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Analytic and Experimental Interior Ballistics of Closed Breech Guns

by

Otto K. Heiney, 1st Lt, USAFR

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74

ANALYTIC AND EXPERIMENTAL INTERIOR BALLISTICS
OF CLOSED BREECH GUNS

by

Otto K. Heiney, 1st Lt, USAFR

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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.

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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.

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CONTENTS

Section		Page
	NOMENCLATURE	vii
I.	INTRODUCTION	1
II.	ANALYSIS	2
	Energy Balance	2
	Pressure Gradient and Gas Kinetic Energy	4
	Gas Production	13
III.	COMPUTER PROGRAM	15
	Input Data and Usage	15
	Results	16
	Computer Program	16
IV.	EXPERIMENTAL RESULTS	27
	Normal Deflagration	27
	Shock-Driven Deflagration	31
	REFERENCES	36

ILLUSTRATIONS AND TABLES

Figure

1.	Density Gradient as Function of Shot Velocity	7
2.	δ Value as Function of Projectile Velocity	9
3.	Shot Pressure to Static Pressure Ratio, $T = T_0$	11
4.	Shot Pressure to Static Pressure Ratio, $T = .7T_0$...	12
5.	Graph of 20mm Performance 0.015 Web	19
6.	Graph of 20mm Performance 0.020 Web	23
7.	Device to Measure Pressure-Time History and Muzzle Velocity	27
8.	Ignition and Propellant Loading Techniques	28
9.	Pressure Time Plot With $\Delta = 57.0 \text{ in.}^2/\text{in.}^3$	29
10.	Pressure Time Plot With $\Delta = 61.0 \text{ in.}^2/\text{in.}^3$	30
11.	Pressure Time Plot With $\Delta = 65.5 \text{ in.}^2/\text{in.}^3$	30
12.	Pressure Time Plot With $\Delta = 76.7 \text{ in.}^2/\text{in.}^3$	32
13.	Pressure Time Plot With $\Delta = 80.0 \text{ in.}^2/\text{in.}^3$	33
14.	Pressure Time Plot With $\Delta = 82.0 \text{ in.}^2/\text{in.}^3$	33
15.	End Cap After Detonative Reaction	34

ILLUSTRATIONS AND TABLES (CONTINUED)

Table		Page
I.	PROGRAM INPUT: TYPICAL PROPELLANT AND CASE DATA CARDS	17
II.	COMPUTER PRINTOUT OF 20MM PERFORMANCE 0.015 WEB ...	18
III.	COMPUTER PRINTOUT OF 20MM PERFORMANCE 0.020 WEB ...	21
IV.	INTERIOR BALLISTIC PROGRAM FORTRAN ⁴ LISTING	24
V.	CHARGE CHARACTERISTICS	31

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^P	= 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_O	= Breech Gas Density
ρ_S	= Density of Gas at Projectile
ϕ	= Pressure Gradient Factor
w_O	= Initial Propellant Web
Δ	= Burning Surface Factor

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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:

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

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.

$$F_p = RT_0 \quad (2)$$

Where T_0 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

$$E_1 = E_2 + E_3 + E_4, \text{ where}$$

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^c = distance from X_0 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

$$P \left[(V_c + AX) - \frac{(C_w - N_b)}{\rho_p} - \eta N_b \right] = \frac{N_b F_p T}{T_0} \quad (3)$$

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

$$E_2 = 1/2 m_p \bar{v}^2$$

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

$$E_3 = 1/2 \beta m_A \bar{v}^2$$

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

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

We may define

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

Then

$$E_2 + E_3 + E_4 = (1 + \beta) (1/2) m_A \bar{v}^2 \quad (5)$$

Defining Y by equation (6)

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

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

$$N_b F_p (1 - T/T_o) = 1/2 (Y - 1) (1 + \beta) m_A \bar{v}^2 \quad (7)$$

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

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

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.

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

Equation (11) is integrated with the boundary conditions

$$\text{BD 1. } x = x_0 = 0, v = 0$$

$$\text{BD 2. } x = X, v = V = \frac{dx}{dt}$$

$$\int_0^V dv = C \int_0^X dx$$

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

at boundary 2

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

then

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

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

$$E_G = 1/2 \int_0^X A \rho v^2 dx = \frac{A \rho}{2} v^2 \int_0^X \frac{x^2}{X^2} dx = (1/2) (1/3) A \rho X v^2$$

but

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

then

$$E_G = (1/2) (1/3) \frac{C_w v^2}{g} = 1/2 \frac{C_w v^2}{\delta g} \quad (14)$$

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

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

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.

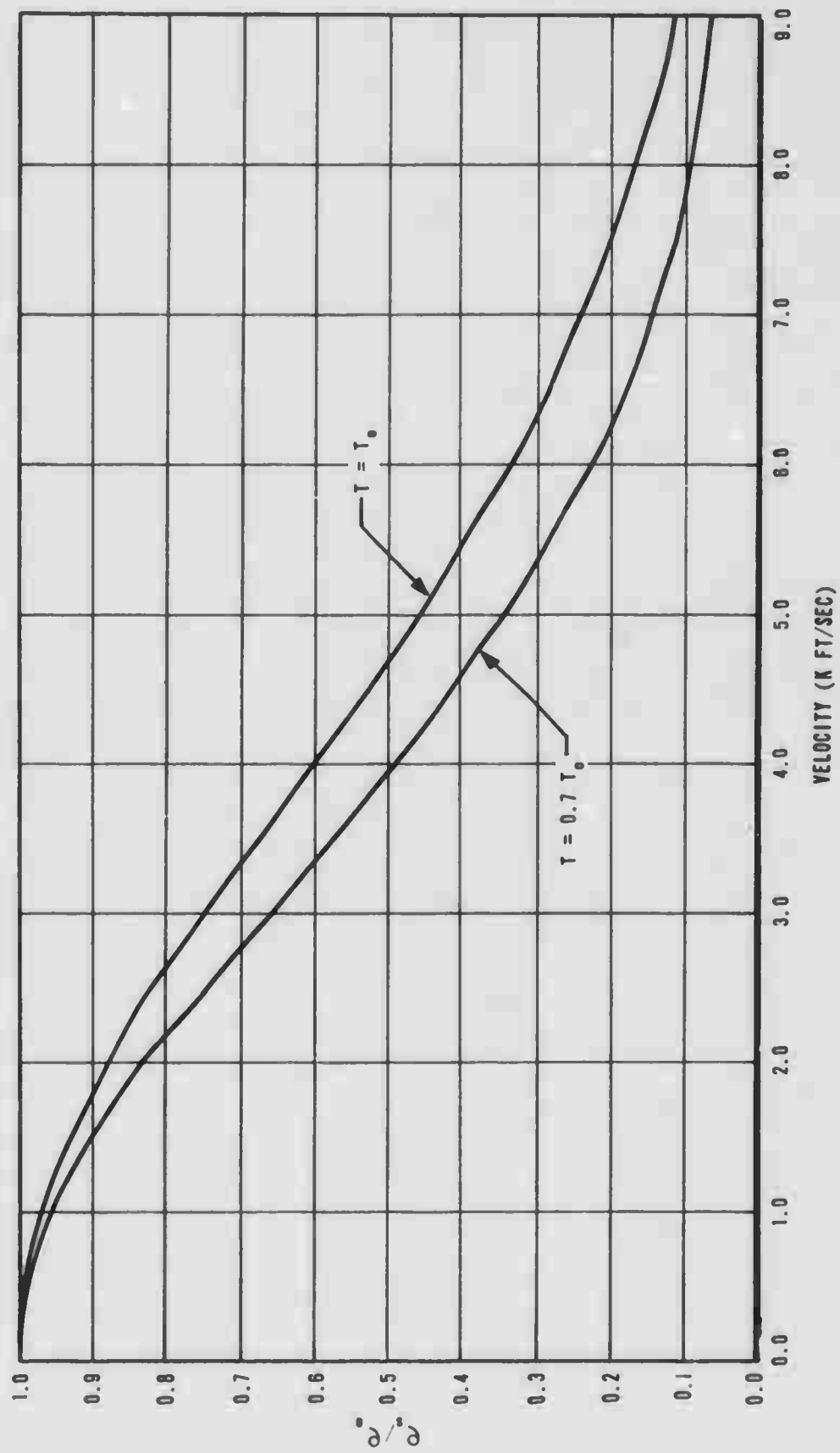


Figure 1. Density Gradient as Function of Shot Velocity.

