Chuffing and Nonacoustic Instability Phenomena in Solid Propellant Rockets

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Rocket motor firings, laboratory experiments, and theoretical studies have been initiated to develop better understanding of chuffing and low-frequency nonacoustic instability (LFI). Attempts have been made to determine the relationship of these phenomena to each other, to motor parameters, and to combustion processes. The dependence of frequency and amplitude on pressure suggests that chuffing and LFI operate through a common mechanism. Burning aluminized propellant strands also exhibited periodic behavior in a closed bomb. No effect of motor-free volume or grain port velocity on the frequency of LFI has been observed. These observations suggest LFI to be an intrinsic propellant property with its manifestation in rockets only indirectly dependent on motor parameters. Similar dependence for chuffing is suggested. A logarithmic relationship between induction time and the pressure associated with quasi-steady reaction before a chuff has been predicted, assuming initiation by thermal explosion and Arrhenius-type surface reactions. Motor firing data are shown to obey this relationship. The logarithm of time to "ignition" of propellant samples contacting a heated block depended inversely on absolute block temperature. This observation is shown to be consistent with motor data and the proposed theory.

Nomenclature

A_p/A_t = ratio of grain port to motor throat area
b = coefficient in Vielle's burning rate law
c = heat capacity
C_D = discharge coefficient
E = apparent activation energy of condensed phase subsurface reaction
E' = apparent activation energy of surface decomposition
k = thermal conductivity
K = ratio of grain surface to motor throat area
n = pressure exponent in Vielle's burning rate law
P = pressure
P_i = pressure associated with quasi-steady reaction between chuffs
Q = heat of explosion for condensed phase decomposition
$\bar{r}$ = linear burning rate
R = gas constant
t = time
t_i = induction time for a chuff
T = temperature
T_0 = temperature of thermal block
T_s = surface temperature of propellant during quasi-steady reaction between chuffs
x = effective depth of surface decomposition zone
X = distance beneath propellant surface
Z = pre-exponential factor for subsurface decomposition
Z' = pre-exponential factor for surface decomposition
ρ = density
τ = induction time for thermal explosion

Introduction

"CHUFFING," one of the earliest combustion anomalies observed in solid propellant rocket motors, is good combustion momentarily followed by a combustion period at near-atmospheric pressure (see Fig. 1A). This process, which repeats itself numerous times, is generally manifest in rockets operating at low pressures and/or at low conditioning temperatures. Although numerous qualitative explanations of the chuffing mechanism have been given, only a few attempts have been made to obtain a fundamental understanding of the phenomenon through combined experimental and theoretical treatment.

Low frequency (nonacoustic) instability is a recently identified combustion anomaly, which, by current understanding, is thought to be similar to chuffing. The low-frequency instability of rocket motors is characterized by a periodic pressure disturbance of very low frequency (from a few to a few hundred cycles per second). LFI is much more regular in nature than chuffing, and the pressure usually does not decay to near-ambient between cycles as it does in chuffing. Because the frequency of LFI is not identifiable with natural acoustic or mechanical vibrational modes of the system (see Fig. 1B),‡ it is tempting to suggest that LFI is an intrinsic property of propellant combustion. Since LFI and chuffing have many common features, they are discussed jointly in this paper.

Some problems, not all, associated with these phenomena are obvious; thus it seems appropriate to give several real and hypothetical examples. Chuffing would be disastrous in a missile system from a mission standpoint and possibly hazardous to property and personnel. Chuffing has been of primary concern historically during the "ignition" or early operating periods of a rocket motor; however, it is also important during final "tailoff" or burnout.

LFI may cause vibrations excitation in a missile system, since its very low frequency approaches the general region of the natural vibrational mechanical modes of most missile structures. Low-frequency disturbances are in the same general frequency range as the natural acoustic modes of large solid propellant rocket motor cavities; therefore, it is quite possible that coupling between the combustion disturbances and the acoustic properties of the motor will occur, with the disturbances being subsequently amplified by a large factor (acoustic instability). Experimental confirmation that such coupling will occur has been obtained by E. W. Price.

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‡ Acoustic instability is also a continuous and periodic pressure disturbance, but by definition the disturbance necessarily corresponds to resonant acoustic modes of the motor system.

