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INTERIOR BALLISTICS MODELING APPLIED TO SMALL ARMS SYSTEMS

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The empirical models currently used in the design of small arms interior ballistics systems are reviewed. The development of propellant deterrent technology and closed bomb burning-rate techniques is discussed. Propellant grain size distribution and averaging techniques, temperature sensitivity, and energy losses are also covered. The current use of two-phase, nonsteady flow methods to describe interior ballistics systems is reviewed. It is concluded that each of the models performs a different task in the proper design of a weapon system.

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INTRODUCTION

Significant progress has been made in recent years in modeling the interior ballistics of small arms weapons systems. In the past, small caliber ammunition designers resorted to empirical methods (ref. 1) based on experimental data (ref. 2) to design propelling charges. However, with the vast amount of research done on deterred small arms propellants, enough information has now been obtained to successfully model the burning of these propellants and the interior ballistics in a variety of small caliber weapon systems.

EMPIRICAL MODELS

The most successful empirical small arms interior ballistics model was probably developed by H. P. Manning at Frankford Arsenal (ref. 2). This model comprises a series of curves on experiments by which selected optimum ballistic parameters of propellant weight (C), projectile weight (W), maximum pressure (P), and expansion ratio U_m/U_o are related. From these sets of curves, the ballistic performance of many small arms systems can be calculated. The velocity of a system with given values of C/W, P, and U_m/U_o can be obtained by using the equation:

$$V = V_{5,60} \left(\frac{V_x}{V_5}\right)\left(\frac{V_m}{V_{60}}\right)$$

where $V_{5,60}$ is the velocity at that ratio of C/W obtained at an expansion ratio of U_m/U_o = 5 and peak pressure of P_m = 60,000 psi (413.7 MPa); V_x/V_5 is the relative velocity normalized to unity at an expansion ratio of 5, and V_m/V_{60} is the velocity relative to the velocity at a peak pressure of 60 kpsi (figs. 1-3). The Manning curves work well for both IMR and ball propellant within the range of C/W, U_m/U_o, and P_m shown in figures 1 through 3. For example:

Given the following data for .30 caliber ball cartridge M2,

Projectile weight	150 grains (9.72×10^{-3} kg)
Propellant weight	49.9 grains (3.23×10^{-3} kg)
Bore area	0.0732 in.^{2} (4.72×10^{-5} m^2)
Case volume	0.25 in.^{3} (4.10×10^{-6} m^3)
Bullet travel	21.9 in. (.556 x m)
Maximum pressure	51.2 kpsi (353 MPa)

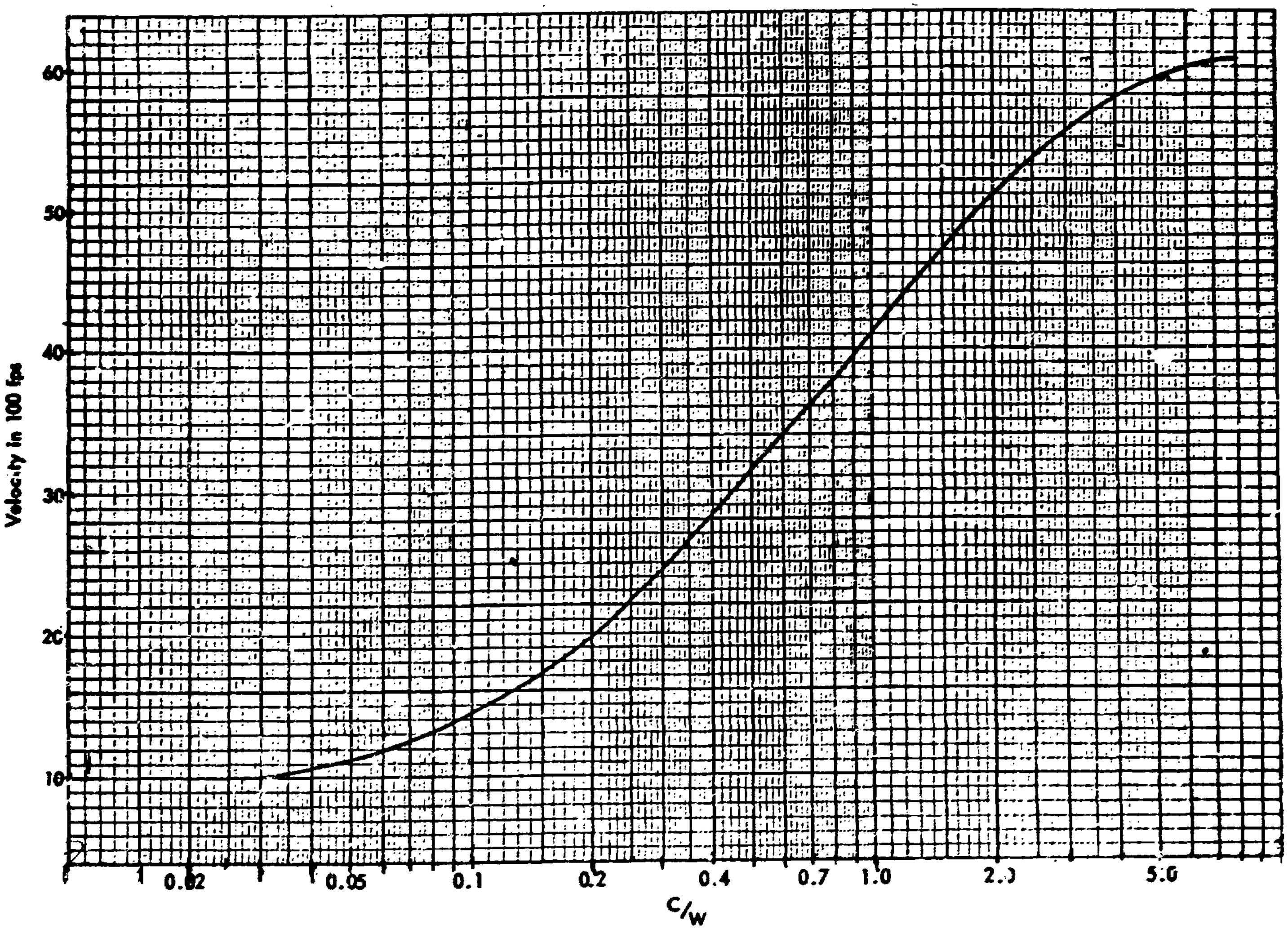

Figure 1. Velocity at U_m/U_o = 5 and P_m = 60 kpsi as a function of C/W.