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

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

$$E_G = \frac{A \rho_0}{2} \sum \frac{\rho_N}{\rho_0} V_N^2 \Delta X_N = 1/2 \frac{C_w}{g \delta} v^2 \quad (16)$$

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_0 by two independent methods and then empirically determine a P_{AV} to P_s relationship. A value for the ratio of P_s/P_0 may be obtained by means of the "quasi-isentropic" assumption used for densities above.

$$P/P_0 = \left(1 + \frac{\gamma - 1}{2} \frac{v^2}{gRT} \right)^{-\gamma/\gamma-1} \quad (17)$$

The results of this relation are plotted on Figures 3 and 4 for the temperatures $T = T_0$ & $T = .7T_0$ 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:

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

$$v dv = - \frac{dp}{\rho} \quad (19)$$

combining equations (18) and (19) and integrating

$$\int_0^v v dv = - \int_{P_0}^{P_s} \frac{RT}{P} dP$$

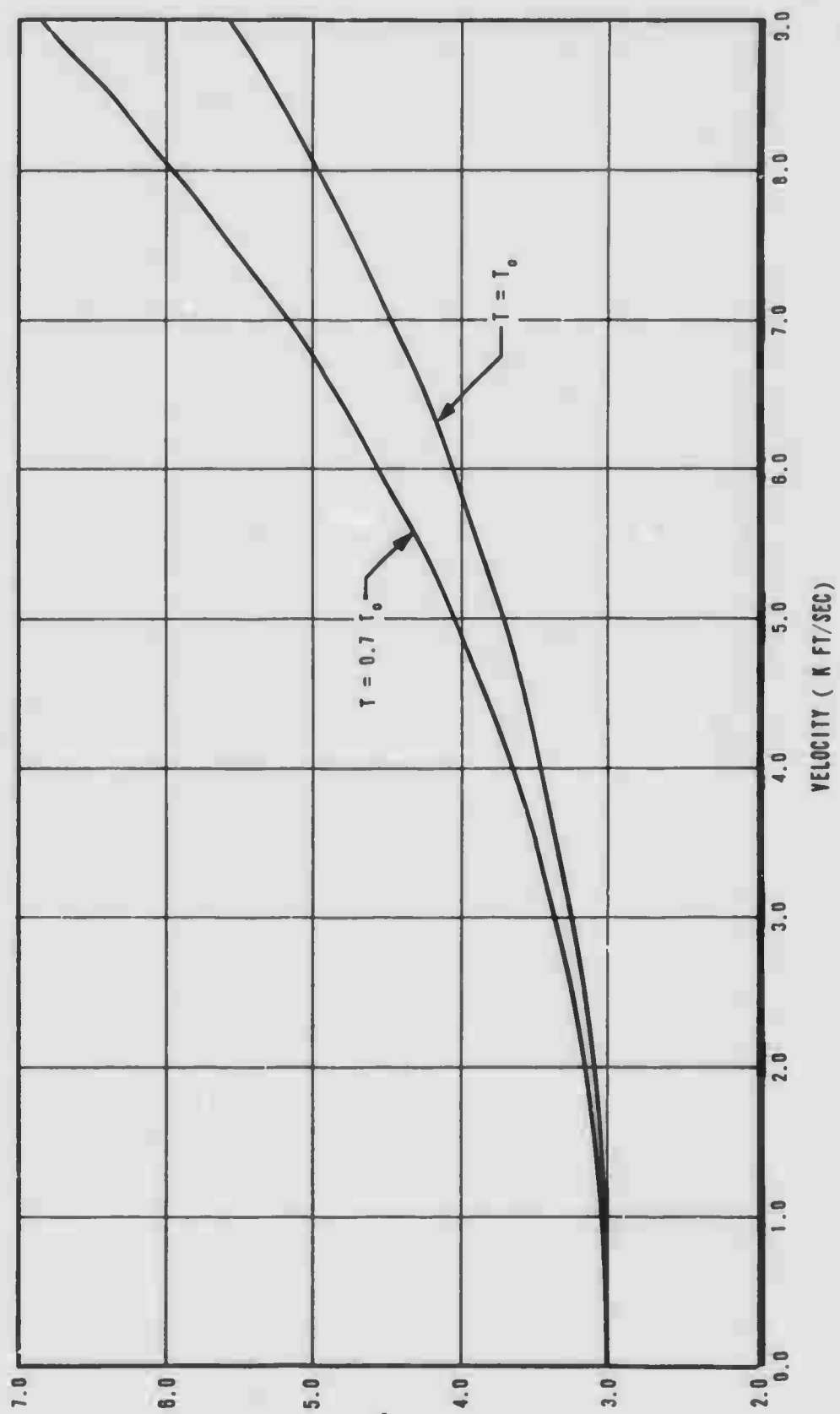


Figure 2. δ Value as Function of Projectile Velocity.

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

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

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

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:

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

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

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.

