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PRESSURE BUILDUP DUE TO BURNING IN A VENTED CHAMBER

by

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ABSTRACT

A theoretical analysis is made of the pressure buildup in a vented magazine in which a propellant is burning. Differential equations are derived relating the pressure and density of the gas to the rate of burning, heat of reaction, vent area, chamber volume, and time. The solutions of these equations indicate that for excess pressures in the magazine in the order of 15 to 20 psi, the peak excess pressure is directly proportional to the burning rate, inversely proportional to the vent area, and almost directly proportional to the heat of reaction. The peak pressure under these conditions is independent of the magazine volume. Under the same conditions, the time at which the peak pressure is reached varies mainly as the ratio of magazine volume to vent area. The theory does not predict the effective amount of afterburning.

INTRODUCTION

The analysis presented in this report is one phase of a project requested by the Bureau of Ships in connection with the design of storage magazines for rocket motors.[1] A safety feature in the design of the magazine is the provision for a vent to relieve the resultant pressures should the rocket propellant accidentally ignite. The venting should be sufficient to prevent the pressure from building up to a critical pressure which might burst the bulkheads.

The theoretical equations derived here relate the pressure and gas density in the magazine chamber to the characteristics of the rocket propellant and to the size of the magazine and area of the vent. In particular, a formula is derived which gives the size of vent required to keep the peak pressure below specified limits.

The relation between vent area and peak pressure has also been investigated in a program of small-size and full-scale tests,[2] and the combined conclusions of both theory and experiment have been communicated to the Bureau of Ships.[3,4]

EQUATIONS FOR GAS IN CHAMBER

DIFFERENTIAL EQUATIONS

We will discuss conditions under which three specific equations are sufficient to describe the state of the gas in the chamber. These equations are for the energy and material balance of the gas and for the rate of efflux of gas through the vent.

First, consider the energy balance within the chamber during an infinitesimal time interval dt. During this time, a mass $\mu_1 dt$ of propellant burns, forming dn_1 mols of gas which mix with the n mols of gas already in the chamber, and a mass of $\mu_2 dt$ or dn_2 mols of gas flows out through the vent. Some of the dn_1 mols react further with the oxygen in the chamber.

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[1]References are listed on page 12.

It is assumed that the external heat transfer in this time interval is negligible so that the change in internal energy of the mass $\mu_1 dt$ and of the n-dn_2 mols of gas which remain in the chamber, plus the work done on the efflux gases must add to zero. It is assumed further that all gases are perfect, that thermodynamic equilibrium is attained immediately, and that the internal energy change of any component of the gas is, in general, $\frac{nR\Delta T}{\gamma - 1}$ where n is the number of mols, R the gas constant, ΔT the change in temperature, and γ the ratio of specific heats.

The internal energy change of any component during the interval dt may be calculated by any convenient process which has the same end states as the actual process since internal energy is a function of state only. We will assume the process shown schematically in Figure 1. First the mass $\mu_1 dt$ reacts at constant volume V_0 and constant temperature equal to the initial temperature T_0 of the chamber, with an internal energy increase of $-\epsilon_0 \mu_1 dt$ where ϵ_0 is the constant-volume heat of reaction per unit mass at temperature T_0. Then the product gases expand to volume V and temperature T with a further increase in the internal energy