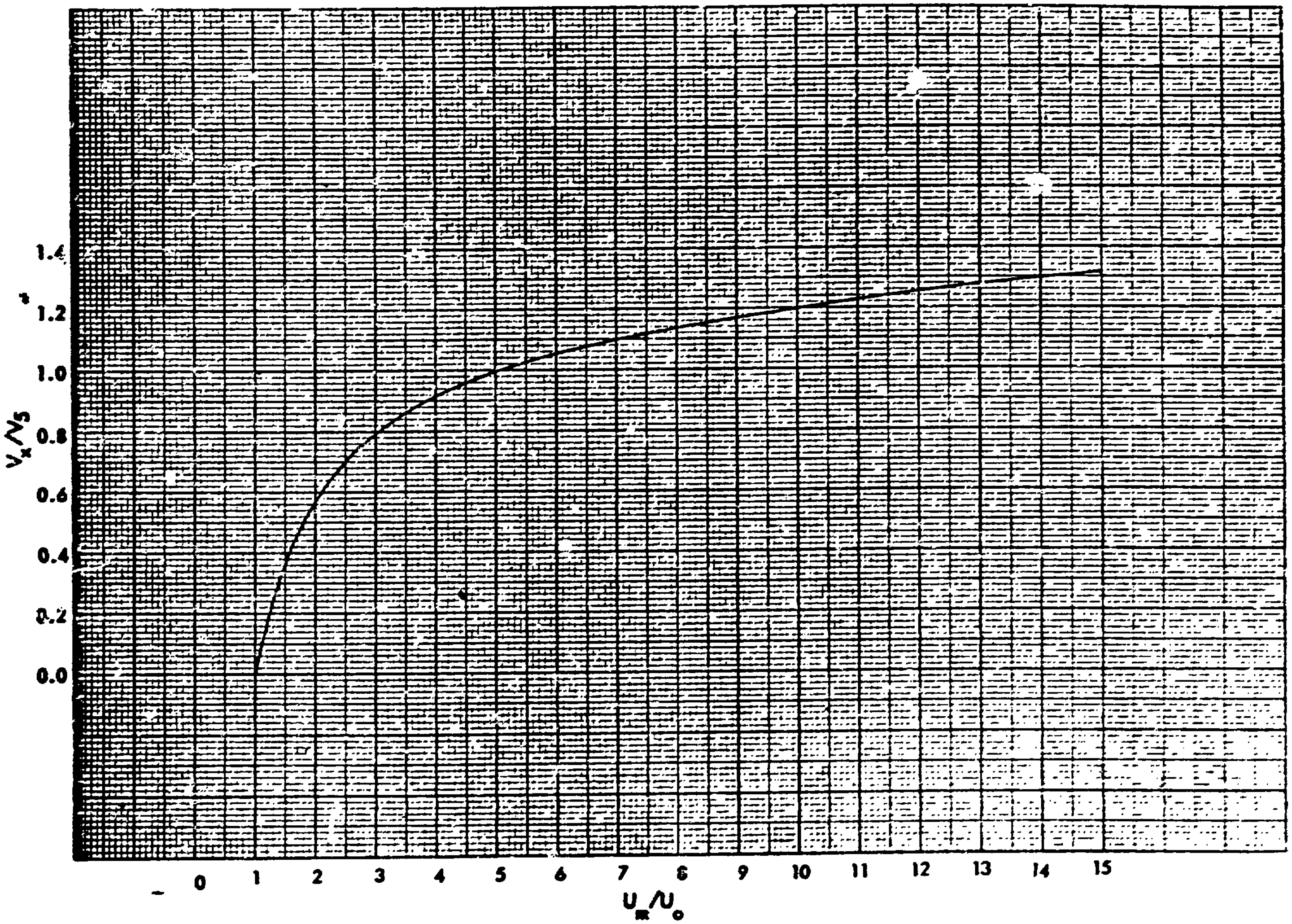

Figure 2. Relative velocity normalized to unity at an expansion ratio of 5 as a function of expansion ratio.

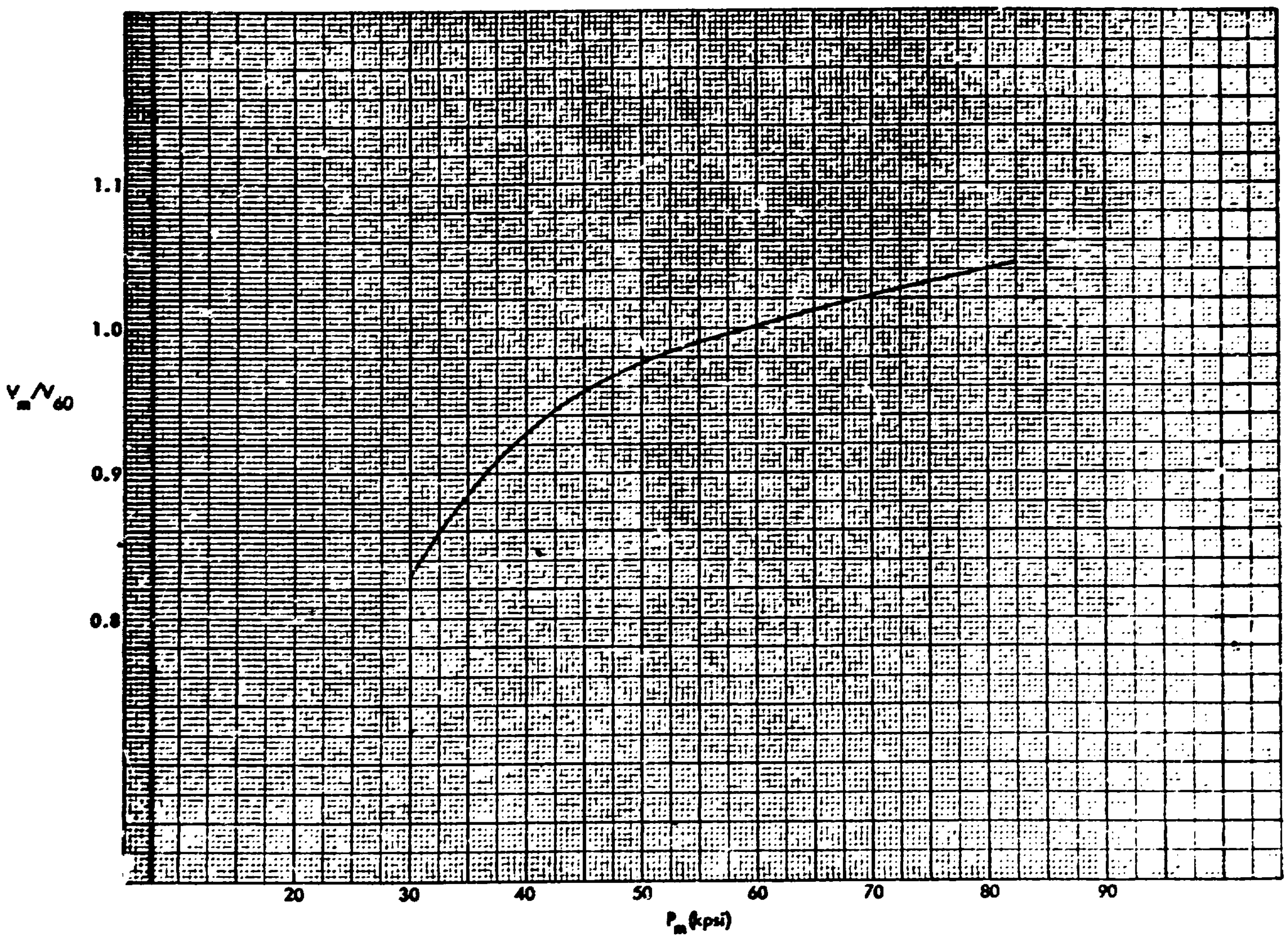

Figure 3. Velocity relative to the velocity at a peak pressure of 60 kpsi as a function of peak pressure.

calculate the muzzle velocity as follows:

$$\frac{C}{W} = \frac{49.9}{150} = 0.333$$

$$\frac{U_m}{U_o} = \frac{0.0732 \times 21.9 + 0.25}{0.25} = 7.41$$

$$V = V_{5,60}\left(\frac{V_r}{V_5}\right)\left(\frac{V_m}{V_{60}}\right) = 2610 \times 1.106 \times 0.981 = 2832 \text{ ft/sec (863 m/s)}$$

where: 2610 is read from figure 1, 1.106 is read from figure 2 and 0.981 is read from figure 3. For comparison, the muzzle velocity was actually recorded as 2832 ft/sec (863 m/s).