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

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

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

then

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

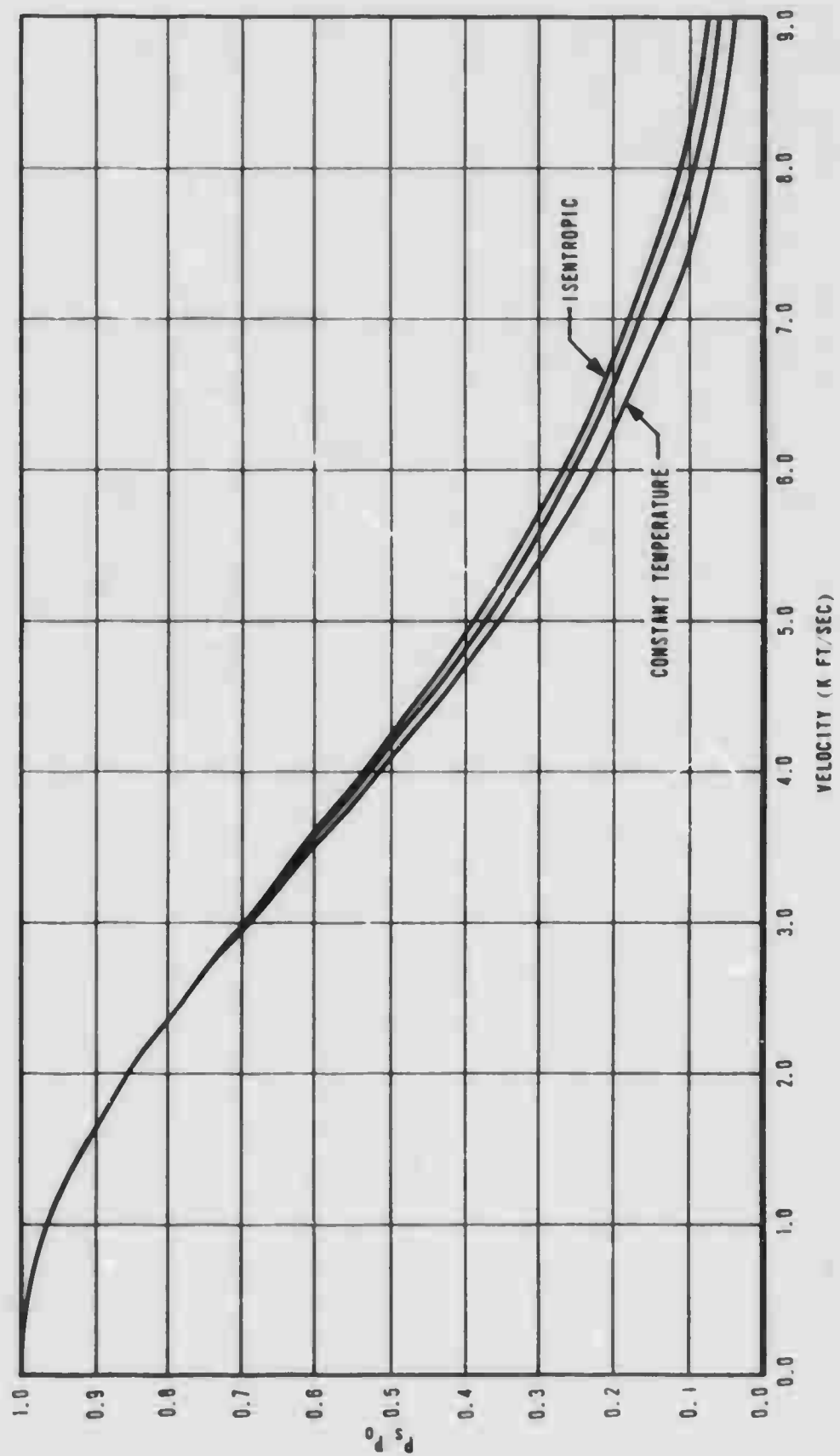


Figure 3. Shot Pressure to Static Pressure Ratio, $T = T_0$.

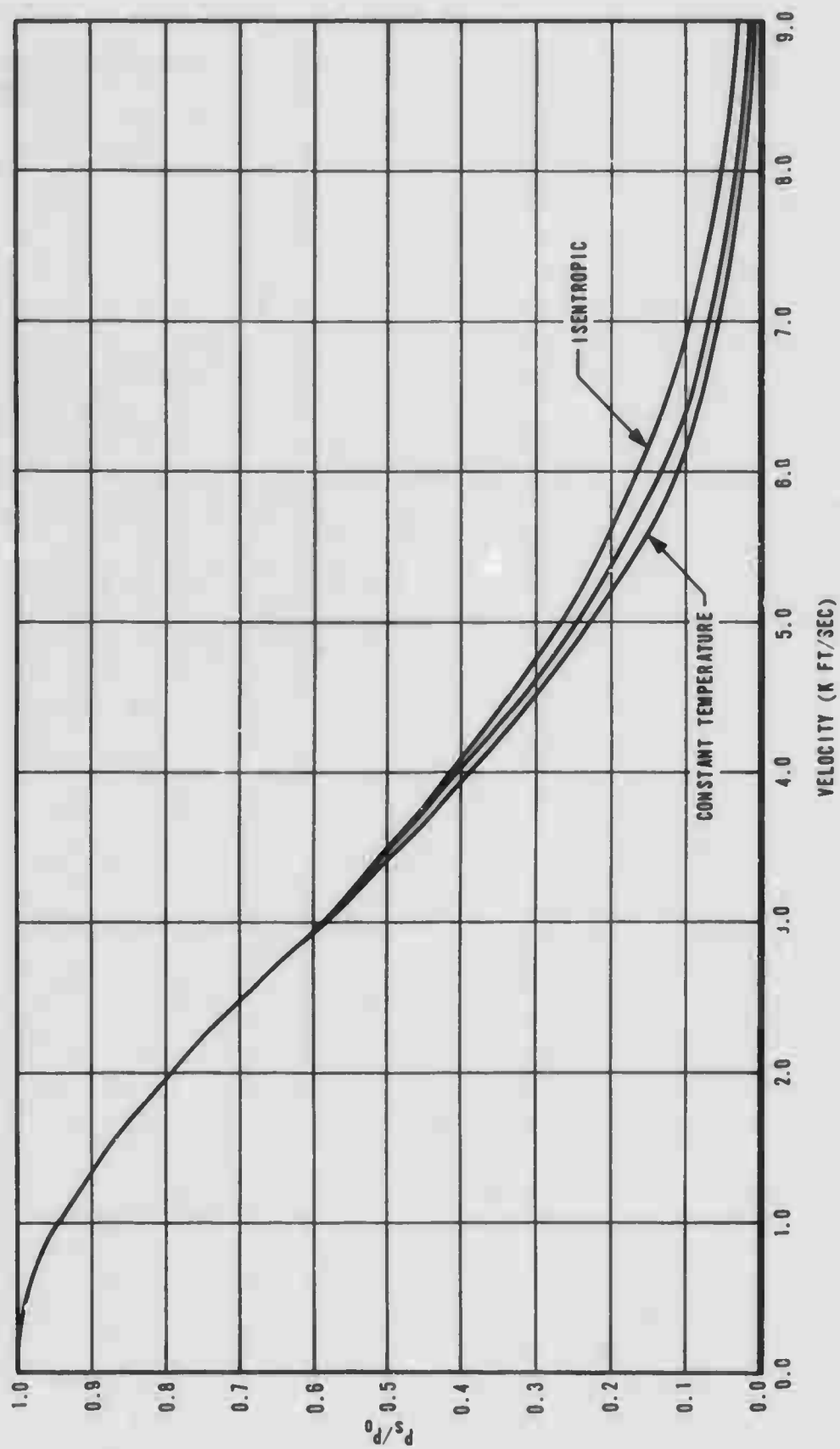


Figure 4. Shot Pressure to Static Pressure Ratio, $T = .7T_0$

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.

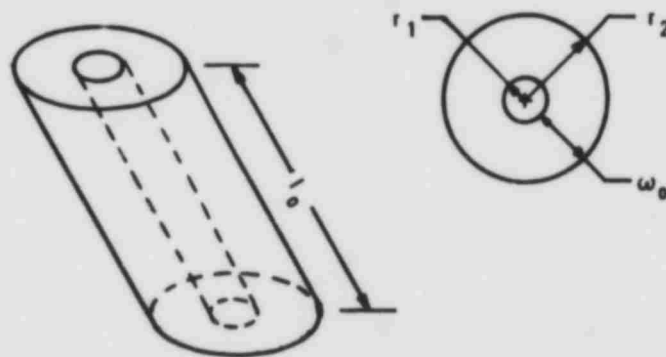
GAS PRODUCTION

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 Vieille'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.



$$w_0 = r_{2,0} - r_{1,0} \text{ for a propellant with } \frac{w_0}{l_0} \ll 1.$$

Burning surface for each grain will be

$$S_{I,0} = 2l_0 \pi (r_2 + r_1)$$

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.

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

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

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

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

[illegible]

UT: TYPICAL PROPELLANT AND CASE DATA CARDS.

			1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30																											
M - 10																														
1 500 .	2 000 .	2 500 .	3 000 .	4 000 .	5 000 .																									
3 0000 .	4 0000 .	5 0000 .	7 0000 .	100 000 .	2 00000 .																									
. 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	4 000 .																											
22	. 3	. 18	4 000 .																											