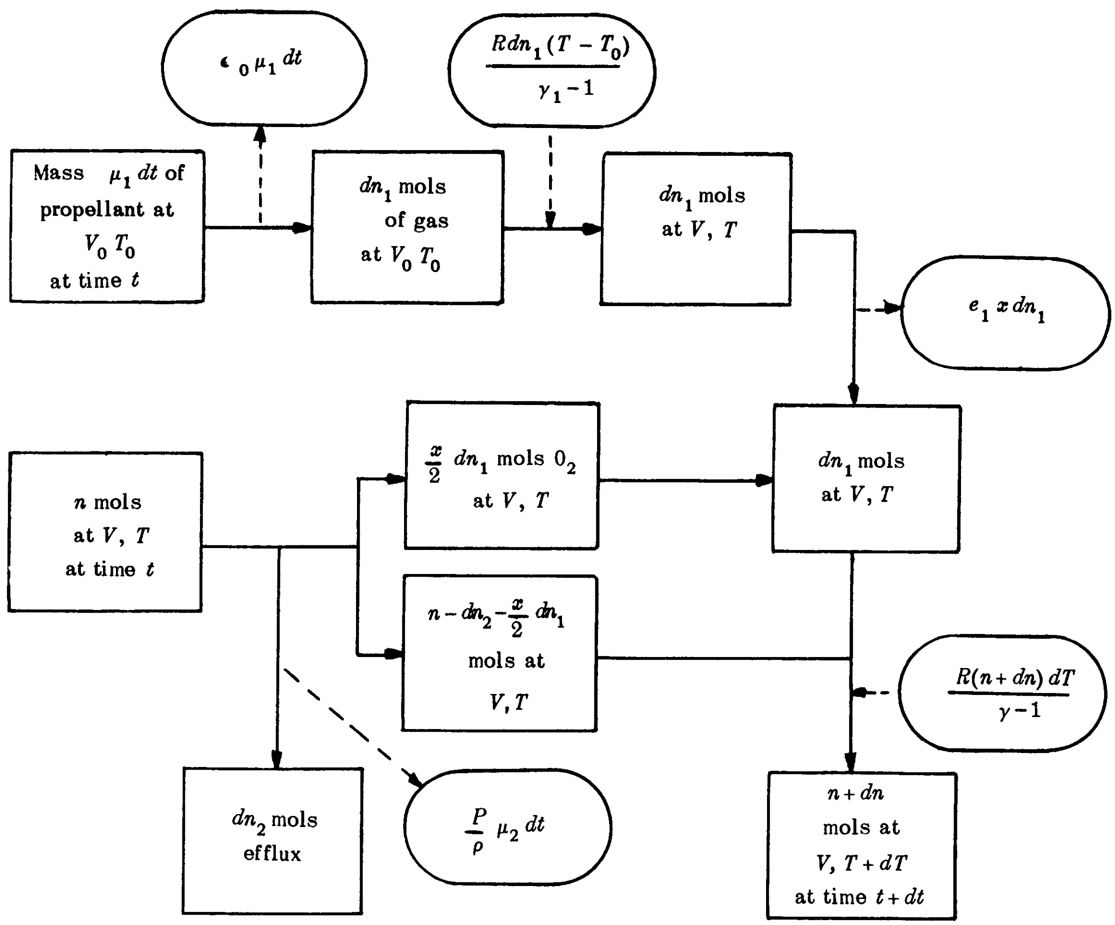

Figure 1 - Schematic Process for Burning of Propellant and Efflux of Gas During Time dt

of $\frac{Rdn_1}{\gamma_1 - 1}(T - T_0)$ where γ_1 is the specific heat ratio of the product gases; γ is the instantaneous average value for the gases in the chamber. Now assume that of the dn_1 mols of product gas, a certain fraction χ consists of CO or H_2 which will further react with the oxygen in the chamber according to the equations

$$CO + \frac{1}{2} O_2 \longrightarrow CO_2$$

$$H_2 + \frac{1}{2} O_2 \longrightarrow H_2O$$

This decreases the internal energy by $e_1 \chi\, dn_1$, where e_1 is the average heat of reaction per mol of the two reactions above, and decreases the number of mols in the chamber by $\frac{1}{2}\chi dn_1$ (since the oxidation converts $1\frac{1}{2}$ mols to 1 mol). Finally, it is assumed that the $(n + dn)$ mols which remain in the chamber are heated at constant volume to the temperature $T + dT$ with an internal energy change of $R\,(n + dn)\, dT/\gamma - 1$. Also, during this time interval, an amount of work $\frac{P\mu_2 dt}{\rho}$ has been done on the mass $\mu_2 dt$ of efflux gas, where P and ρ are the instantaneous pressure and density within the chamber, respectively. Hence the energy balance equation can be written

$$-\epsilon_0 \mu_1\, dt + \frac{Rdn_1}{\gamma_1 - 1}(T - T_0) - e_1 \chi dn_1 + \frac{(n + dn)\, RdT}{\gamma - 1} + \frac{P}{\rho}\, \mu_2 dt = 0 \qquad [1]$$