In the current low-frequency instability and chuffing program, a literature survey and a data review obtained from exploratory experiments are the bases for a working theory and experiments to evaluate various aspects of the theory. This paper should be considered more as a progress report than a final dissertation on the subject.

Background

The first experimental data concerning the chuffing mechanism was reported by Crawford, and others.[1] These experiments showed that "fizz" burning (characterized by incomplete propellant combustion at near-atmospheric pressure) occurred during the low-pressure regions between chuffs. The work also suggested that the transition to high pressure was associated with reactions in the gas phase. Later, Huffington[2] performed extensive experimentation on motor chuffing. His experimentation showed that the chuffing mechanism was consistent with the Frank-Kamenetzky thermal explosion theory. Clemmow and Huffington[3] extended this theory. On the basis of thermal explosion theory, reasonable agreement between theory and experiment was found. Of particular importance was that their chuffing-mechanism theory was based only on condensed phase reactions. Huggett[4] favored a gas phase mechanism for the rapid-reaction initiation of a chuff which suggests that combustible gases formed by solid phase exothermic reactions ignite upon reaching some critical concentration. This gas phase mechanism is consistent with Crawford's experiments.

Considerable effort has also been expended to determine motor and propellant parameters which influence chuffing behavior and LFI phenomena. Work conducted at Jet Propulsion Laboratory,[5] using ammonium perchlorate-polyurethane propellant, showed that a critical operating pressure region existed where chuffing and LFI occurred. This region was a function of propellant burning rate and port to throat area ratio. Sehgal,[6] following the concepts laid down by Akiba and Tanno,[7] proposed the theory that the mechanism of instability involved the interaction between the lag in propellant burning rate response to pressure disturbances and the lag involved in exhausting gases from the chamber. Price[8] has since reasoned that, for high port velocity (low A_p/A_t), the residence time of combustion products in the motor may be so short that complete reaction may not be achieved and instability (chuffing or LFI) may result.

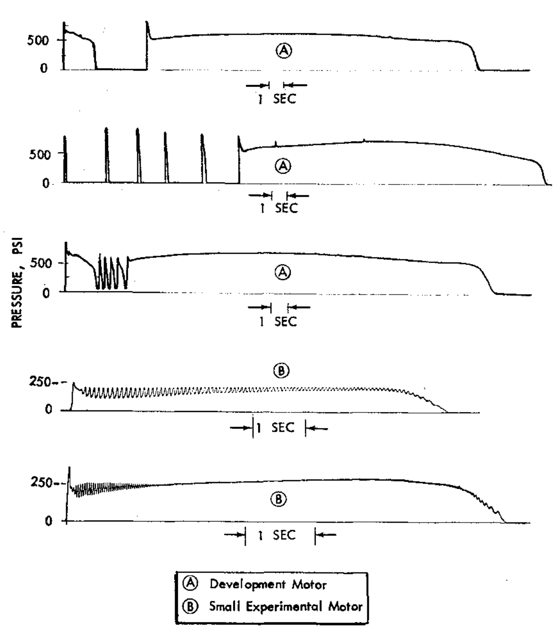

Fig. 1 Examples of chuffing and LFI.

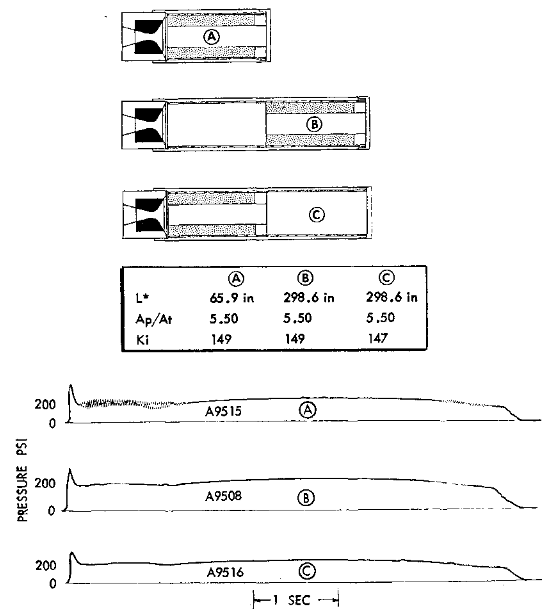

Fig. 2 Schematic of motor free volume experiments and associated pressure-time records obtained from motor firings.