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

SHOT WT.	CHANGE	WFM	M. LENGTH	CHB VOL	HOMR AREA	
.40	.200	.0220	64.0	5.74	.76	
0000	4000.0		.001	.0027	37466827.5	4000.0
0001	4936.7		.004	.0060	44723334.4	4936.7
0002	6054.4		.009	.0094	53923001.5	6054.4
0003	7402.4		.014	.0146	63735600.1	7402.4
0004	8946.2		.031	.0202	75458412.4	8946.2
0005	10842.7		.044	.0267	87596429.3	10842.7
0006	13072.4		.070	.0341	99010671.9	13072.4
0007	15547.4		.044	.0427	111229256.4	15547.4
0008	18324.4		.134	.0524	124020755.7	18324.4
0009	21424.1		.143	.0635	137938537.0	21424.1
0010	24477.4		.219	.0763	152968438.1	24477.4
0011	24701.4		.309	.0904	167549065.0	24701.4
0012	32840.5		.342	.1072	176296540.3	32840.5
0013	37247.4		.442	.1251	179851744.3	37247.4
0014	41744.2		.610	.1445	177555371.8	41744.2
0015	44243.1		.744	.1652	167942184.3	44243.1
0016	50431.7		.404	.1871	153298853.6	50431.7
0017	54244.2		1.043	.2102	134076228.8	54244.2
0018	57416.1		1.303	.2343	11180355.0	57416.1
0019	60345.4		1.540	.2542	85908750.3	60345.4
0020	62543.3		1.805	.2847	59766233.0	62543.3
0021	64037.4		2.044	.3107	34247727.2	64037.4
0022	64446.4		2.420	.3369	10637852.3	64446.4
0023	64149.4		2.772	.3632	-10126502.8	64149.4
0024	64406.4		3.152	.3444	-27508949.0	64406.4
0025	64214.7		3.541	.4154	-41348734.5	64214.7
0026	64145.0		3.947	.4411	-51783245.0	64145.0
0027	61440.4		4.441	.4465	-59150429.2	61440.4
0028	60411.4		4.941	.4414	-63874372.3	60411.4
0029	58414.4		5.447	.5154	-66465412.9	58414.4
0030	57153.0		6.007	.5397	-67365417.6	57153.0
0031	55444.4		6.571	.5632	-66986763.1	55444.4
0032	53744.2		7.157	.5861	-65674414.0	53744.2
0033	52142.3		7.744	.6085	-63709183.4	52142.3
0034	50549.4		8.345	.6305	-61315026.5	50549.4
0035	49046.7		9.045	.6521	-58659040.6	49046.7
0036	47500.3		9.714	.6732	-55868375.1	47500.3
0037	46143.4		10.402	.6434	-53036011.4	46143.4
0038	44437.7		11.104	.7141	-50228279.4	44437.7
0039	43442.0		11.811	.7341	-47490913.4	43442.0
0040	42344.7		12.571	.7536	-444854162.1	42344.7
0041	41273.3		13.327	.7729	-42334794.0	41273.3
0042	40214.4		14.044	.7418	-39442954.0	40214.4
0043	34214.4		14.844	.8104	-37424121.4	34214.4
0044	34270.4		15.644	.8286	-35874577.8	34270.4
0045	37373.4		16.503	.8465	-34016715.2	37373.4
0046	34423.4		17.313	.8641	-3221274.3	34423.4
0047	34714.4		14.174	.8414	-3060664.1	34714.4
0048	34441.4		14.042	.8445	-2944746.5	34441.4
0049	34224.4		14.400	.9142	-27444372.1	34224.4

.0011	34216.3	14.844	.0104	-37836121.4	2667.99	32169.2
.0011	34210.4	14.844	.0286	-35874977.8	2696.03	31159.4
.0011	34773.4	14.503	.0465	-34016718.2	2742.60	30205.8
.0012	34423.1	17.333	.0641	-32261274.3	2787.77	29305.0
.0012	35716.4	14.174	.0814	-30606644.1	2831.64	28453.8
.0012	34411.9	14.042	.0985	-29044746.5	2874.26	27644.8
.0012	36225.2	14.900	.9142	-27586372.1	2915.72	26847.0
.0014	33544.5	20.741	.9317	-26212013.9	2956.05	26165.7
.0013	32440.2	21.674	.9480	-24921454.7	2995.34	25482.1
.0014	32257.2	22.574	.9640	-23711010.3	3033.62	24833.7
.0013	31466.4	23.494	.9799	-22574441.6	3070.96	24218.2
.0014	31100.0	24.421	.9955	-21508658.8	3107.39	23633.4
.0014	30562.4	25.354	1.0109	-20507440.1	3142.97	23077.3
.0014	30064.4	26.306	1.0109	-195125915.0	3177.73	22548.0
.0014	29421.4	27.264	1.0109	-185125915.0	3210.98	21567.3
.0015	28444.4	28.233	1.0109	-175125915.0	3242.83	20658.7
.0015	27444.4	29.210	1.0109	-165125915.0	3273.34	19815.2
.0015	26444.4	30.144	1.0109	-155125915.0	3302.72	19030.6
.0015	25444.4	31.141	1.0109	-145125915.0	3330.93	18294.5
.0016	24244.4	32.195	1.0109	-135125915.0	3358.09	17617.0
.0016	23244.4	33.206	1.0109	-125125915.0	3384.26	16978.6
.0016	22244.4	34.224	1.0109	-115125915.0	3409.51	16380.7
.0016	21244.4	35.242	1.0109	-105125915.0	3433.90	15814.7
.0017	20244.4	36.245	1.0109	-95125915.0	3457.48	15292.5
.0017	19244.4	37.324	1.0109	-85125915.0	3480.29	14746.4
.0017	18244.4	38.373	1.0109	-75125915.0	3502.30	14248.9
.0017	17244.4	39.427	1.0109	-65125915.0	3523.79	13807.7
.0018	16244.4	40.488	1.0109	-55125915.0	3544.56	13470.7
.0018	15244.4	41.554	1.0109	-45125915.0	3564.72	13076.3
.0018	14244.4	42.626	1.0109	-35125915.0	3584.30	12702.7
.0019	13244.4	43.705	1.0109	-25125915.0	3603.34	12348.3
.0019	12244.4	44.784	1.0109	-15125915.0	3621.85	12011.9
.0019	11244.4	45.874	1.0109	-5125915.0	3639.88	11692.1
.0019	10244.4	46.972	1.0109	5125915.0	3657.43	11387.9
.0019	9244.4	48.072	1.0109	14025874.4	3674.54	11098.2
.0020	8244.4	49.177	1.0109	13428774.7	3691.23	10821.9
.0020	7244.4	50.247	1.0109	12867707.7	3707.50	10556.3
.0020	6244.4	51.401	1.0109	12339921.0	3723.39	10306.6
.0020	5244.4	52.521	1.0109	11842912.5	3738.91	10065.9
.0021	4244.4	53.645	1.0109	11374404.7	3754.07	9835.6
.0021	3244.4	54.773	1.0109	10932321.5	3768.90	9615.2
.0021	2244.4	55.906	1.0109	10514767.4	3783.40	9403.9
.0021	1244.4	57.043	1.0109	10120009.8	3797.58	9201.3
.0022	13625.0	58.184	1.0109	9746462.7	3811.47	9006.8
.0022	13341.3	54.330	1.0109	9392672.2	3825.06	8820.0
.0022	13146.4	60.479	1.0109	9057304.3	3838.38	8640.5
.0022	12920.1	61.633	1.0109	8739133.1	3851.44	8467.9
.0023	12701.4	62.790	1.0109	8437030.6	3864.24	8301.8
.0023	12440.7	63.951	1.0109	8149958.1	3876.79	8141.8
.0023	12244.4	65.114	1.0109	7876957.4	3889.10	7987.7
.0023	12040.0	66.245	1.0109	7617144.3	3901.19	7834.0
.0024	11849.4	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 1924.3 FEET PER SECOND

