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Pressure Transients for Boron–Potassium Nitrate Igniters in Inert, Vented Chambers

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ABSTRACT

Equations which will describe the pressure–time curves for the ignition of cylindrical, boron–potassium nitrate, igniter pellets in vented, inert chambers are derived on the assumption that the burning rate is independent of pressure. This assumption is justified on the basis of closed chamber experiments.

Experimental firings were conducted over a considerable range of igniter weights and nozzle throat sizes. Smooth, reproducible pressure–time histories were obtained which showed excellent agreement with the analytically predicted curves.

I. INTRODUCTION

A logical approach to the analysis of the ignition pressure transient for a solid propellant rocket motor is to examine separately the contribution of the igniter in an inert motor of the same internal configuration, and the contribution of the propellant grain. This Report is concerned with boron–potassium nitrate igniters fired in inert, vented, motor configurations. Specifically, the object is to develop equations expressing pressure as a function of time for cylindrical boron–potassium nitrate pellet igniters.

The required function is derived by applying the law of the conservation of mass and the perfect gas law to the burning of a group of pellets. By assuming that burning proceeds normal to the pellet surface, and that all pellets are initiated simultaneously (Ref. 1), these two equations may be solved for pressure as a function of time. For the general case where burning rate is dependent on pressure, the solution can be arrived at by means of a stepwise technique. The equations derived in this Report are based on the assumption that the burning rate is independent of pressure and an analytical solution was achieved. The validity of this assumption for the boron–potassium nitrate pyrotechnic used is partially demonstrated by the results of the firing of a set of igniters in closed chambers under different pressures. The burning time of the pellets, as measured by time to peak pressure, does not vary monotonically when pressure is varied.

The term K_p, which is analogous to c^*, is incorporated into the mass balance equation. It relates rate of gas flow through the nozzle to the chamber pressure (Ref. 2). Another parameter which appears is $M/\alpha T$, a property of the igniter reaction product. Both K_p and $M/\alpha T$ are assumed constant for a given igniter firing. When K_p and $M/\alpha T$ are known, along with the easily-measured igniter and chamber parameters, a pressure–time curve may be generated. Additional equations, derived under the assumptions stated previously, permit calculation of K_p and $M/\alpha T$ from an experimental pressure–time history.

II. MATHEMATICAL DEVELOPMENT

The law of the conservation of mass and the perfect gas law, applied to the burning of pyrotechnic, is:

$$rA_b\rho = \frac{V}{R}\frac{M}{\alpha T}\frac{dp}{dt} + \frac{454gA_tp}{K_p}, \qquad (1)$$

when $M/\alpha T$ is constant. This relation between pressure and time is subject to the boundary condition: $p(0) = P_a$. K_p is defined by Eq. 2:

$$w_N = \frac{454gA_tp}{K_p} \qquad (2)$$

or, in equivalent form,

$$K_p = \frac{454gA_t \int p\,dt}{w}. \qquad (3)$$

For cylindrical pellets, where the burning rate, K_p, and $M/\alpha T$ are constant, Eq. 1 may be solved giving pressure as a function of time.

$$p = K_1t^2 - K_2t + K_3(1 - e^{-K_4t}) + P_ae^{-K_4t}, \text{ for } 0 \leqq t \leqq t_b \qquad (4)$$

and

$$p = p_be^{-K_4t}, \text{ for } t > t_b,$$

where

$$K_1 = \frac{6\pi N\rho r^3K_p}{454gA_t},$$

$$K_2 = 2\pi N\rho\left[\frac{6Vr^3K_p^2(M/\alpha T)}{(454gA_t)^2R} + \frac{(4R_0 + L_0)r^2K_p}{454gA_t}\right],$$

$$K_3 = 2\pi N\rho\left[\frac{6V^2r^3K_p^3(M/\alpha T)^2}{(454gA_t)^3R^2} + \frac{(4R_0 + L_0)Vr^2K_p^2(M/\alpha T)}{(454gA_t)^2R} + \frac{(R_0^2 + R_0L_0)rK_p}{454gA_t}\right],$$

and

$$K_4 = \frac{454gA_tR}{VK_p(M/\alpha T)}.$$

For $t > t_b$, the solution of Eq. 1 may be written

$$\ln p = \frac{-454gA_tR}{VK_p(M/\alpha T)}t + c, \qquad (5)$$

where c is constant.