Dickey (ref. 3) has programmed these curves for use on a computer:

$$V_{5,60} = 3213 \log_{10} C/W + 4120$$

$$\frac{V_x}{V_o} = 0.668 \; V_m^{.25}$$

$$\frac{V_m}{V_{60}} = 0.545\,P^{.148} \text{ where P has units of kpsi}$$

Powley (ref. 4) has formulated another empirical model from his many years of experience with small caliber weapons. He also references several other such models that have evolved over the years (ref. 5).

As has been previously mentioned, empirical curves apply to systems which use selected optimum ballistic parameters. To obtain information about systems with parameters (i.e., C/W, P_m, or U_m/U_o) outside of normal limits or to obtain more detailed information about system characteristics, one must use more sophisticated analytical interior ballistics models.

ANALYTICAL INTERIOR BALLISTICS MODELS

Propellant Deterrent Technology

Propellant with uniform chemical composition is used in large caliber ammunition. Conversely, small arms weapons generally operate at higher loading densities and pressures and shorter ballistic cycle times, requiring the use of deterred propellants. Deterrents are applied to the surface of the propellant and diffuse into the grain. They reduce the energy content of the gases and slows the burning rate during the initial burning phase. This leads to a more progressive type of burning. Progressivity in large caliber ammunition is normally achieved by the geometric design of the grain. However, because of the higher loading densities required, progressivity can be better achieved in small arms by use of deterrent. Although the deterrent content is only a small percentage of the propellant grain (i.e., 2 to 10%), the surface of the propellant contains a considerably higher concentration.

The advance in small arms propellant deterrent technology (ref. 6) has permitted better understanding of and simulation of small caliber interior ballistics systems. This technology has evolved through the application of such investigative techniques as microtoming followed by chemical and microscopic examination to establish the nature of the composition gradient (refs. 7-10).

Also, additional investigations involve the use of infrared spectroscopy (ref. 11) and autoradiography (refs. 12-13) to determine composition gradients. Much information has been obtained through the use of closed bombs. Stiefel and Davis (ref. 14) obtained apparent burning rates of small arms propellants from closed bomb data and suggest the Serebryakov (ref. 15) method for establishing the deterrent gradient.

The most successful use of closed bombs for obtaining burning rate data on deterred small arms propellants was probably achieved by Riefler and Lowery (ref. 16). They used specially prepared propellant samples of various homogeneous compositions in a closed bomb. Data from the ignition and burnout phase are neglected so that the empirical constants during the complete burning phase alone are calculated. Using statistical techniques, they obtain the burning rate coefficient and exponent for the burning rate equation of the form $R = AP^n$. These factors are described in terms of the percentage of deterrent (DBP) and the percentage of nitroglycerin (NG) and polynominals involving web size.

In the development of small arms ammunition, two terms, relative force and relative quickness, are used to describe propellants on the basis of their closed bomb performance. Relative force is the ratio of the force or impetus of a test propellant to the force of a standard propellant, measured at the same initial temperature and loading density in the same closed chamber. Relative quickness is defined as the time rate-of-change of pressure (dp/dt) of a test propellant to that of a standard propellant measured at the same initial temperature and loading density in the same closed chamber[1].

Analytical models of deterrent concentrations and thermochemical characteristics have been formulated for interior ballistics models. Trafton (ref. 17) simulates the variation of surface deterrent concentration with depth by assuming that the surface deterrent concentration is considerably larger than the average measured value of the total grain and that it then decreases linearly (with grain volume burned) to a value of zero at some depth in the grain. To compute the penetration depth of the deterrent, he assumes that the deterrent does not change the propellant density and that the changes in deterrent concentration occur between equal volume increments of the grain. He has further modified (ref. 18) his model to include a stepwise concentration to a given depth.

Gottlieb (ref. 19) et al, have conducted both analytical and experimental studies on the effective progressivity of deterred propellants. They have been able to simulate $\dot{P}$ vs P traces of both adiabatic and nonadiabatic closed vessel firings. To accomplish this a system of differential equations by which pressure, fraction of web burned, amount of gas generated, system temperature, and wall temperature are related as functions of time was formulated and solved to simulate closed chamber firings.

In the United States today, the ball propellant used in almost all small arms ammunition is manufactured by a solvent emulsion process that results in bulk mixtures of varying grain sizes and different chemical compositions (i.e., different levels of deterrent) for different sieve sizes. Trafton assumes the deterrent content varies inversely with grain size. Thus with this model, one can take into account both the effect of different grain size distribution on gas production and the effect of different grain size on the chemical composition.

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[1]Olin Corporation uses WC 846, which is the propellant for 7.62 mm, as a reference propellant. E.I. DuPont de Nemours Co. uses IMR 4350 as a standard.

Trafton also uses a separate thermochemical computer model to calculate impetus and flame temperatures for the varied chemical compositions that include the assumed deterrent concentrations combined with the base propellant. Also, with his model, one is able to treat nonsimultaneous ignition of the propellant charge by use of the simplified assumption that the total surface of the propellant grain ignites smoothly at a uniform rate from the primer end of the charge forward as a function of time. This effect can be important in simulating small arms interior ballistics.

Analysis

The interior ballistic equations used by Trafton were modified from those of Baer and Frankle (ref. 20) to include the effects of deterrent coating and nonsimultaneous ignition. These equations are shown in table 1 and include:

1. Energy equation.

2. Equation of state.

3. Mass fraction burn rate equations.

4. Equations of projectile motion.

Goldstein (ref. 21) has modified Trafton's program to accept a simplified model describing the thermochemical properties and burning rate of deterred rolled ball propellant. His model includes the following:

Assumption No. 1

Each grain in the charge is of uniform geometry and has dimensions determined by the equivalent mean radius $\bar{R}$ obtained from the sieve size distribution of the propellant lot. This dimension is given by:

$$\left[\frac{\sum_i Ri^2 \frac{Fi}{Voi}}{\sum_i Fi/Voi}\right]^{1/2}$$

where Ri = average radius of a propellant grain from a given sieve cut (ref. 22).

Voi = initial volume of propellant grain of radius Ri.

Fi = fraction of charge weight or volume with radius Ri.

Table 1. Interior ballistics equations.