PIEZOMETRIC EFFICIENCY IS 33.4 PERCENT

CORRECTED PIEZOMETRIC EFFICIENCY IS 37.9 PERCENT

BALLISTIC EFFICIENCY IS 34.7 PERCENT

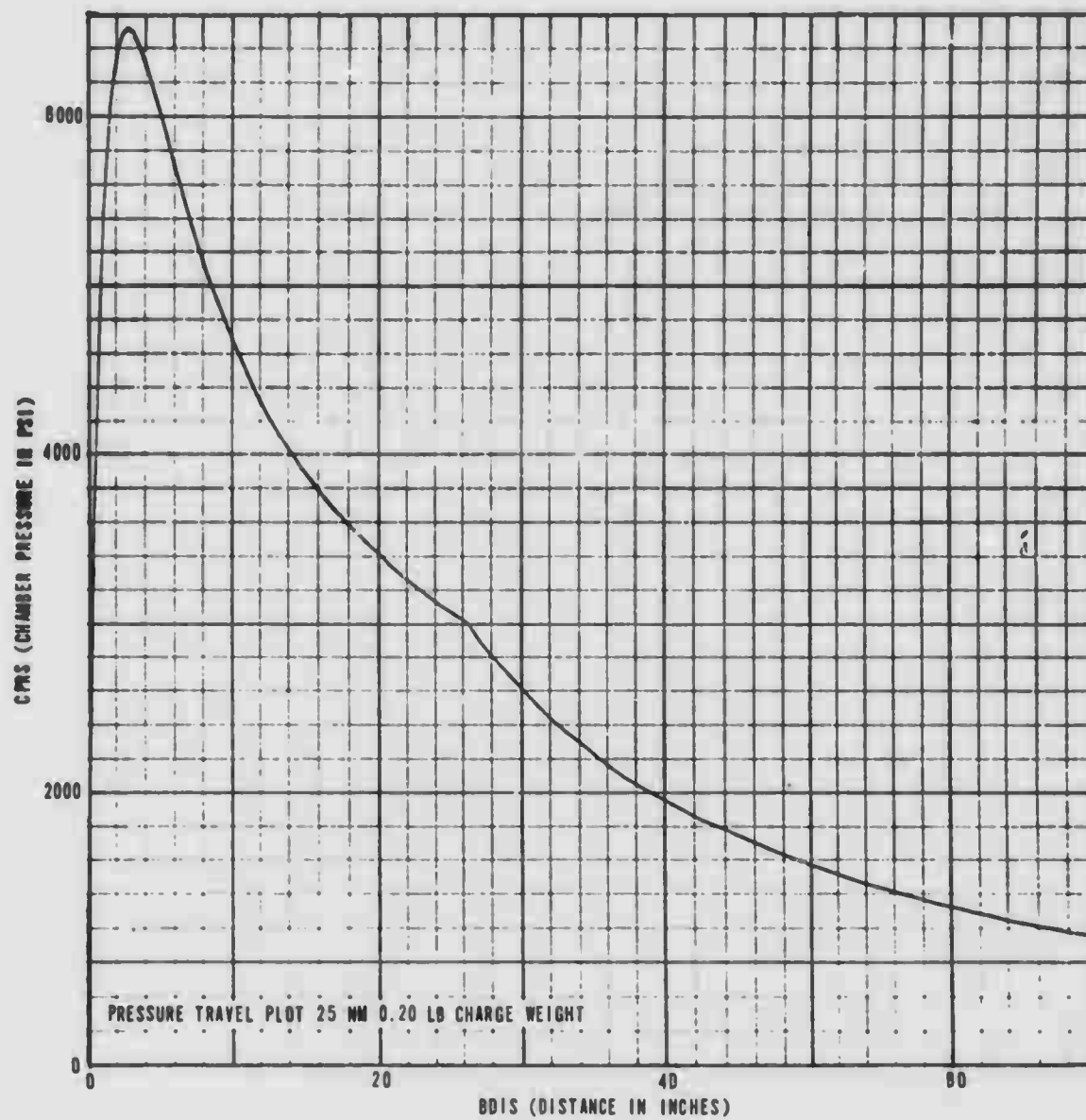


Figure 5. Graph of 20mm Performance 0.015 Web.

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

SHOT WT.	CHARGE	WFM	M. LENGTH	CHG VOL	WUM AREA	TIME	CHARGE PMS	TRAVFL	PROP TURNED	PRES SLOPE	VELOCITY	RS PMS
.40	.140	.0220	69.0	5.74	.76	.0000	4000.0	.001	.0027	29640546.3	6.17	4000.0
						.0001	4741.0	.004	.0054	34139304.6	13.48	4741.0
						.0002	4544.5	.014	.0095	39557022.5	22.10	5544.5
						.0003	4543.4	.017	.0138	45465753.5	32.25	6543.3
						.0004	7720.1	.024	.0146	51784485.4	44.15	7719.8
						.0005	4014.4	.044	.0242	59074131.1	58.05	4014.3
						.0006	10441.4	.044	.0305	66494321.2	74.22	10440.6
						.0007	12154.1	.049	.0376	72872565.5	92.95	12152.1
						.0008	13475.9	.120	.0455	79411504.7	114.44	13472.3
						.0009	15441.2	.144	.0542	85470003.4	139.04	15444.4
						.0010	14110.4	.204	.0638	92360045.4	167.00	14100.0
						.0011	20419.4	.249	.0745	98556620.7	198.45	20402.4
						.0012	22443.4	.324	.0843	10509401.4	233.49	22856.4
						.0013	24510.4	.400	.0944	110832946.5	272.95	25469.2
						.0014	24241.7	.444	.1138	11540445.7	316.45	24218.7
						.0015	31146.4	.549	.1244	117065760.1	364.36	31074.5
						.0016	34043.4	.707	.1461	114717553.1	416.71	33458.3
						.0017	44414.4	.841	.1634	110124444.4	473.40	36764.9
						.0018	34714.4	.942	.1827	103277387.3	534.21	39444.3
						.0019	42244.4	1.142	.2022	92745444.4	598.46	41437.1
						.0020	44414.4	1.352	.2224	80477046.9	666.41	44140.6
						.0021	44624.4	1.543	.2433	66476117.0	737.85	46124.5
						.0022	44302.7	1.744	.2646	52837240.0	811.11	47523.3
						.0023	44423.7	2.050	.2863	34621443.1	886.14	44657.9
						.0024	44444.4	2.327	.3043	24454665.1	962.31	44414.8
						.0025	41210.4	2.627	.3305	11479920.5	1034.11	49814.5
						.0026	41510.1	2.940	.3527	333017.4	1116.00	44877.2
						.0027	41518.4	3.247	.3750	-9470462.7	1142.53	44640.2
						.0028	41271.7	3.444	.3972	-18524447.0	1268.29	49143.9
						.0029	44444.4	4.047	.4142	-25643059.4	1342.95	44431.4
						.0030	44147.4	4.471	.4411	-31244109.7	1416.25	47544.8
						.0031	44445.2	4.947	.4627	-35579106.4	1487.98	46524.4
						.0032	44445.4	5.344	.4841	-34684249.1	1557.98	4506.0
						.0033	47524.4	5.741	.5052	-40761914.1	1626.15	44221.3
						.0034	44509.4	6.339	.5240	-41945754.1	1692.44	42447.1
						.0035	44440.0	6.457	.5445	-42509456.2	1756.41	41755.5
						.0036	44347.2	7.343	.5666	-42474768.4	1814.27	40514.4
						.0037	4335.1	7.444	.5845	-42013447.4	1874.83	34246.3
						.0038	42244.4	8.521	.6040	-41214403.4	1938.54	34043.1
						.0039	41254.4	9.111	.6252	-40180924.4	1995.45	34043.1
						.0040	41244.4	9.714	.6442	-38470827.1	2050.60	35778.0
						.0041	40275.7	10.341	.6628	-37404906.2	2104.04	34685.2
						.0042	34330.4	10.440	.6810	-36602359.1	2155.43	33631.7
						.0043	3445.4	11.044	.6940	-35328737.4	2206.21	32618.3
						.0044	34532.7	12.303	.7166	-34019064.4	2255.00	31045.7
						.0045	34441.7	12.447	.7334	-32697370.3	2302.35	30714.1
						.0046	34444.4	13.444	.7504	-31342032.2	2348.32	24823.1
						.0047	34444.4	14.444	.7676	-30046470.3	2392.94	24471.4
						.0048	34444.4	15.444	.7840	-28422040.7	2436.40	24154.2
						.0049	34444.4	16.447	.8002	-27544744.4	2478.62	23443.9
						.0050	31447.1	17.444	.8161	-24410050.2	2514.64	24644.4
						.0051	31254.4	18.449	.8314	-25269544.5	2554.48	25434.1
						.0052	31445.1	19.443	.8472	-24175267.3	2594.43	25266.6
						.0053	30020.7	20.444	.8625	-23124531.4	2636.60	24625.1