Setting the derivative of the first part of Eq. 4 equal to zero yields Eq. 6, a relationship between t_m and the igniter and chamber parameters.

$$\left[\frac{6r^3VK_p^2(M/\alpha T)}{(454gA_t)^2R} + \frac{(4R_0 + L_0)r^2K_p}{454gA_t} + \frac{R(R_0^2 + R_0L_0)r}{V(M/\alpha T)} - \frac{454P_agRA_t}{2\pi N\rho VK_p(M/\alpha T)}\right]e^{\left(\frac{-454gRA_t}{VK_p[M/\alpha T]}\right)t_m} + \left[\frac{6r^3K_p}{454gA_t}\right]t_m - \left[\frac{6r^3VK_p^2(M/\alpha T)}{(454gA_t)^2R} + \frac{(4R_0 + L_0)r^2K_p}{454gA_t}\right] = 0 \qquad (6)$$

Combining Eq. 4 and Eq. 6 gives, for peak pressure, the expression:

$$p_M = \frac{2\pi N\rho K_p}{454gA_t}\left[3r^3t_m^2 - (4R_0 + L_0)r^2t_m + (R_0^2 + R_0L_0)r\right]. \qquad (7)$$

III. APPARATUS AND INSTRUMENTATION

A. Igniter

The igniter which was tested consisted of a perforated cellulose acetate butyrate tube, loaded with pyrotechnic pellets and initiated with a Du Pont S-89 squib. (See Figure 1.) The pyrotechnic was U.S. Flare Corporation 2A pellets, whose composition is given in Table 1. The pellets are cylinders ⅛ in. in diameter and 3/16 in. long.

Table 1. Composition of U.S. Flare Corporation 2A pyrotechnic pellets

Ingredient	Wt. %
Boron	23.7
KNO_3	70.7
Binder	5.6

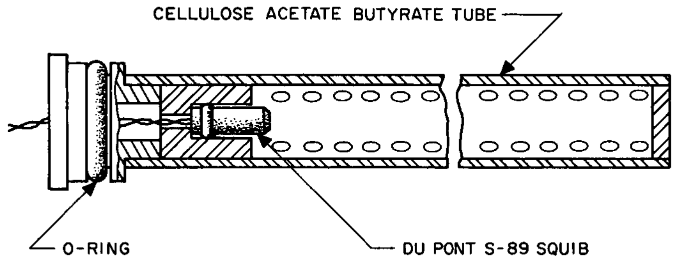

Figure 1. Igniter assembly

B. Test Chamber

The igniter was fired in a cylindrical steel chamber, 3 in. in diameter and 6 in. long, equipped with a nozzle (Figure 2). In some cases, the inside of the chamber wall was lined with 0.004-in. cellulose acetate tape. For the closed chamber tests, the nozzle was replaced by an end plate.

C. Instrumentation

In the vented chamber tests, pressure was measured with a Photocon transducer in conjunction with a Dynagauge discriminator and Kin-Tel DC amplifier. The output signal was then applied to a galvanometer oscillograph, and recorded photographically on paper moving at 48 in./sec. Reproducibility was sufficiently high to enable a clear comparison between calculated pressure–time curves and experimental data.

In the closed chamber tests, pressure was measured by means of a Tabor transducer and a Miller carrier system, and recorded in the same manner as in the vented chamber tests.