This can be simplified by using the equation of state and the following relations between the number of mols and the average molecular weights M_1 and M of the product gases and chamber gases, respectively:

$$P = \frac{\rho}{M}\, RT$$

$$VdP = nRdT + RTdn$$

$$dn_1 = \frac{\mu_1 dt}{M_1}$$

$$dn_2 = \frac{\mu_2 dt}{M}$$

$$dn = dn_1\left(1 - \frac{\chi}{2}\right) - dn_2$$

Then, if M_0, P_0, and ρ_0 are initial values of M, P, and ρ and if terms of only the first order in dt are retained

$$- \mu_1 \epsilon_0 dt + \frac{MP\mu_1 dt}{M_1(\gamma_1 - 1)\rho} - \frac{M_0 P_0 \mu_1 dt}{M_1(\gamma_1 - 1)\rho_0} - \frac{e_1 \chi \mu_1 dt}{M_1}$$

$$+ \frac{VdP}{\gamma - 1} - \frac{MP}{\rho(\gamma - 1)} \left[\frac{\mu_1 dt}{M_1}\left(1 - \frac{\chi}{2}\right) - \frac{\mu_2 dt}{M}\right] + \frac{P}{\rho}\mu_2 dt = 0$$

and the equation for the energy balance becomes

$$\frac{dP}{dt} = \left[\frac{(\gamma - 1)\mu_1}{V}\left(\epsilon_0 + \frac{\chi e_1}{M_1}\right) + \frac{\gamma - 1}{\gamma_1 - 1}\,\frac{M_0}{M_1}\,\frac{\mu_1 P_0}{V\rho_0}\right]$$

$$- \left[\frac{\gamma - \gamma_1}{\gamma_1 - 1} + \frac{\chi}{2}\right]\frac{M}{M_1}\,\frac{\mu_1 P}{V\rho} - \frac{\gamma\mu_2 P}{V\rho} \qquad [2]$$

A differential equation for the mass balance within the chamber can be written

$$\frac{d\rho}{dt} = \frac{\mu_1 - \mu_2}{V} \qquad [3]$$

The equation for the rate of efflux of gas might presumably be calculated from an energy and mass balance on the efflux gases. However, the mass balance is very difficult to analyze theoretically because the true vena contracta is substantially smaller than the vent opening. Hence we will use an empirical formula for the steady state flow of air from a region of pressure P, through a sharp-edged orifice of area A, into a region of pressure P_0. Adapting the results of Reference 5,

$$\mu_2 = 40.8A(\rho P)^{1/2}\left(1 - \frac{P_0^2}{P^2}\right)^{1/2} ; \quad \frac{P}{P_0} \leq 1.9 \qquad [4a]$$

$$\mu_2 = 38.8\,A(\rho P)^{1/2}\left(1 + 0.54\,\frac{P_0}{P}\right)\left(1 - \frac{P_0}{P}\right)^{1/2} ; \quad \frac{P}{P_0} \geq 1.9 \qquad [4b]$$

The numerical factor in this formula is appropriate for a special set of units of the variables; namely, P in pounds per square inch absolute, ρ in pounds per cubic foot, A in square feet, and μ_2 in pounds per second. It is shown in Reference 5 that this equation is equivalent to the finding that the area of the vena contracta ranges from 0.6 to 0.85 times the area of the vent, depending on the pressure ratio.

In order to specify completely the pressure and density within the chamber as functions of time, it would be necessary to augment Equations [2], [3], and [4] with auxiliary equations which would specify the amount of after burning, χ in Equation [1], in terms of the amount of oxygen in the chamber and the conditions in the jet stream of the rocket motor. Also it would be necessary to add equations which describe the variation with time of M, the mean molecular weight, and of γ. A general equation for the afterburning is not known; it will be necessary to restrict the further analysis to situations where Equations [2], [3], and [4] are sufficient to describe the pressure and density.

VENT CLOSED

The simplest version of these equations occurs in the case where there is no vent (A, $\mu_2 = 0$), and it is required to find the final pressure after all the propellant has reacted. We shall assume that the total mass of propellant, $W = \int \mu_1 dt$, is small compared with the mass of air $\rho_0 V$. In that case $M \simeq M_0$, γ is constant, and the equations become

$$\frac{dP}{dt} = \left[\frac{(\gamma - 1)\,\mu_1}{V} \left(\epsilon_0 + \frac{\chi e_1}{M} \right) + \frac{\gamma - 1}{\gamma_1 - 1}\,\frac{M_0}{M_1}\,\frac{\mu P_0}{\rho_0} \right] - \left[\frac{\gamma - \gamma_1}{\gamma_1 - 1} + \frac{\chi}{2} \right] \frac{M_0}{M_1}\,\frac{\mu_1 P}{\rho V}$$