Energy Equation

$$T = \frac{\sum_{i=1}^{n}\left[\frac{F_i C_i z_i}{\gamma_i - 1}\right] + \frac{F_I C_I}{\gamma_I - 1} - \frac{v^2}{2g}\left(W_p + \frac{\sum_{i=1}^{n} C_i}{\delta}\right) - A\int_o^x p_r\,dx - E_h}{\left[\sum_{i=1}^{n}\frac{F_i C_i z_i}{(\gamma_i - 1)T_{o_i}}\right] + \frac{F_I C_I}{(\gamma_I - 1)T_{o_I}}}$$

where:

$$E_h = \frac{0.38c^{1.5}\left(x_m + \frac{V_o}{A}\right)\left(\frac{\sum_{i=1}^{n} C_i T_{o_i}}{\sum_{i=1}^{n} C_i} - T_s\right)v^2}{\left[1 + \frac{0.6c^{2.175}}{\left(\sum_{i=1}^{n} C_i\right)^{0.8375}}\right]v_m^2}$$

Equation of State

$$\bar{p} = \frac{T}{V_c}\left[\left(\sum_{i=1}^{n}\frac{F_i C_i z_i}{T_{o_i}}\right) + \frac{F_I C_I}{T_{o_I}}\right]$$

where:

$$V_c = V_o + Ax - \sum_{i=1}^{n}\frac{C_i}{\rho_i}(1 - z_i) - \sum_{i=1}^{n} C_i z_i b_i$$

$$P_b = \frac{\bar{p}}{1 + \frac{\sum_{i=1}^{n} C_i}{W_p \delta}}$$

$$p_b = \frac{P_b}{(1 - a_o)^{-n'-1}}$$

Mass-Fraction Burning-Rate Equations

$$\frac{dz_i}{dt} = \frac{1}{V_{g_i}} S_i r_i$$

$$r_i = \beta_i (\bar{p})^{\alpha_i}$$

or:

$$r'_i = r_i + K_v v + K_x x$$

Equations of Projectile Motion

$$a = \frac{Ag\left(p_b - p_g - p_r\right)}{W_p}$$

$$v = \int_o^t a\,dt$$

$$x = \int_o^t v\,dt$$

This method of defining R has been used previously when one considers heat and mass transfer and reaction at the fluid particle surface interface (ref. 23). Kitchens, (ref. 24) in treating flame spreading through a propellant bed, used mean diameters discussed by Zabrodsky (ref. 25). They are described by the equations

$$\frac{1}{d_A} = \frac{X1}{d1} + \frac{X2}{d2} + \ldots + \frac{Xn}{dn}$$

or

$$d_B = X1d1 + X2d2 + \ldots + Xndn$$

where X1 is the weight fraction of a narrow fraction of diameter d1. Subscripts A and B are used to represent the two different methods of determining the mean diameter. Smith (ref. 26) assumes that the characteristic grain dimension (i.e., diameter) is distributed normally about a mean value.

Assumption No. 2

The penetration of the propellant grain by the deterrent follows Levy's findings that the migration of modifiers into ball propellant can be characterized by a diffusion front exhibiting high concentration gradients that result in sharp lines of demarcation between various layers. This is in accordance with normal plasticizer-polymer difusion systems. Smith assumes that the deterrent diffuses in a manner similar to conduction of heat in a semi-infinite solid. Since the penetration depth of the deterrent represents a distribution of values, a three layer grain model was used and found to give satisfactory results.

Assumption No. 3

The penetration of the nitroglycerin into the propellant grain is complete. This assumption applies mainly to relatively small grains with high nitroglycerin-to-nitrocellulose ratio and it simplifies calculations and yields favorable results.

Assumption No. 4

The geometry of the propellant grain is that of a disc with rounded edges (fig. 4).

If ϕ is the distance the deterrent has penetrated a grain of rolled ball propellant, then the equivalent mean volume of the central nondeterred region (V_y) for this assumed geometry is

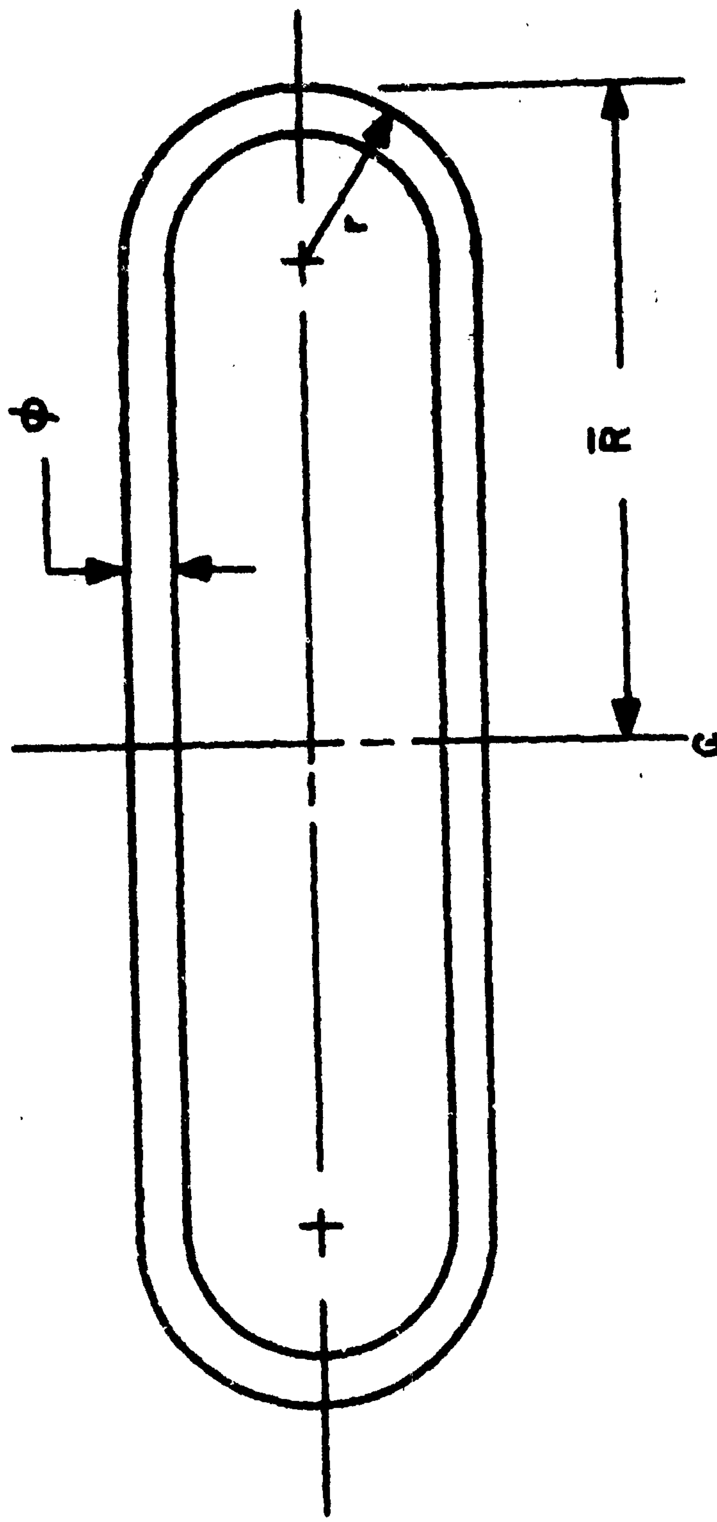

Figure 4. Geometry of rolled ball grain.

$$V_y = 2\pi\,(\bar{R} - r_o)^2 (r_o - \phi) + \pi^2 (r_o - \phi)^2 \left[(\bar{R} - r_o) + \frac{4}{3\pi}(r_o - \phi)\right]$$

where r_o is the radius of the outside edge of the propellant grain (web/2). This rolled-ball grain becomes an oblate spheroid in Trafton's model whose volume is given by

$$Vgi = (\pi/6)\, Di^2\, di$$

Also, his model (ref. 27) can handle other geometric forms including single perforated grains with different burning mechanisms inside and outside the grain. By assuming a surface deterrent concentration and complete nitroglycerin penetration, Goldstein was able to calculate the composition of both the deterred and nondeterred regions as well as the depth of deterrent penetration. To determine burning rate in each region, he used Muraour's equation (ref. 28) that relates burning rate (r) with flame temperature (T_o), i.e., $\ln r = A + B\,T_o$ where A and B are constants at a given pressure and are obtained from empirical data (refs. 29,30).