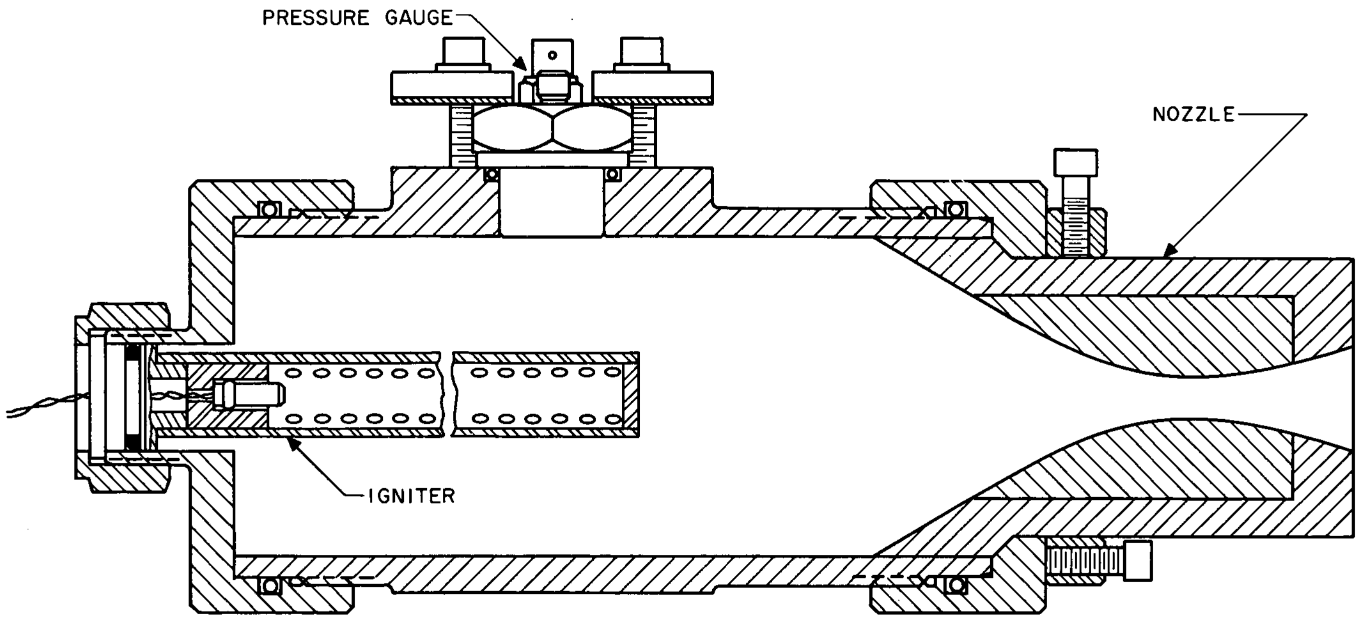

Figure 2. Vented chamber assembly

IV. METHODS OF CALCULATING IGNITER CONSTANTS FROM PRESSURE–TIME HISTORIES

Pyrotechnic burning rate is determined for closed chamber firings by substituting in the equation:

$$r = \frac{R_0}{t_m}. \tag{8}$$

Vented chamber pressure–time histories are needed to determine K_p and $(M/\alpha T)$. The first of these igniter gas parameters is calculated by means of Eq. 3, while two methods are available for calculating $M/\alpha T$. One way is to solve Eq. 6 for $M/\alpha T$. The alternative is to plot $\ln p$ vs t for the tail-off portion of the pressure–time history. In general, this is a straight line, in accordance with Eq. 5. A typical curve of this type is shown in Figure 3. The term $M/\alpha T$ may be calculated by substituting the slope S of this line into the equation:

$$M/\alpha T = \frac{454 g A_t R}{V S K_p}.$$

The latter method gives very consistent results when the nozzle throat area is small.

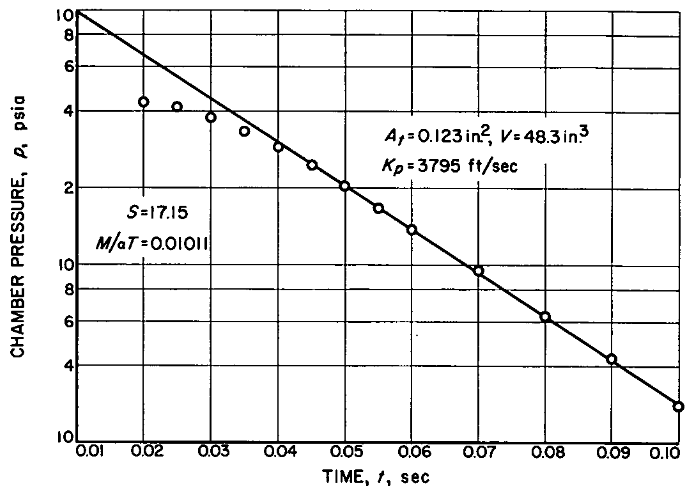

Figure 3. Plot of ln p vs t for the tail-off portion of the pressure–time curve

V. EXPERIMENTAL PROGRAM

A. Closed Chamber Tests

That the burning rate of boron–potassium nitrate pyrotechnic is in fact nearly independent of pressure is supported by the results of closed chamber tests. Three identical igniters were fired in sealed chambers whose volumes were 48, 90, and 176 in.³ The pressure–time histories for these three firings are shown in Figure 4. The time-to-peak pressure t_m may be taken as a rough measure of the total burning time of the igniter pellets. If burning rate were some increasing function of pressure over the entire range tested, then t_m would decrease regularly in going to successively higher pressure–time curves. However, this is not the case (see Figure 4). Similar reasoning could be applied if the burning rate were a decreasing function of pressure. Hence, the burning rate must be approximately constant over the range of pressures tested. The burning rate calculated from these data is 1.5 in./sec.