$$\frac{d\rho}{dt} = \frac{\mu_1}{V}$$

Eliminating t and writing ϵ for $\epsilon_0 + \chi e_1/M$,

$$\frac{dP}{d\rho} = \left[(\gamma - 1)\,\epsilon + \frac{\gamma - 1}{\gamma_1 - 1}\,\frac{M_0}{M_1}\,\frac{P_0}{\rho_0} \right] - \left[\frac{\gamma - \gamma_1}{\gamma_1 - 1} + \frac{\chi}{2} \right] \frac{M_0 P}{M_1 \rho} \qquad [5]$$

which for $\rho - \rho_0 << \rho_0$ becomes

$$P - P_0 \simeq \left[(\gamma - 1)\,\epsilon + (1 + \frac{\chi}{2})\,\frac{M_0}{M_1}\,\frac{P_0}{\rho_1} \right] \frac{W}{V} \qquad [6]$$

The increase in pressure is simply proportional to the weight of reacting material. The dominant term in the proportionality constant is due to the total heat of reaction, including afterburning. This result can be used to predict the pressure in a chamber immediately after an explosive charge has detonated. The result is also important because it suggests a simple experimental method of checking the parameters in Equation [2].

CONSTANT BURNING RATE, VENT OPEN

In most rocket motors, the propellant is ordinarily designed to have a constant burning rate. We shall calculate the peak pressure as a function of vent area for this case, and as a matter of convenience, we shall further assume that ϵ, γ, M, and χ remain constant during the burning. Subsequently we will discuss the effect of variations in these other parameters.

It is convenentient to use nondimensional coordinates. Take

$$P' = \frac{P}{P_0}; \qquad \rho' = \frac{\rho}{\rho_0}$$

$$t' = \frac{\mu_1 t}{\rho_0 V}; \qquad \mu' = \frac{\mu_2}{\mu_1} \qquad [7]$$

Then the differential equations become

$$\frac{dP'}{dt'} = \left[\frac{(\gamma-1)\epsilon\rho_0}{P_0} + \frac{\gamma-1}{\gamma_1-1}\frac{M_0}{M_1}\right] - \left[\frac{\gamma-\gamma_1}{\gamma_1-1} + \frac{\chi}{2}\right]\frac{M_0}{M_1}\frac{P'}{\rho'} - \frac{\gamma\mu' P'}{\rho'} \qquad [8]$$

$$\frac{d\rho'}{dt'} = 1 - \mu' \qquad [9]$$

$$\mu' = \frac{KA}{\mu_1}\rho'^{1/2}\left(P' - \frac{1}{P'}\right)^{1/2}; \qquad P' \leq 1.9 \qquad [10a]$$

$$\mu' = 0.96\,\frac{KA}{\mu_1}\rho'^{1/2}\,P'^{1/2}\left(1 + \frac{0.54}{P'}\right)\left(1 - \frac{1}{P'}\right)^{1/2}; \qquad P' \geq 1.9 \qquad [10b]$$

Where $K = 44.5$ pounds per square foot second for the case where the efflux is into a medium at standard pressure and density.

It is significant that V does not occur explicitly in the equations and that A and μ_1 occur only in their ratio. For any value of A/μ_1, Equations [8], [9], and [10] may be solved simultaneously to give values of P' and ρ' as functions of t'. For each such solution, there will be a maximum value of P' which depends only on the parameter A/μ_1. Thus, under the assumed conditions, *the peak pressure in the chamber is independent of its volume and depends only on the ratio of vent area to burning rate.* Also, for each solution of the equations, there will be a value for t' at which the maximum pressure is reached; this value of the reduced time will be independent of V. However, in true time units, the *time at which the peak pressure is reached varies in direct proportion to the volume of the chamber.*

NUMERICAL CALCULATIONS OF PEAK PRESSURE

Practical structures for rocket magazines might withstand excess pressures up to say 20 psi. Hence we are interested in ratios of the vent area to burning rate for which the peak value of P' reaches 2.3. In order to determine this, the differential equations, [8], [9] and [10], were solved by standard numerical techniques for three values of the ratio A/μ_1, for four values of the total heat of reaction ϵ, and for two values of the mol fraction in afterburning χ, i.e., eight solutions in all. The parameters used were

