimes can be defined:

$\Delta < 75$	Proper deflagration
$75 < \Delta < 86$	Shock-driven deflagration
$\Delta > 86$	Detonation like response

These particular Δ values are doubtless a function of propellant composition and ignition technique. They do graphically demonstrate, however, that the ballistic designer must be cautious when approaching very high loading densities to be certain that the regimes, other than normal propellant regression, are avoided.

REFERENCES

1. Heiney, O.K., "Simplified Interior Ballistics of Propellant Actuated Devices," JPL SPS 47-43.

2. Corner, J., "Theory of the Interior Ballistics of Guns," John Wiley, New York, 1950.

3. Hirschfelder, Kershner, and Curtiss, "Interior Ballistics," Volumes I and II, February and April 1943, NDRC Reports A-142 and A-180 (declassified).

4. Kent, R. H., "Some Special Solutions for the Motion of the Powder Gas," Physics 7, 1936.

5. NACA Report 1135, "Equations, Tables and Charts for Compressible Flow," 1953.

6. Serebryakov, M.E., "Interior Ballistics," Moscow 1949, translated at Catholic University of America under Contract NORD 10, 260

7. CPIA, "Solid Propellant Manual," Chamical Propulsion Information Agency, Johns Hopkins University, Silver Spring, Md, 1965 (Confidential).

8. "Internal Ballistics," Philosophical Library, New York, 1951.

9. "Interior Ballistics of Guns," U. S. Army Materiel Command Pamphlet 706-150, February 1965.

10. Heiney, O.K., "A New Computer-Oriented Formulism for Gun Ballistics," Volume II, 3rd ICRPG/AIAA Solid Propulsion Conference Proceedings, CPIA Publication, April 1968.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Air Force Armament Laboratory Air Force Systems Command Eglin Air Force Base, Florida	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

ANALYTIC AND EXPERIMENTAL INTERIOR BALLISTICS OF CLOSED BREECH GUNS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report

5. AUTHOR(S) (First name, middle initial, last name)

Heiney, Otto K., 1st Lt, USAFR

6. REPORT DATE May 1969	7a. TOTAL NO. OF PAGES 46	7b. NO. OF REFS 10
8a. CONTRACT OR GRANT NO. b. PROJECT NO 62405094-2560 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) AFATL-TR-69-42 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10. DISTRIBUTION STATEMENT This document is subject to special export controls, and each transmittal to foreign nationals or foreign governments may be made only with prior approval of the Air Force Armament Laboratory (ATWG), Eglin Air Force Base, Florida 32542.

11. SUPPLEMENTARY NOTES Available in DDC	12. SPONSORING MILITARY ACTIVITY Air Force Systems Command Andrews AFB, Wash, DC 20331

13. ABSTRACT

A closed breech incremental interior ballistic formulism is presented along with a Fortran 4 computer program which utilizes the system. Typical input and output data, both plotted and tabular, are included. A unique characteristic of the system is that it avoids the inaccuracies associated with approximate analytic propellant regression expressions in that regression rates are determined by a tabular routine. Various pressure gradient expressions are investigated. Correlation of the mathematical model and computer predictions to experimental device firings are presented. A shock-driven deflagration effect which may be initiated during the ignition transient is described and a postulated correlation parameter defined.

DD FORM 1 NOV 65 1473

UNCLASSIFIED

Security Classification

Interior ballistics Ammunition propellants Guns						

UNCLASSIFIED

Security Classification