B. Vented Chamber Tests

Igniters were fired in vented chambers under a wide range of conditions in order to test the validity of the

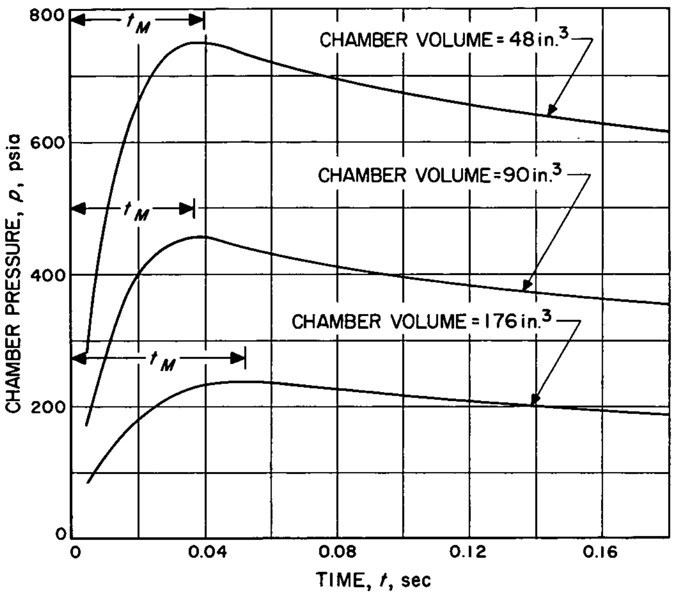

Figure 4. Igniter pressure–time histories for closed chambers

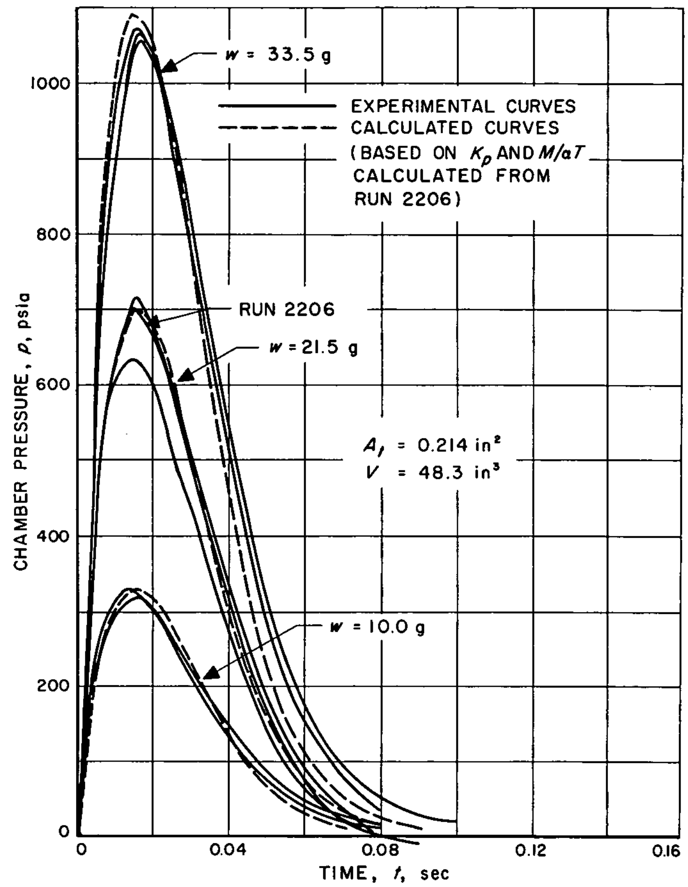

Figure 5. Calculated and experimental pressure–time curves for igniters fired in a cellulose acetate-lined chamber; $A_t = 0.214$ in.²

above equations, and to determine values of the igniter gas constants K_p and $M/\alpha T$. A number of interesting relationships were established.

1. Relationship between Igniter Gas Constants and Weight of Pyrotechnic

Eight igniters, whose pyrotechnic weights were 10.0, 21.5, or 33.5 g, were fired in 48.3-in.³ chambers lined with cellulose acetate. The nozzle throat area was 0.214 in.² One of these firings was Run No. 2206, where the pyrotechnic weight was 21.5 g. The igniter gas constants were calculated for this particular run by means of Eq. 3 and 6, giving $K_p = 3645$ ft/sec and $M/\alpha T = 0.0102$ gm/gm-mol-°R.