$A/\mu_1 = 0.055,\ 0.073,$ and 0.091 square foot second per pound

$\epsilon\ = 700,\ 850,\ 1000,$ and 2700 cal per g

$\chi\ = 0$ and 0.8; $M_0 = M_1$

$P_0\ = 14.7$ psi; $\rho_0 = 0.081$ pounds per cubic foot

$\gamma\ = 1.4$; $\gamma_1 = 1.25$

The results of one of these calculations for P' and ρ' as functions of time are shown in Figure 2. The pressure rises to an initial peak value from which it decays and approaches an equilibrium value. At this equilibrium pressure, the rate of efflux is equal to the rate of burning and the density is also at an equilibrium. It is interesting to observe how quickly ρ'

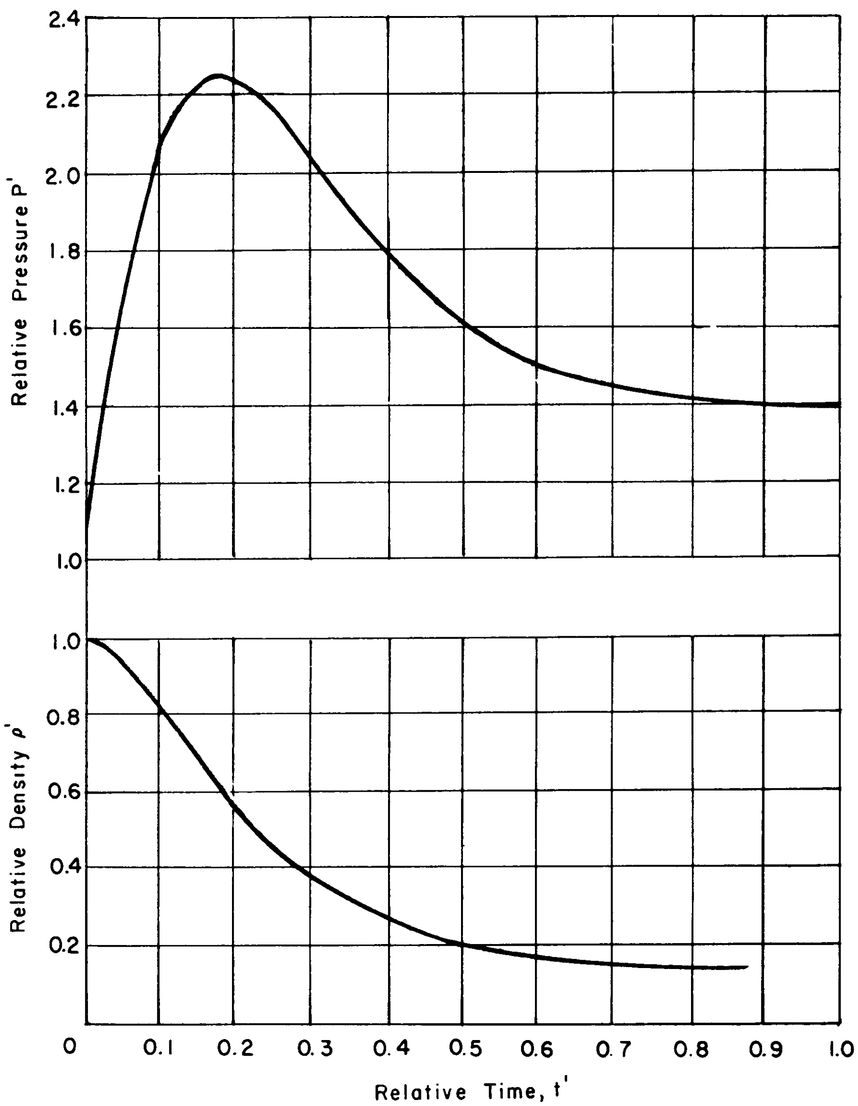

Figure 2 - Variation of Pressure and Density in Magazine with Time. $\epsilon = 850$ cal per g; $A/\mu_1 = 0.073$ sq ft sec per lb.

decreases. At the time of the peak pressure, the gas density in the chamber has decreased to 60 percent of its initial value.