In Trafton's model, the burning rate varies linearly with flame temperature. At a fixed pressure level, note that the flame temperature alone may not be the single factor by which the propellant burning rate is determined. Adams (ref. 31) in his study of the combustion of double-base propellants, also points out the effect of chemical structure in addition to flame temperature on the burning rate.

Trafton's model has also been expanded to take into account temperature effects on the ballistic performance of small caliber ammunition (ref. 32). The temperature of the ammunition used in small arms has a significant effect on the performance of the weapon (ref. 33). The two factors that were considered most important in determining the temperature effects were the temperature sensitivity and the low temperature fracturability of the propellant.

Sensitivity $(\pi_\gamma)_p$ is defined as $(\pi_\gamma)_p = \left(\frac{\partial \ln r}{\partial Ts}\right)_p$

On integration, the following is obtained $r = r_o' e^{(\pi_\gamma)_p (Ts - Tso)}$ where r is the burning rate at conditioning temperature Ts, and r_o' is the burning rate at some reference temperature Tso. The relationship between the burning rate and the flame temperature can be derived on the assumption that the gas phase reaction rate independently controls the burning rate (ref. 34) For pressures normally encountered in small arms ammunition, this assumption appears reasonable.

The temperature sensitivity is thus given as $(\pi_\gamma)_p = \frac{E\ C_s}{2\ Ru\ Tf^2\ Cp}$

where E = activation energy for gas phase reaction (ref. 35)

C_s = specific heat of the solid per unit mass

Ru = universal gas constant

Cp = specific heat at constant pressure

The sensitivity of each layer can thus be determined because the flame temperature is directly related to the composition of the propellant layer under combustion.

Fracturability is believed to be the cause of the anomalous behavior (refs. 36, 37) of ball propellant at low temperatures. Internal stresses are induced into ball propellant during the rolling process at the time that it is manufactured. This leads to breakup during low temperature firings when the matrix has become embrittled. This can in turn produce pressure-time records for the chamber that are equal to or greater than those obtained at ambient firings. Ashley defines the term "fracturability" (ψ) as the increase in weight percentage of smaller diameter propellant particles fractured by the primer blast.

Trafton used the Pidduck-Kent function (refs. 38,39) in his model to describe the pressure gradient in a small arms weapon. This approximation appears to work satisfactorily for small arms systems. He later (ref. 40) included frictional effects between the barrel and gas. However, recent tests (ref. 41) have shown that the ratio of projectile base pressure to breech pressure (which the Pidduck-Kent describes as a constant) does indeed vary as the projettile travels down the barrel. Other inputs to his model include bullet pull, estimate of muzzle velocity, primer thermochemical information and empirical ignition delay, and engraving and frictional resistance of the projectile.

Energy losses resulting from heat loss are estimated by a semi-empirical relationship described by Hunt (ref. 42) and Corner (ref. 43). This is the same equation that is used in the Baer and Frankle model. Krier (ref. 44) has developed a small arms heat transfer model that solves the unsteady, turbulent, compressible boundary layer developed behind a moving projectile. This boundary layer is coupled to an inviscid core that supplies the boundary conditions at the edge of the boundary layer. The inviscid core solution is obtained from previous experimental investigations.

The boundary layer solution provides the necessary information to solve for the temperature history at the barrel wall. This solution is used together with a one-dimensional axisymmetric heat analysis to calculate the radial heat conduction and temperature distribution in the gun wall. Also, proper account is made of the curvature of the barrel wall. Experimental data (ref. 45) on the heat transfer rates in small arms cartridges are available.

SPECIALIZED INTERIOR BALLISTICS MODELS

In recent years, substantial progress has been made in describing interior ballistics phenomena in terms of nonsteady two-phase flow (ref. 46). This technology has also been used in small arms interior ballistics.

A two-phase flow model by which one can take into account shock waves in the barrel has also been developed (ref. 47). With this model, one can use the method of characteristics to solve the mixed hyperbolic-parabolic equation used to describe the system. The potential advantages of models in which the method of characteristics approach is used over the classical models (such as the Baer-Frankle model which use lumped parameters) are extracted from reference 48 and listed in table 2.

Several interior ballistic models (ref. 49, 50) have evolved in which the Lagrangean form of the equations is used for time dependent fluid flow. Joglekar and Phadke use an interactive model building approach to build their interior ballistics model (ref. 50).

Table 2. Comparison of approaches.

Classical method	Method of characteristics
Motion of the propellant is unaccounted for.	Motion of the propellant can be handled in the weapon.
Burning rate is a function of either chamber pressure or space mean pressure.	Burning rate is a function of local gas pressure and velocity.
Correction factor is needed to estimate gas velocity and pressure gradient. (Piccuck-Kent approx.).	Gas velocity and pressure gradient can be calculated at any location and time.
Effect of chamber geometry (chambrage) cannot be accounted for.	Any chamber geometry can be handled.
Pressure waves behind projectile cannot be handled. Modification is required to predict pressure distribution in high performance small arms rifle systems.	Method of characteristics has capacity for high performance small arms rifle systems by being able to handle chambrage, wave motion, gas friction, propellant motion, and gas venting.

SPECIAL ASPECTS OF SMALL ARMS INTERIOR BALLISTICS

Small arms interior ballistics systems have characteristics that are quite different from larger caliber systems. Small arms systems are normally cycled by gas energy from the propellant gases. This function requires the gases to leave the barrel some time before muzzle exit and to continue escaping for a considerable length of time afterward. As a result, enough gas can be removed from the barrel to affect the ballistic performance of the system. Also, since many types of small arms are shoulder-fired, some gas energy may be used in the weapon recoil (ref. 51). The small bore area of small arms also creates greater problems with heat transfer and erosion (ref. 52).

Gas Transmission Systems

Many small arms systems are gas-operated automatic weapons that have a gas-driven mechanism to operate the bolt and its associated moving components. The timing and pressure of the gas cylinder are regulated by the location of the port along the barrel and by the diameter of the orifice through which the gas flows.

Several types of gas systems are used in small arms systems today (refs. 53,54,55). In some systems, gases pour into a gas chamber when the projectile passes the port. This then results in pressure on a piston whose motion is delayed by bolt locks that are not released until chamber pressure has dropped to safe levels for cartridge case extraction.

Another system that has been extensively studied (refs. 56-60) incorporates a long gas tube through which a portion of the propellant gas in the barrel, drawn off when the bullet passes the port, is sent to a bolt mechanism in the rear of the rifle to cycle the weapon.

In designing pressure ports in automatic weapons, Beans (ref. 53) assumes that the flow is incompressible and turbulent and that the pressure losses through the different passages are determined from pipe fitting data in which nozzle and diffuser efficiencies are used. He also treats in detail the flow into a power cylinder where a connecting rod is actuated.

Spurk (ref. 56) obtains a solution to the problem of describing the flow in the gas tube by making use of the method of matched asymptotic expansions. He also assumes a simple polytropic relationship between the pressure and temperature to specify these parameters at the port after the projectile has passed:

$$\frac{T(t)}{T(o)} = \left[\frac{P(t)}{P(o)}\right]^{\frac{\gamma-1}{\gamma}}$$

Similarily, he uses incompressible flow contraction coefficients to describe the decrease in mass flow through the port.