This pair of constants was then substituted into Eq. 4, and pressure–time curves generated for 10.0-, 21.5-, and 33.5-g igniters. (N equals 147, 316, and 493 respectively.) The three calculated curves, superimposed on the eight experimental pressure–time histories, are shown in Figure 5. Two conclusions may be drawn from the agreement illustrated in Figure 5.

(1) The function defined by Eq. 4 is a valid model of the pressure–time transient when the correct constants are substituted.

(2) The values of K_p and $M/\alpha T$ are independent of pyrotechnic weight when chamber and nozzle parameters are fixed. If this were not true, the constants determined from a 21.5-g igniter could not generate accurate pressure–time curves for 10.5- and 33.5-g igniters. (The only case where this reasoning fails is where K_p, $M/\alpha T$, and possibly other parameters all vary with pyrotechnic weight in such a manner that they compensate for each other).

This procedure was repeated for lined chambers of different nozzle throat areas, as well as for unlined chambers. The experimental and theoretical pressure–time curves are shown in Figures 6, 7, and 8 and confirm the conclusions of the previous paragraph.

2. Relationship between Igniter Gas Constants and Nozzle Throat Area

A set of 21.5-g igniters were fired in lined 48.3-in.³ chambers equipped with nozzles whose throat area ranged from 0.123 to 3.009 in.² Pyrotechnic batch #34-9 was used for this group of tests. A value of K_p and $M/\alpha T$ was calculated from each pressure–time history ($M/\alpha T$ was determined by means of Eq. 6). These two parameters are plotted vs A_t in Figure 9, along with a similar plot for unlined chambers.

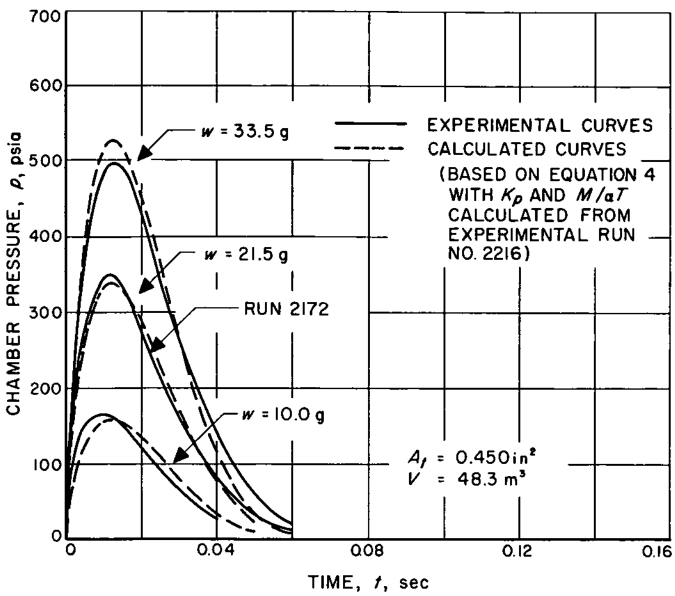

Figure 6. Calculated and experimental pressure–time curves for igniters fired in unlined chambers; $A_t = 0.450$ in.²