The calculated values for the peak pressure P_m' and the time t_m' at which it occurs in the eight cases are given in Table 1. The appropriate values for the constant term in Equation [7], which is a nondimensional function of the total heat of reaction,

$$F(\epsilon) = \left[\frac{(\gamma - 1)\,\epsilon\,\rho_0}{P_0} + \frac{\gamma - 1}{\gamma_1 - 1}\,\frac{M_0}{M_1}\right] \qquad [11]$$

and for the nondimensional parameter KA/μ_1 in Equation [9] are also tabulated. It is anticipated that the peak *increase* in pressure within the chamber $(P_m' - 1)$ should vary in some simple way with the two parameters $F(\epsilon)$ and KA/μ_1. Hence the calculated values of the peak excess pressure per unit value of the energy function and per unit value of μ_1/KA are also tabulated. Finally, for similar reasons, the value of the nondimensional time t_m' at which the peak pressure occurs, per unit value of μ_1/KA, is tabulated.

TABLE 1

Results of Numerical Solutions of Differential Equations

ϵ $\frac{\text{cal}}{\text{gm}}$	$\frac{A}{\mu_1}$ $\frac{\text{ft}^2\text{sec}}{\text{lb}}$	χ	$F(\epsilon)$	$\frac{KA}{\mu_1}$	P_m'	t_m'	$\frac{(P_m'-1)KA}{F\mu_1}$	$\frac{t_m' KA}{\mu_1}$
700	0.055	0	16.6	2.45	2.38	0.23	0.204	0.56
700	0.091	0	16.6	4.05	1.83	0.15	0.202	0.61
850	0.055	0	19.8	2.45	2.64	0.23	0.203	0.56
850	0.073	0	19.8	3.25	2:24	0.18	0.203	0.59
850	0.091	0	19.8	4.05	2.00	0.14	0.204	0.57
1000	0.073	0	23.0	3.25	2:44	0.18	0.204	0.59
2700	0.091	0	60.0	4.05	3.78	0.11	0.187	0.45
2700	0.091	0.8	60.0	4.05	3.69	0.11	0.182	0.45

It appears that the peak excess pressure in the chamber is directly proportional to the burning rate, inversely proportional to the vent, area, and almost directly proportional to the heat of reaction. In the range of interest

$$P_m' - 1 = 0.20\,\frac{\mu_1}{KA}\left[\frac{(\gamma - 1)\,\epsilon\,\rho_0}{P_0} + \frac{\gamma - 1}{\gamma_1 - 1}\,\frac{M_0}{M_1}\right] \qquad [12]$$

$$\Delta P = 0.20 \frac{\mu_1}{KA} \left[(\gamma - 1) \, \epsilon \, \rho_0 + \frac{\gamma - 1}{\gamma_1 - 1} \frac{M_0}{M_1} P_0 \right] \qquad [13]$$

For the special case of a propellant with a heat of reaction of 1000 cal per g and other constants as originally specified, this equation in practical units becomes

$$\Delta P \text{ (psi)} = 1.54 \frac{\mu_1 \text{ (lb/sec)}}{A \quad (\text{ft}^2)} \qquad [14]$$

It also appears from the calculations that t'_m and t_m are approximately proportional to μ_1/A in the range of interest

$$t_m \text{ (sec)} \simeq 0.57 \frac{\mu_1}{KA} \frac{\rho_0 V}{\mu_1} \simeq 1.0 \times 10^{-3} \frac{V}{A} \text{ (ft)} \qquad [15]$$

This means that in true time units, the time to reach peak pressure in the chamber is approximately independent of the burning rate and heat of reaction and is proportional to the ratio of chamber volume to vent area.

APPLICATION OF CALCULATED RESULTS

The results have been derived on the basis of many assumptions which require verification or further analysis before they can be applied to a real situation. In reality the product gases are not ideal, the vent opening is not an ideal sharp-edge orifice, and γ and M are not constant. These factors are probably not significant for the accuracy required in engineering calculations. Thus in Table 1 it is seen that the peak pressure is reached at times up to $t'_m = 0.23$. From the definition of t' in Equation [7], this means that up to this time the product gases total up to 33 percent of the weight of the original air in the chamber. Since, in general the product gases themselves have a γ and M which are not greatly different than those for air, the change in the average γ and M in the magazine chamber should be small.