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PIEZOMETRIC PRESSURE IS 10071.3M

MUZZLE VELOCITY IS 1679.3 FEET PER SECOND

PIEZOMETRIC EFFICIENCY IS 47.0 PERCENT

CORRECTED PIEZOMETRIC EFFICIENCY IS 41.7 PERCENT

BALLISTIC EFFICIENCY IS 33.4 PERCENT

0012	10000.0	13.000	0.750	-3130000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-3000000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-2800000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-2600000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-2400000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-2200000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-2000000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-1800000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-1600000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-1400000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-1200000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-1000000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-800000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-600000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-400000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	-200000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	0.0	2342.94	2471.04
0012	10000.0	13.000	0.750	200000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	400000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	600000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	800000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	1000000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	1200000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	1400000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	1600000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	1800000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	2000000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	2200000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	2400000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	2600000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	2800000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	3000000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	3200000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	3400000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	3600000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	3800000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	4000000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	4200000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	4400000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	4600000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	4800000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	5000000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	5200000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	5400000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	5600000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	5800000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	6000000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	6200000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	6400000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	6600000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	6800000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	7000000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	7200000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	7400000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	7600000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	7800000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	8000000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	8200000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	8400000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	8600000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	8800000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	9000000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	9200000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	9400000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	9600000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	9800000.0	2342.94	2471.04
0012	10000.0	13.000	0.750	10000000.0	2342.94	2471.04

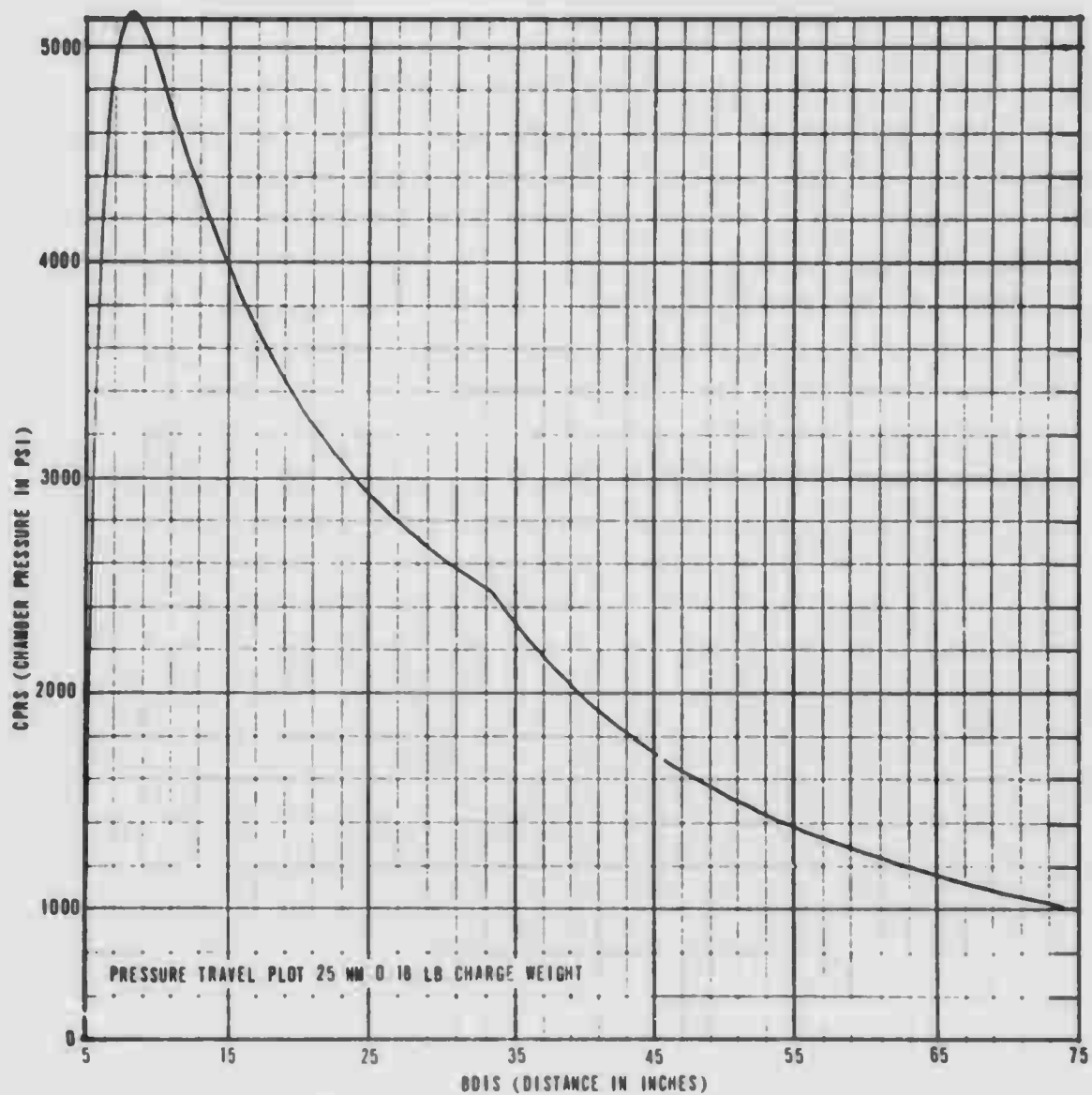


Figure 6. Graph of 20mm Performance 0.020 Web.