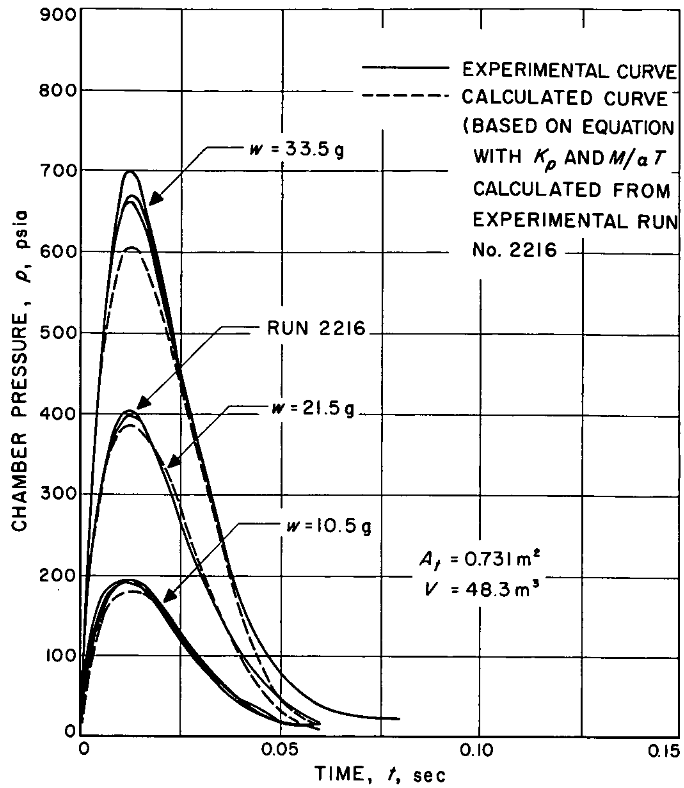

Figure 7. Calculated and experimental pressure–time curves for igniters fired in a cellulose acetate-lined chamber; $A_t = 0.731$ in.²

While the scatter is great, it is evident that as nozzle throat area is increased, K_p tends to decrease and $M/\alpha T$ gets larger. The phenomenon is believed to be primarily kinetic in nature. For a large throat area, residence time of the reaction product in the chamber is short; combustion does not proceed to completion, and therefore temperature is relatively low. It is known that K_p varies directly with $T^{\frac{1}{2}}$, and $M/\alpha T$ inversely with T. It follows then that, for a large nozzle throat area, K_p will be small and $M/\alpha T$ high. While the slopes of the K_p and $M/\alpha T$ curves are not related to each other precisely in accordance with this explanation, the order of magnitude of this relationship is correct.

It is noted that the values of $M/\alpha T$, particularly at small nozzle throat areas, are consistent with a value of .0116 g/g-mol-°R calculated by an independent investigator (Ref. 3) for a stoichiometric boron–potassium nitrate mixture from thermochemical data and equations. These calculations are summarized in Table 2.

The reason for the scatter in the $M/\alpha T$ data of Figure 9, while K_p is consistent, is not clear.

3. Relationship between Igniter Gas Constants and Inside Surface of Chamber

The data of Figure 9 establish that K_p is higher and $M/\alpha T$ lower for lined chambers than for unlined chambers. This effect is clearly illustrated in Figure 10, which presents pressure–time histories for 21.5-g igniters in two

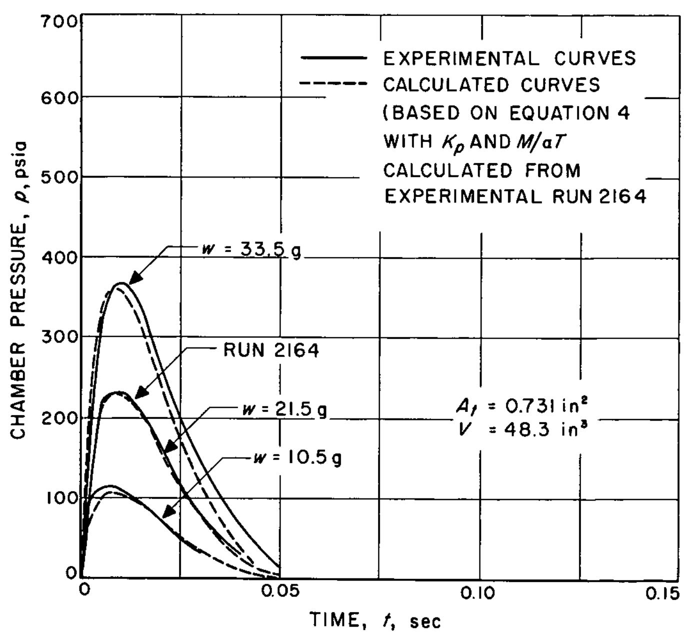

Figure 8. Calculated and experimental pressure–time curves for igniters fired in unlined chambers; $A_t = 0.731$ in.²