Using the method of characteristics approach (table 2), Goldstein (ref. 58) simulated the compression and shock waves measured by Horchler (ref. 61) in the gas tube. Experimental data of the flow of the gases through the port have been obtained and a theoretical model (ref. 62) developed to describe both the nonsteady flow that occurs when the projectile first passes the port and the quasi-steady flow following port opening. In this model, the method of characteristics is used to describe the nonsteady flow from the barrel and through the port, and a two-dimensional compressible potential flow solution employing the Karmen-Tsien pressure correction formula is used to describe the quasi-steady flow.

After the projectile leaves the barrel, Hugoniot's equations (ref. 38) are used to describe the flow of the gases from the muzzle. Also, through the use of the Lagrange approximation, the fluid properties in the barrel at the port location are determined and, therefore, the boundary conditions for the flow through the port are specified. More recently, (ref 63) interest has been directed toward finding a three-dimensional viscous tube flow by which the Lagrange's approximation can be satisfied.

Pressure Waves

Shock waves and/or combustion instabilities have often been observed in the testing of guns (refs. 64-67). Since the start of the work done by Kuo (ref. 68) mathematical models have been developed to the extent that these ballistics anomalies can now be partly understood.

Kitchens (ref. 69) and Gerri (ref. 70) have used the method of characteristics to extend the KVS model (ref. 68) over a different length propellant bed. Recent work (ref. 71) done by Gerri with the use of a 7.62 mm I.D. vented bomb with a shear disc indicates (figs. 5 and 6) that:

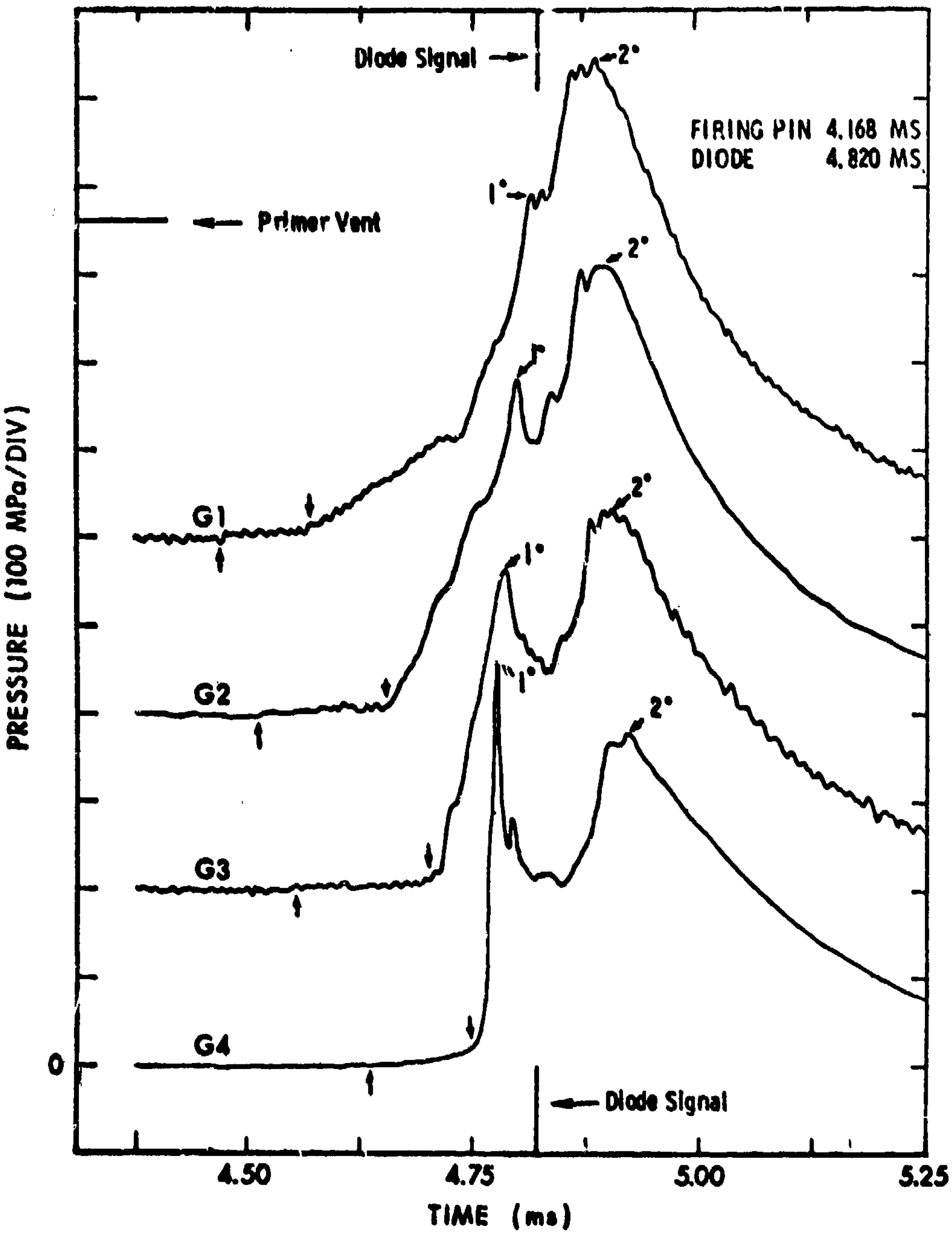

Figure 5. Pressure-time records obtained under standard conditions.