The characteristics of LFI in double-base propellants containing metal additives have also been studied at Allegany Ballistics Laboratory (ABL); much of the data has been summarized previously. A qualitative theory involving solid-gas phase reaction was proposed.[9] These and other generalizations on the behavior of LFI and chuffing are summarized as follows:

1) Chuffing and LFI phenomena (not unique to a given class of solid propellant) have been observed in conventional double-base, double-base containing lead salts and metal additives, cast-modified double-base, and polyurethane-ammonium perchlorate composite propellants.

2) Both chuffing and LFI are experienced at pressures well below 500 psi, although LFI has been noted at pressures up to 850 psi.

3) The frequency of LFI increases almost linearly with increasing base pressure (lowest pressure between successive pressure peaks). The frequency range experienced with LFI has ranged from a few cps up to 250 cps. Chuffing frequency generally ranges from a fraction of a cycle per second to a few cycles per second. The amplitude of LFI generally decreases with increasing base pressure; hence, the amplitude generally decreases with increasing frequency.

4) The frequency of chuffing decreases as the peak pressure of the chuff increases.

5) There is indication that the frequency and amplitude of LFI increase with increasing propellant conditioning temperature.

6) The amplitude of LFI increases as the concentration of metal additive increases. No significant effect of concentration on frequency has been noted.

7) There is good indication that frequency, not amplitude, is influenced by the reactivity (reaction rate) of the metal additive used.

8) Neither amplitude nor frequency of LFI has been affected by changing the charge size.

Experiments and Results

Since previous results suggested that LFI (and possibly chuffing) was an intrinsic property of propellant combustion, further work was done to determine if coupling between propellant combustion and some other rocket motor parameters existed.

The effect of residence time on LFI was studied by comparing data from 10-lb charge firings in which the free volume and position of the charge in the motor were drastically changed. All firings were otherwise identical relative to A_p/A_t, operating K, and propellant. LFI was observed in all cases (see Fig. 2); the frequency was independent of free volume, and the amplitude was approximately inversely proportional to the free volume. Failure to observe a dependence on frequency suggested a constant driving force for the oscillations. These tests showed that the residence time alone was not a strong controlling factor in LFI. A firing using a double-length motor was essentially identical in all respects except for the A_p/A_t ratio which was 2.8 instead of the previous 5.5. Little or no change in the frequency and amplitude of oscillation was noted (see Fig. 3). These firings further confirmed that motor parameters had little or no influence on the driving force involved.

High-impulse, composite-modified double-base (CMDB) propellant systems containing high aluminum-metal concentrations were also examined for susceptibility to chuffing and LFI. A perforated cylindrical charge weighing approximately 40 lb was used. Both chuffing and LFI were present at low operating pressures. The frequency of LFI increased as the base pressure increased; the amplitude decreased with increasing operating pressure and increasing free volume. The chuffing amplitude was observed to decrease as the pressure associated with the base pressure between the chuffs increased. The time between chuffs showed an inverse dependence on the base pressure. This base pressure was found to depend inversely on the pressure decay rate of the prior chuff.

Combustion Bomb Studies

On the assumption that the low-pressure phenomena of chuffing and LFI are inherent in the propellant combustion process, attempts were made to observe these phenomena in systems independent of rocket motors. Inverted strands of aluminized CMDB propellant burning in a closed combustion bomb exhibited periodic phenomena. At pressures between 25 and 100 psig of nitrogen, these strands periodically built up and ejected aluminum globules from the surface. At pressures less than 25 psig, flakes of material which retained the original cross-sectional area of the strand fell periodically from the surface. Visual examination and chemical analysis indicated that the flakes consisted mostly of unreacted aluminum particles that were partially fused together. In some instances, several flakes fell from the surface as a unit.

This same propellant, burning both in air and with a slow nitrogen flow across the surface, exhibited fluctuations in flame intensity with periods of approximately 0.1 sec. Other samples burning in a vented vessel of large relative free volume gave luminosity fluctuations of a similar period plus corresponding pressure variations. Solid combustion products with the same layered structure as described previously were also noted in these experiments. Copious quantities of nitrogen oxides were released during combustion.