[illegible]

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90 15 WRITE(6,17)11F,CPHS,B01S,FPU,DPUL,ULDT,PREX
17 FORMAT(15.4,F15.1,F15.3,F15.4,F15.1,F15.2,F10.1)
    NPTS=NPTS+1
    PCPRS(NPTS)=CPHS
    PH01S(NPTS)=B01S
    CPKS=CPHS*(DPUL*.000025)
    IF (H01S.GE.MUN) GO TO 74
74 CONTINUE
79 DELV=VEL2-VEL1
    DRUN=DRUN1S-RUN
    ADV=(1.-(DRUN/(H1NC*12.)))*.DELV
    VM=VEL1+ADV
    AO=(VM*VM/MUN)*SHOT*12./((AREA*64.4)
    WRITE(6,40)AO
40 FORMAT(//25M PIEZOMETRIC PRESSURE IS ,F9.2,/)
    WHTF(6,41)VM
41 FORMAT(//14M MI/ZIP VELOCITY IS,F8.1,16M FEET PER SECOND/)
    AR=AO/PIOP
    AF=AW*100.
    WHTF(6,42)AF
42 FORMAT(//26M PIEZOMETRIC EFFICIENCY IS,F7.1,8M PERCENT)
    AR=(AF*EFM*32.17)/SHOT
    FKF=(VM*VM*SHOT)/(2.*32.17)
    TE=CHG*FIMP/(GAHA-1.)
    HE=FE/TE*100.
    WHTF(6,44)AH
44 FORMAT(//36M CORRECTED PIEZOMETRIC EFFICIENCY IS,F7.1,8M PERCENT)
    WHTF(6,43)HE
43 FORMAT(//24M BALLISTIC EFFICIENCY IS,F8.1,8M PERCENT)
    CALL MPL0T
    GO TO 4
END
414FTC MPL0T
    SUBROUTINE MPL0T
    COMMON/ /PCPRS(1000),PH01S(1000),MUN,PTOP,NPTS
    I=0
    XL=PH01S(1)
    XR=PH01S(NPTS)
    YH=PCPRS(1)
    YL=PTOP
    CALL UX0YV(1,XL,AR,DX,N,I,NX,20.0,IERR)
    CALL UX0YV(2,YH,YT,DY,M,J,NY,20.0,IERR)
    IS=I
    JS=J
    CALL GRIJLV(L,XL,XR,YB,YT,DX,DY,N,M,I,J,NX,NY)
    CALL PRINTV(-4,4HRDIS,500,10)
    CALL APHNTV(0,-14,-4,4HCPHS,10,500)
    CALL APL0TV(NPTS,PT(1),PH1(1),1,1,1,55,IERR)
    CALL APL0TV(NPTS,PT(1),PH2(1),1,1,1,38,IERR)
    IX1=NXV(PH01S(1))
    IY1=NYV(PCPRS(1))
    IO 300 IKK=2,NPTS
    IX2=NAV(PH01S(IKK))
    IY2=NYV(PCPRS(IKK))
    CALL LINEV(IX1,IY1,IX2,IY2)
    IX1=IX2
    IY1=IY2
300 CONTINUE
    RETURN
    END

```

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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.

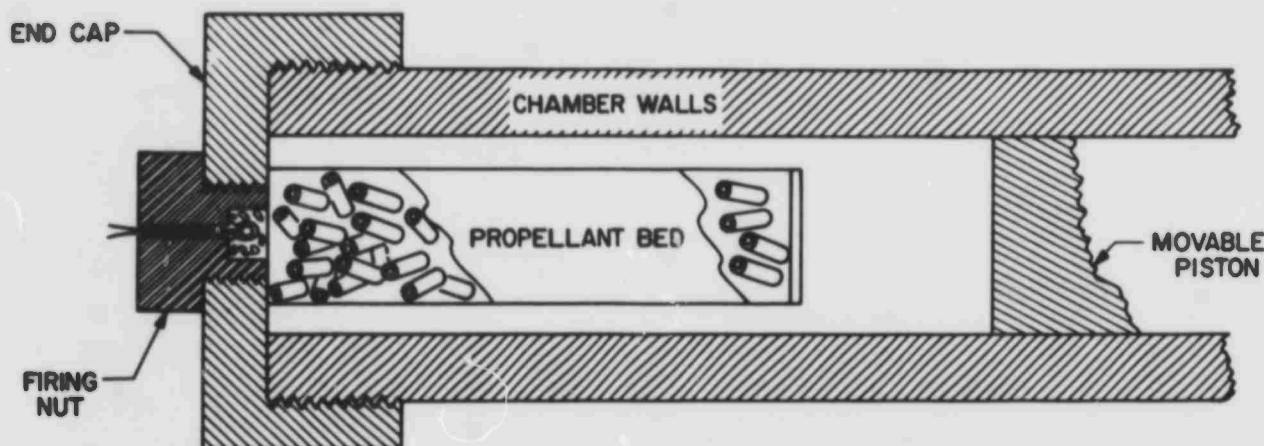


Figure 8. Ignition and Propellant Loading Techniques.

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

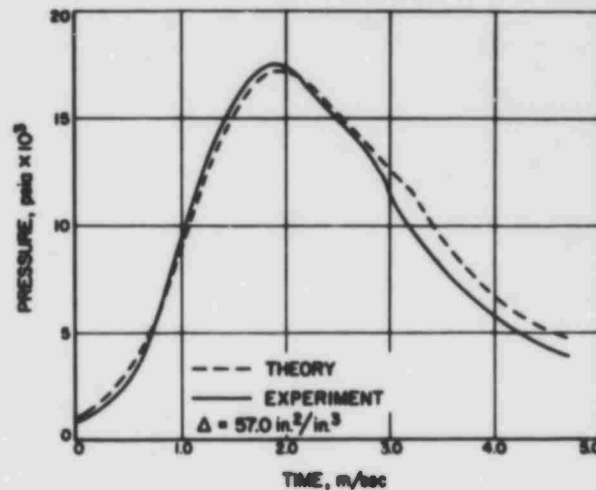


Figure 9. Pressure Time Plot With $\Delta = 57.0 \text{ in.}^2/\text{in.}^3$.