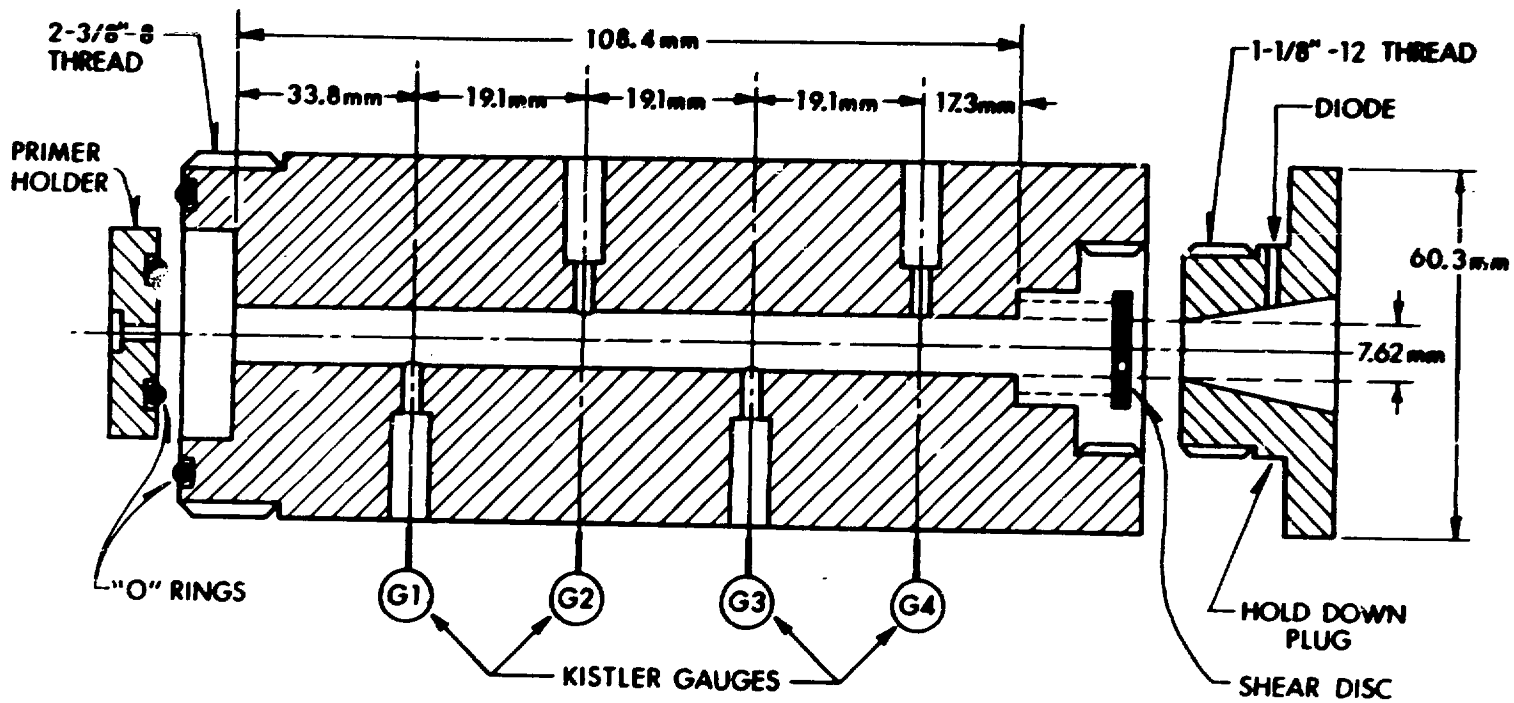

Figure 6. The 7.62-mm I.D. vented chamber.

1. The initial primer pulse and the primer vent geometry set the stage for all subsequent events.

2. Intergranular pressure transmission contributes to the rupture of the shear disc.

3. Propellant grain deformation and frictional forces at the chamber walls greatly affect the progress of the combustion wave through the propellant bed.

Experimental studies (ref. 72) have been conducted on 7.62 mm blank ammunition. These indicate (figs. 7-9) the multiple reflections of shock waves and characteristic waves within the barrel between the month of the cartridge case and the blank firing attachment (BFA). The computer code by which the problem of two-phase flow in a small arms barrel is solved with shock waves has also been developed (ref. 73). Compression waves and shock waves have also been evidenced (ref. 75) in the gas transmission system of some small arms weapons. High-speed photographic studies of small arms firings in a windowed chamber gun have been conducted to gain insight on primer and flamefront phenomena (ref. 74).

A survey (ref. 76) of recent studies in large caliber weapons indicates that the basic mechanisms responsible for generating pressure oscillations in gun systems are associated with the ignition and combustion phases and early projectile motion phase of the interior ballistic cycle.

CONCLUSIONS AND RECOMMENDATIONS

Although there are many different types of small arms interior ballistics models, each has certain advantages for specific applications. However, considerably more experimental testing and modeling are required to determine such quantities as:

1. Engraving, friction, and air pressure forces.
2. Strain energy or work done in deforming barrel walls.
3. Shot start pressures.
4. Recoil energy.

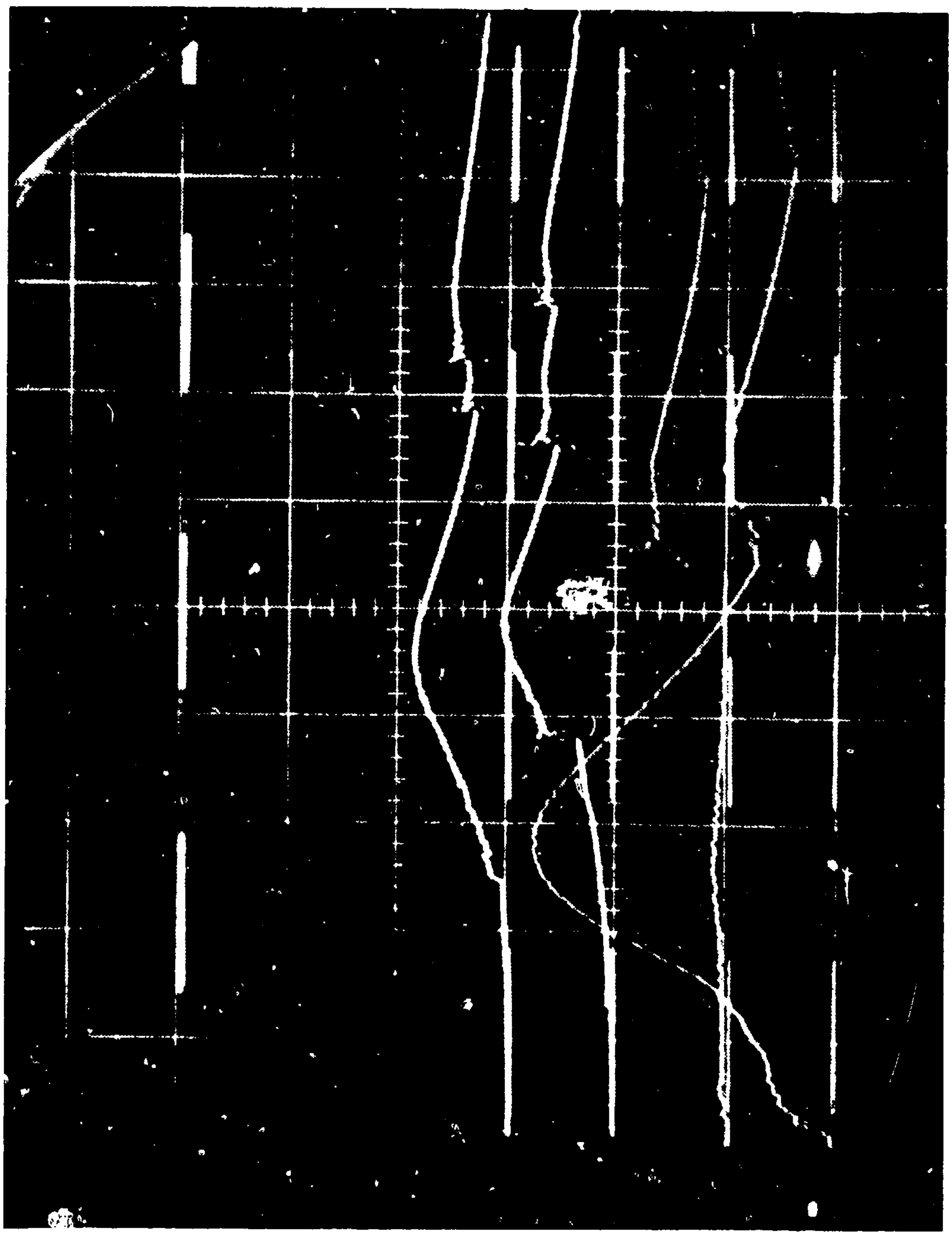

Figure 7. Pressure-time records in test barrel.