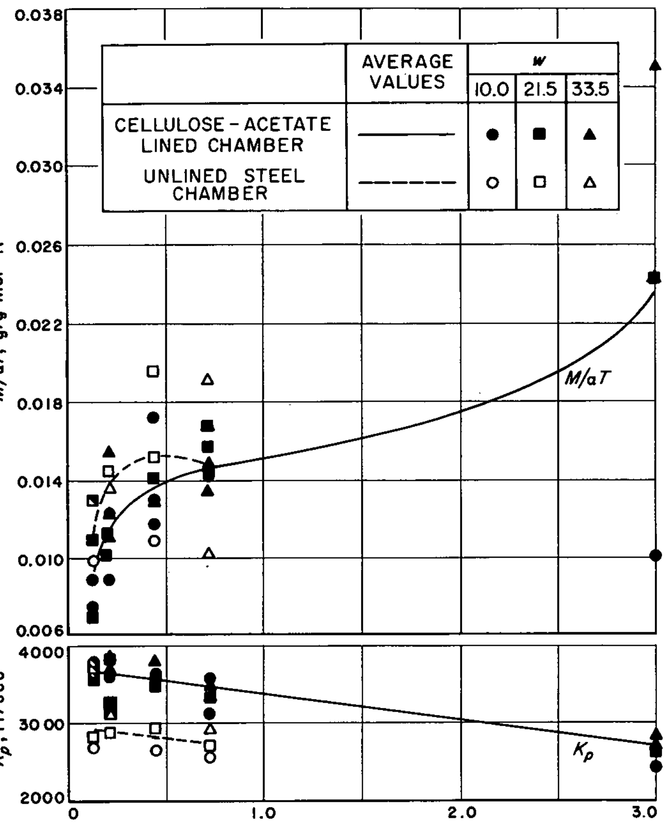

Figure 9. Plot of K_p and $M/\alpha T$ vs A_t

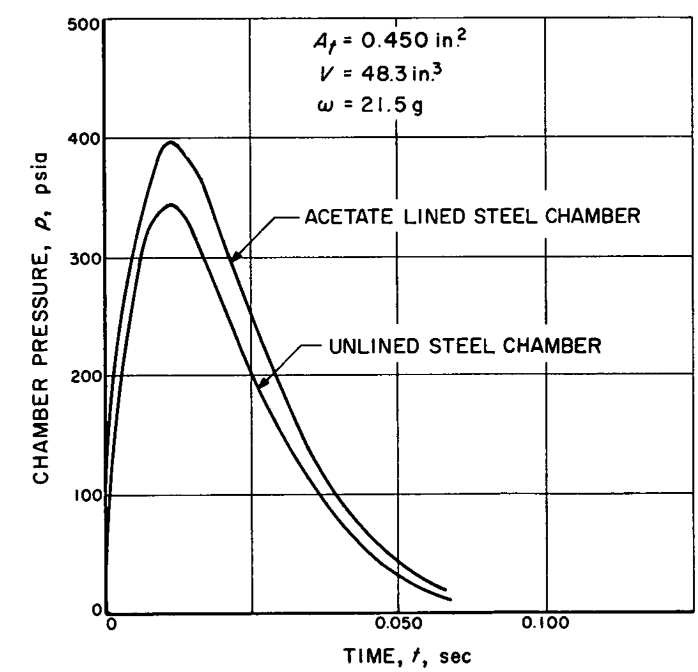

Figure 10. Pressure–time curves for lined and unlined chambers

Table 2. Theoretical reaction products at maximum flame temperatures produced by 100-g stoichiometric mixtures of boron–potassium nitrate igniters

Products at flame temperatures	Number of moles	Weight g
K (g)	0.838	32.7
O_2 (g)	0.209	6.6
N_2 (g)	0.419	11.6
B_2O_3 (L)	0.275	19.1
B_2O_3 (g)	0.430	30.0
$\alpha = 0.809$ Average $M = \frac{80.9}{1.896} = 42.7$ g/g-mol $T = 4540°R$ $M/\alpha T = 0.0116$ g/g-mol-°R	Total 2.171 Total Gas 1.896	100.0 80.9

chambers, lined and unlined, but otherwise identical. In general, pressure will increase directly with degree of insulation at the chamber surface. This is to be expected, since the gas temperature is higher in an insulated chamber. In addition, certain volatile components in the plastic liner may contribute to the chamber pressure at the high temperatures involved.