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

1. $t = 0$ to $t = 1.0 \text{ m/sec}$: 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. $t = 1.0 \text{ m/sec}$ to $t = 1.9 \text{ m/sec}$: 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.

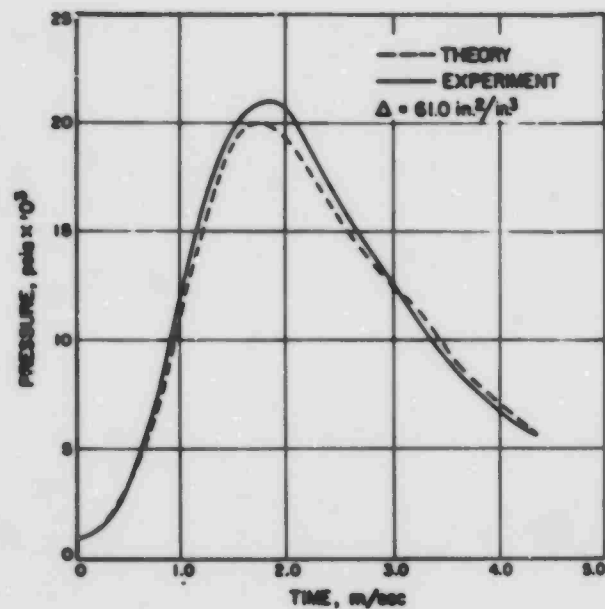


Figure 10. Pressure Time Plot With $\Delta = 61.0 \text{ in.}^2/\text{in.}^3$.

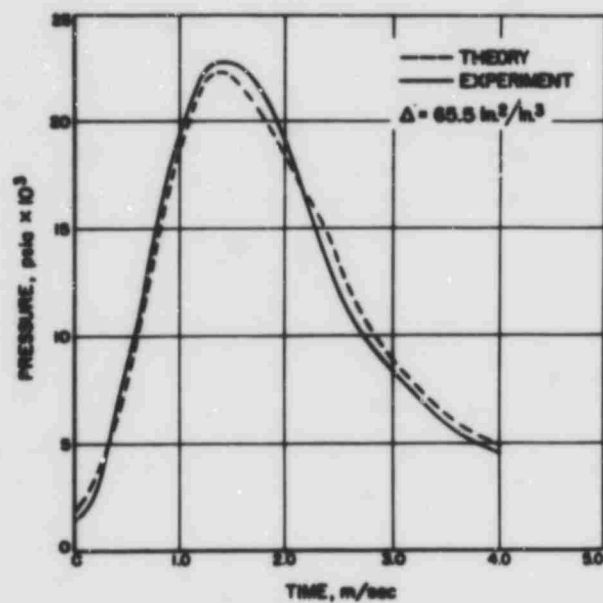


Figure 11. Pressure Time Plot With $\Delta = 65.5 \text{ in.}^2/\text{in.}^3$.

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.

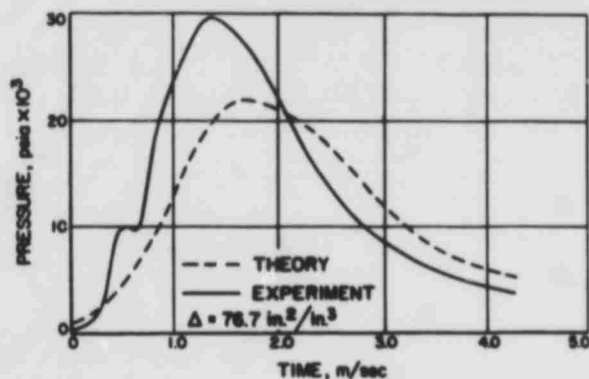


Figure 12. Pressure Time Plot With $\Delta = 76.7 \text{ in.}^2/\text{in.}^3$.

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

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

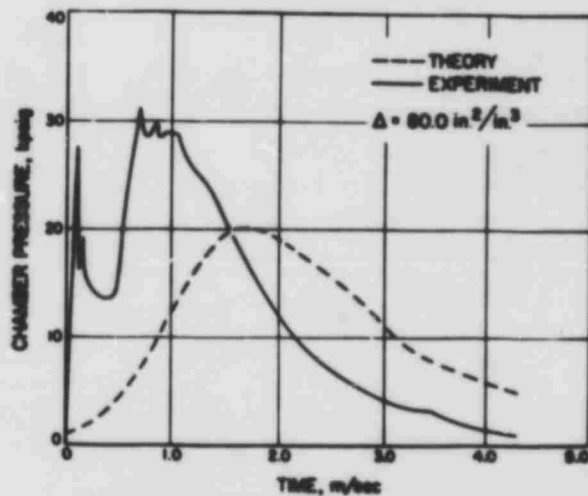


Figure 13. Pressure Time Plot With $\Delta = 80.0 \text{ in.}^2/\text{in.}^3$.

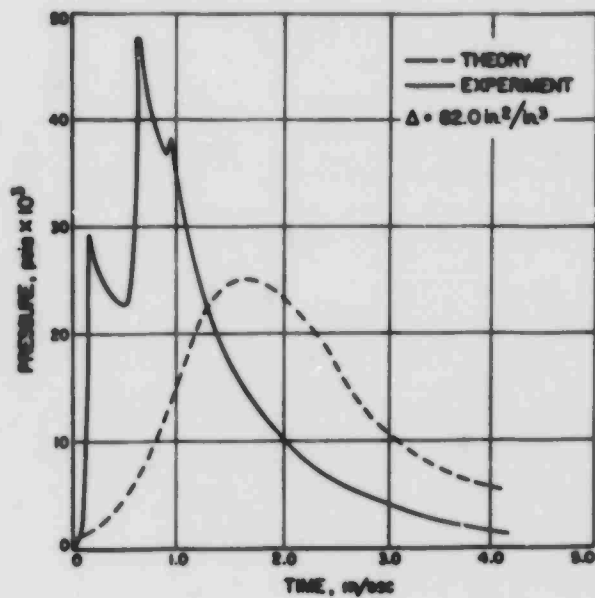


Figure 14. Pressure Time Plot With $\Delta = 82.0 \text{ in.}^2/\text{in.}^3$.

It was mentioned earlier that, for proper deflagration in this system, Δ must be less than $75 \text{ in.}^2/\text{in.}^3$. In Figure 12, $\Delta = 76.7 \text{ in.}^2/\text{in.}^3$ 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.

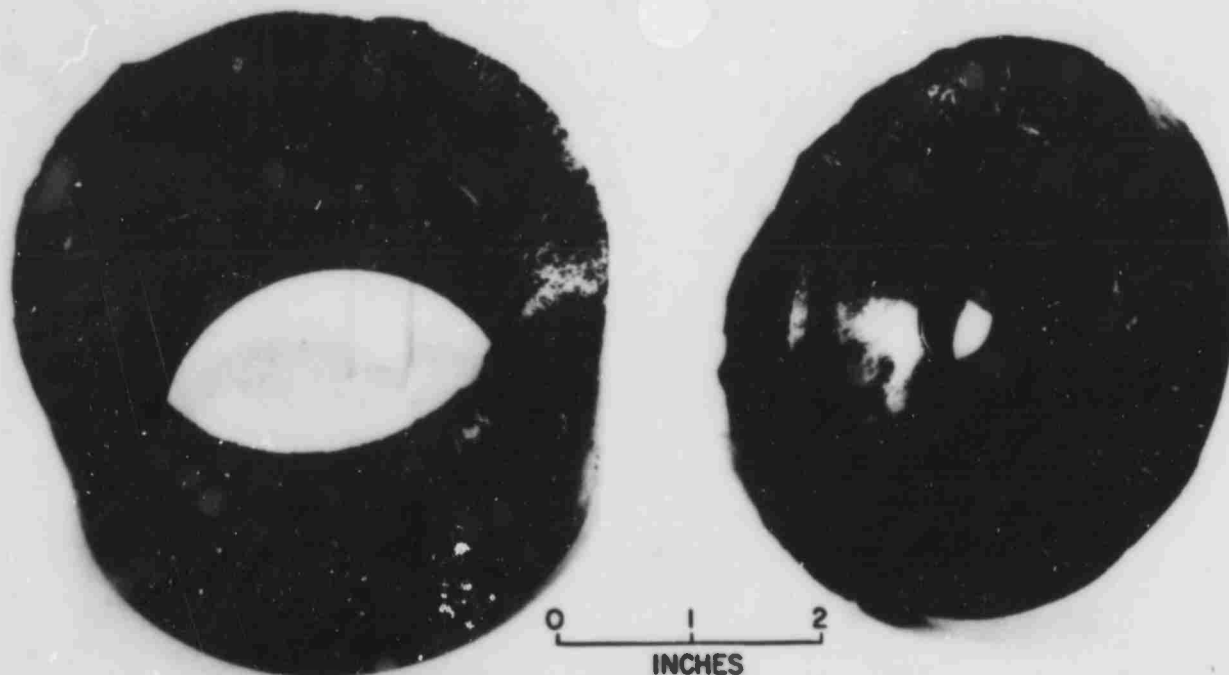


Figure 15. End Cap After Detonative Reaction.

In Figure 13, for which $\Delta = 80 \text{ in.}^2/\text{in.}^3$, 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 $\Delta = 82 \text{ in.}^2/\text{in.}^3$.

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 $\Delta = 86.5 \text{ in.}^2/\text{in.}^3$. 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," Chemical 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.		8b. ORIGINATOR'S REPORT NUMBER(S)	
b. PROJECT NO. ^{H-1} 62405094-2560		AFATL-TR-69-42	
c.		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
d.			
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.			

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Interior ballistics
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