HEAT LOSS

In practice there is some heat transfer to the walls of the magazine, but this also should have negligible effect on the peak pressure. The rate of heat transfer increases with the temperature of the gas in proportion to P'/ρ'. From the numerical results, when P' is a maximum at 2.2, then $\rho' = 0.6$ and the absolute temperature has increased by a factor of $2.2/0.6 = 3.7$ or to, say, 1000 deg K. At this temperature the major rate of heat transfer is presumed to be by radiation. An upper limit to this rate is

$$\dot{q} = \sigma S(T_g^4 - T_s^4) \simeq \sigma S T_g^4$$

where S is the surface area of the magazine,

σ is the radiation constant,

T_g is the gas temperature, and

T_s is the wall temperature.

We can calculate the ratio of this heat-radiation rate to the rate of generation of heat, assuming that the total surface area is 500 times the vent area, ϵ = 850 cal per g, and A/μ_1 = 0.073 sq ft sec per lb. Then

$$\frac{\dot{q}}{\mu_1 \epsilon} = \frac{\sigma S T_g^4}{\mu_1 \epsilon} = \frac{\sigma}{\epsilon} \frac{S}{A} \frac{A}{\mu_1} T_g^4 = 0.18$$

Hence, under typical conditions, the maximum rate of heat loss by radiation is small compared with the rate at which heat is generated by the reaction, and the peak pressure is therefore insensitive to this slight heat loss. However, it is worth noting that this rate of heat loss varies with T^4 and might become appreciable at only a small increase in the gas temperature In practice then, this would serve as an additional factor which would keep the temperature from rising much above 1000 deg K and would help to limit the peak pressure.

NON-UNIFORM BURNING RATES

In actual rockets the burning rate increases rapidly from zero to its nominal steady value. However, if the volume of the magazine is sufficiently small, it is apparent that peak pressure in the magazine could be reached before the burning rate is constant, and the previous numerical calculations do not apply. In that case, the peak pressure might be calculated by a numerical integration of the original differential equations, with proper allowance for a changing burning rate. Or an average "effective" burning rate might be estimated to use in Equation [13]. However, the peak pressure which would be calculated from Equation [13] using the nominal value of the steady burning rate would be a high estimate.

AFTERBURNING

Possibly the most serious defect in the numerical analysis is the assumption of either negligible afterburning or uniform afterburning.

Many propellant grains do not have sufficient oxygen to oxydize their product gases completely, and the product gases could react with the atmospheric oxygen and generate substantially more heat. For a typical grain, the mol fraction of the product gases which is either CO or H_2 may be about χ = 0.7; each gram of product gases may react with about one-half gram of 0_2, or 2 g of air, and can thus generate an additional 2000 cal per g of propellant.

However, it is not known, in general, when and to what extent afterburning occurs in the magazine chamber. If there were no afterburning up to the time of peak pressure (perhaps because of inadequate mixing of the product gases with the air), then the numerical results are directly applicable, taking ϵ as the heat of reaction without afterburning. Or if the afterburning were complete at all times, or occurred at a uniform rate, then the numerical results could be used, taking ϵ as the total heat of reaction with afterburning. The effect on the peak pressure of the mol fraction χ in Equation [8] is minor as can be seen from a comparison of the two solutions tabulated in Table 1, with $\epsilon = 2700$ cal per g and two values of χ. At present, the extent of afterburning must be investigated by direct experiment.

COMPARISON WITH EXPERIMENTS

The experimental results are described in detail and discussed in Reference 2. In the experiments, the pressure buildup in the magazine was measured for a variety of burning rates, vent areas, and magazine sizes. Only one type of propellant grain was used. The test results confirm that when the burning rate is constant, the peak pressure in the chamber is independent of the volume and is proportional to the ratio of burning rate to vent area. If the test results are compared with Equation [13], then the "effective" heat of reaction is the same as if only 20 percent of the possible maximum afterburning occurred in addition to the initial reaction. However, there are other indications from motion pictures of the vented gas that substantial afterburning occurred only long after the peak pressure was reached. The test results also show that the time for peak pressure to be reached is within 30 percent of the time predicted from the theoretical calculations.

Further experiments are necessary in order to determine the extent of afterburning and to verify the applicability of these equations to situations where the burning rate is not constant. The theoretical analysis of this report is presented as a basis for analyzing the results of such experiments.

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