4. Relationship between Igniter Gas Constants and Chamber Volume

Figure 11 is a plot of igniter gas constants vs chamber volume in lined chambers, where pyrotechnic weight was fixed at 21.5 g and nozzle throat area held at 0.123 in.² Pyrotechnic was batch #34-10. The term $M/\alpha T$ was calculated from a plot of ln p vs t for the tail-off portion of the pressure–time curve. There is a tendency toward higher flame temperatures as chamber volume is

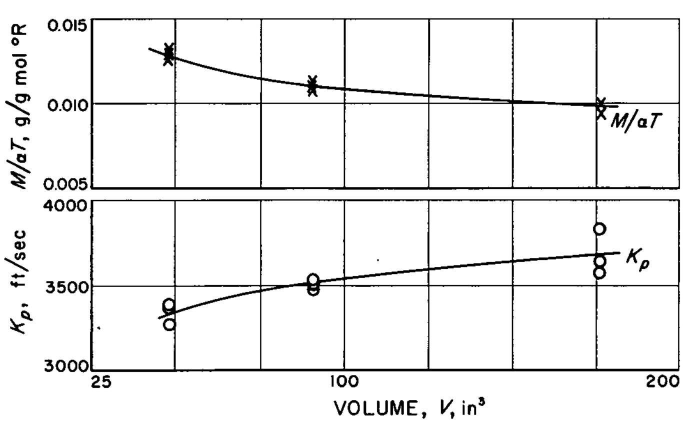

Figure 11. Plot of K_p and $M/\alpha T$ vs chamber volume for cellulose acetate-lined chambers

increased. This is attributed to the greater reaction product residence time for larger volumes which permits more complete combustion of the fuel and oxidizer. The magnitude of this effect, however, is small compared to the effects of heat losses to the chamber wall. For example, in a 48.3-in.^{3} chamber with a nozzle throat area of 0.123 in.^{2}, a four-fold increase in chamber volume increases K_p by 350 ft/sec (Figure 11), while the application of acetate tape to the inside chamber wall increases K_p by 750 ft/sec (Figure 9).

In the case of unlined chambers, Figure 12, no consistent relationship can be defined. Heat losses to the chamber wall are considerable, so that the volume effect cannot be examined.

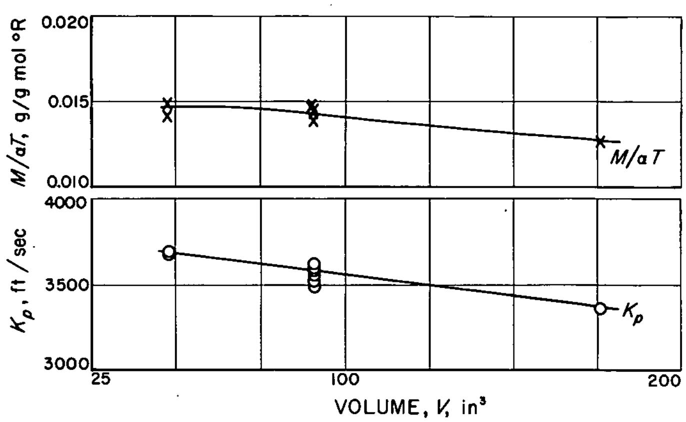

Figure 12. Plot of K_p and $M/\alpha T$ vs chamber volume for unlined chambers

VI. CONCLUSION

A mathematical model has been constructed which permits calculation of igniter pressure–time curves in inert, vented chambers, and conversely, enables calculation of igniter gas constants from experimental pressure–time histories. In both cases, the calculations are consistent with experimental measurements conducted over a wide range of variables, and this is taken as confirmation of the validity of the fundamental assumptions.

NOMENCLATURE

A_b	Total burning surface of igniter pellet, in.^{2}
A_t	Nozzle throat area, in.^{2}
g	Acceleration of gravity, ft/sec^2
K_p	Pyrotechnic nozzle flow constant, ft/sec
L_0	Initial length of cylindrical pyrotechnic pellet, in.
M	Average molecular weight of gas in pyrotechnic reaction product, g/g-mol
N	Number of pyrotechnic pellets in igniter
p	Chamber pressure, psia
p_m	Maximum pressure of a pressure–time curve, psia
P_a	Atmospheric pressure, psia
p_b	Chamber pressure at time of pyrotechnic burnout, psia
r	Burning rate, in./sec
R	Perfect gas constant = 40.7, psi-in.^{3}/g-mol-°R
R_0	Initial radius of a cylindrical pyrotechnic pellet, in.
t	Time, sec
T	Pyrotechnic gas flame temperature, °R
t_m	Time to peak pressure in a pressure–time curve, sec
t_b	Time to burnout of pellets, sec
V	Chamber volume, in.^{3}
w	Pyrotechnic weight, g
w_N	Flow rate of igniter reaction products through the nozzle, g/sec
α	Ratio of weight of gas in reaction products to total weight of reaction products
ρ	Density of pyrotechnic pellet, g/in.^{3}

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