Linear-Pyrolysis Studies

Experiments were designed to study the susceptibility of propellants to thermal explosion and to ascertain whether condensed phase or gas phase processes were involved. The apparatus consists of a mechanism that allows a small propellant strand to make sudden contact with a preheated metal block. The system is enclosed so that the environment may be varied. The pressure increase associated with reaction is detected by a pressure transducer, the luminosity by a photocell, and the temperature of the thermal block by a thermocouple. Outputs of these transducers are recorded on a Visicorder. Induction time to reaction, τ, is taken as the time between contact of propellant with the thermal block and the inception of pressure increase in the system (ignition).

For a typical CMDB propellant, induction time τ vs block temperature T_0 was determined for block temperatures between 150° and 235°C. Experiments were performed at atmospheric pressure in both air and nitrogen and under nitrogen pressures up to 180 psig (see Fig. 4). Below 30 psig, τ was independent of pressure and atmospheric composition; at higher pressures, τ was inversely proportional to pressure. At pressures less than 30 psig, a pressure increase was always detected several tenths of a second before the inception of luminosity. Pressurization and luminosity occurred simultaneously at higher pressures. A thermocouple constructed of 5-mil chromel-alumel wires placed at the propellant-thermal block interface position exhibited a temperature increase to values greater than T_0 before the inception of pressure rise and luminosity (see Fig. 5). Thermocouples placed in the surrounding atmosphere near the interface position detected no temperature increase before "ignition." No dependence of τ on strand length or on the force with which it contacted the thermal block was observed.

Theory and Discussion

Chuffing

The analysis and subsequent interpretation of results have been made more tractable by dividing the phenomenon of chuffing into four separate regions: 1) induction: the region of low-pressure reaction before a chuff; 2) initiation: the region in which a sudden rise in pressure occurs; 3)

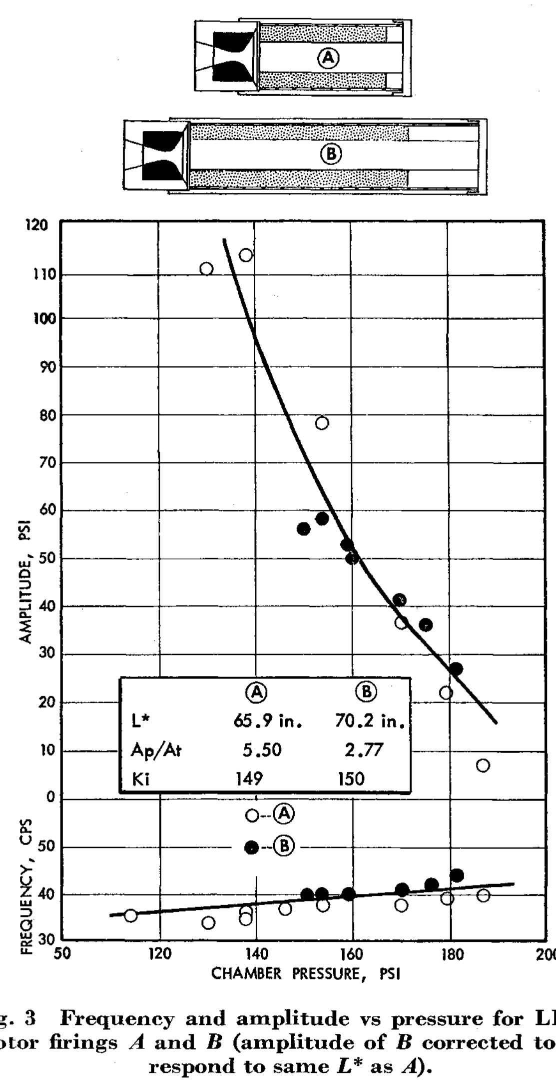

Fig. 3 Frequency and amplitude vs pressure for LFI in motor firings *A* and *B* (amplitude of *B* corrected to correspond to same *L as *A*).**