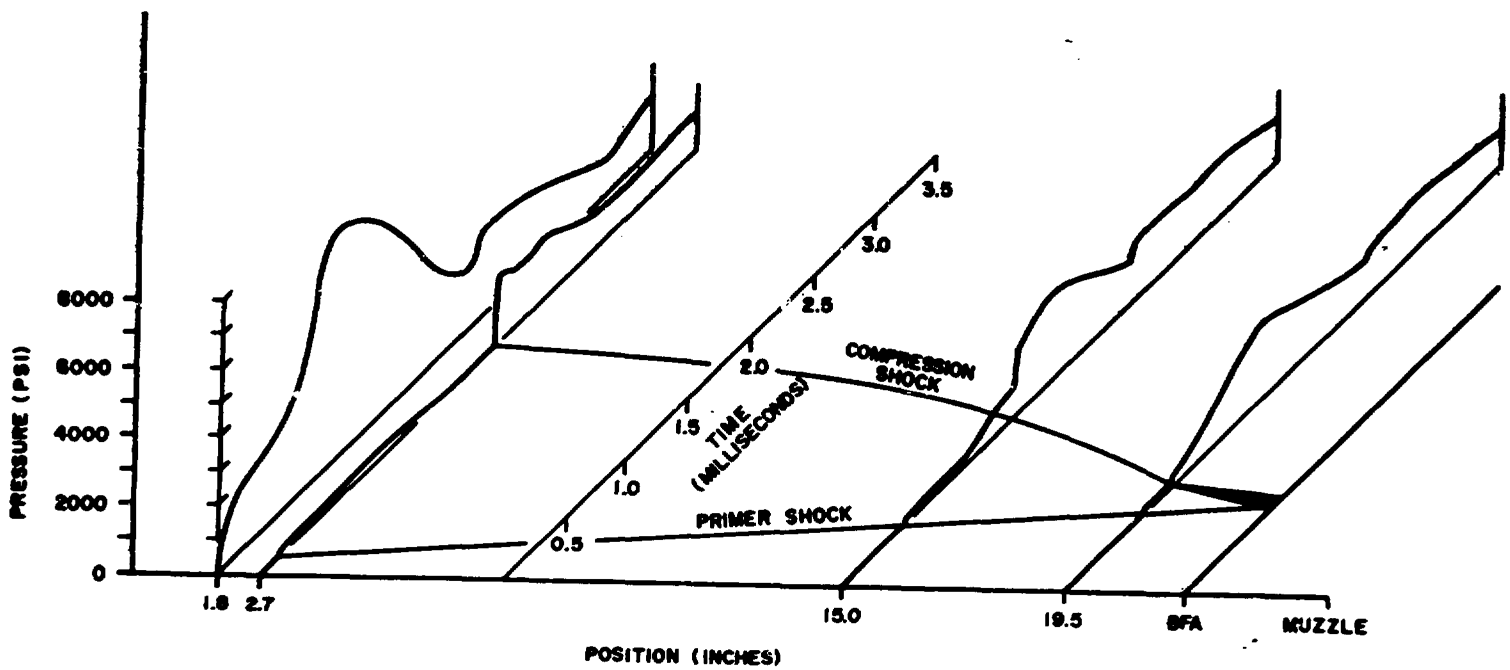

Figure 8. Pressure-time-position within barrel.

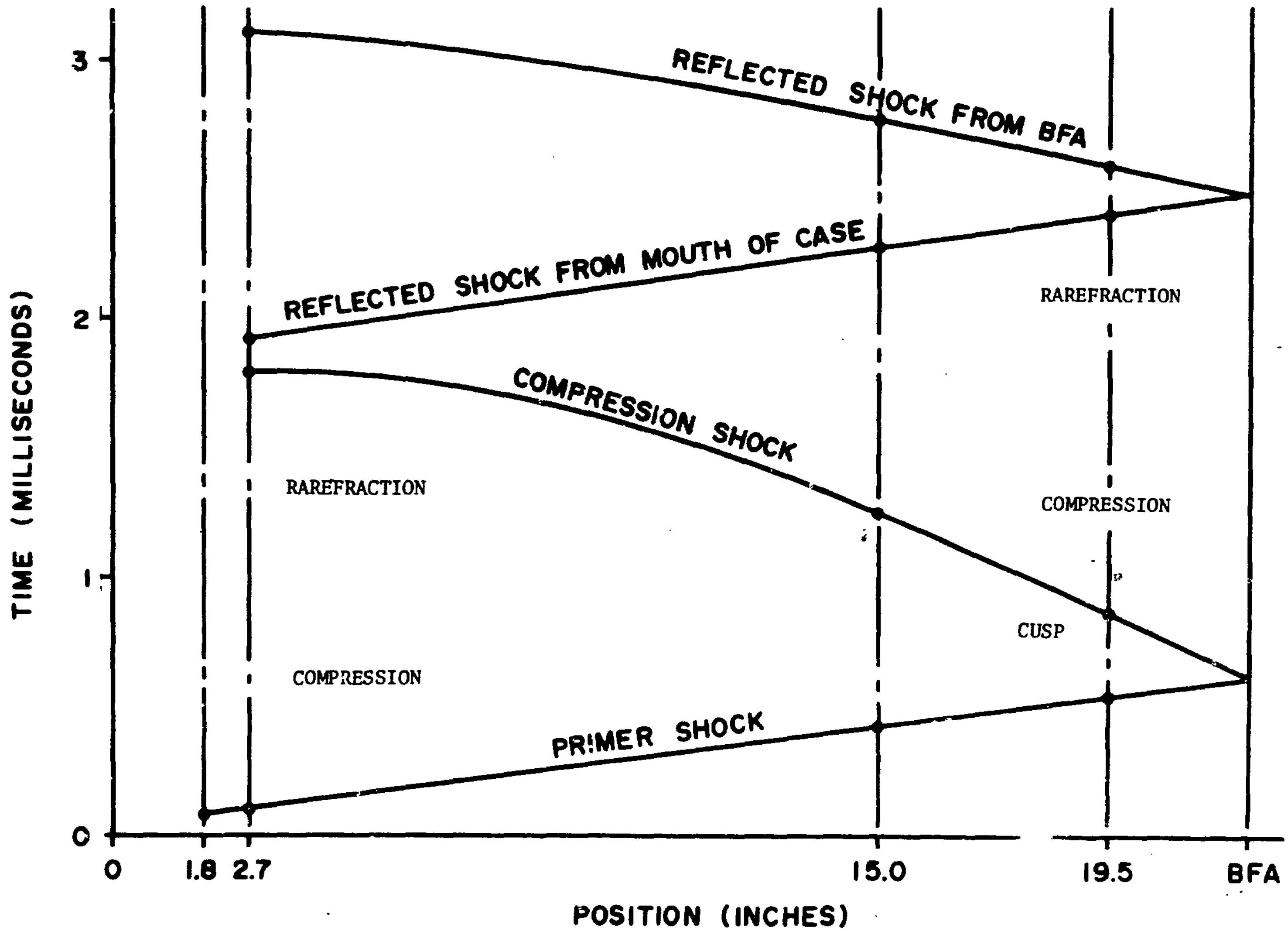

Figure 9. Position-time of shock waves.

5. Kinetic energy of propellant grains.

6. Propellant gas frictional energy.

7. Gas leakage.

8. Pressure transients.

9. Erosion factors.

The empirical models have been programmed and successfully used to predict the performance of different system designs. They are particularly useful in performing system analysis for proposed new weapon requirements. The analytical models have particular application to ammunition design. They can be used to determine the effect of variations in propellant compositions, deterrent concentrations, grain dimensions, and geometry on interior ballistics performance. They are also a means of determining where a specification may be changed or if processing technology is preserving the system's characteristics. Interim ballistics models provide the information needed to determine whether enough energy is available to properly cycle the weapon so that it can function reliably. They also supply input data for the neat transfer and erosion models used to predict barrel temperature and wear.

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