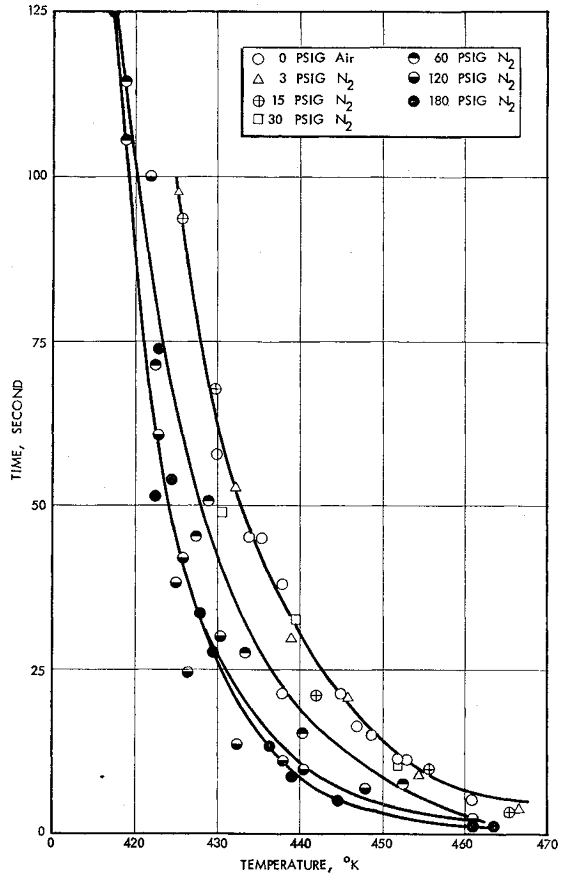

Fig. 4 Induction time vs block temperature for a typical CMDB propellant.

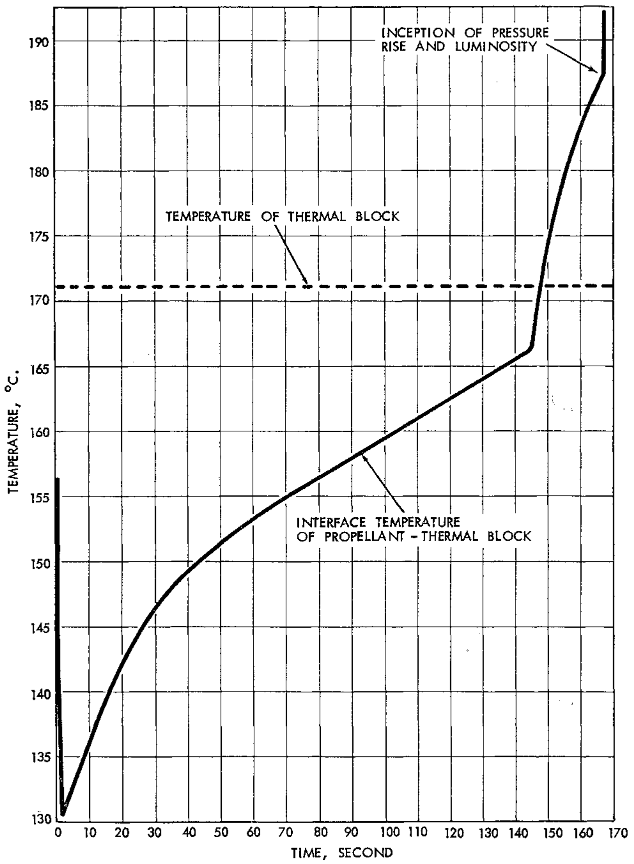

Fig. 5 Temperature-time behavior at propellant-thermal block interface for a CMDB propellant.

propagation: the region of sudden and temporary pressurization; 4) decay: the region in which the pressure decays back to near atmospheric.

Induction region

Since the observed pressure between chuffs is much lower than predicted for the given conditions (on the basis of high-pressure ballistic data) it can be inferred that a relatively inefficient combustion process is occurring if it is assumed that all the surface is reacting. Observations of burning strands at low pressures support this conclusion. Combustion is relatively nonluminous, with nitrogen oxides being formed. Crawford[1] has observed this formation during chuffing for double-base propellant. Various sources of energy for the continuation of this reaction must be considered: 1) energy feedback from the "dark-zone" gas-phase reaction causing a sustained condensed phase decomposition; 2) exothermic condensed phase surface reactions; 3) radiation from hot motor components; and, 4) energy transfer from heat sinks such as hot or burning metal particles on the surface.

The burning rate of the CMDB propellant used in this study (between 0 and 110 psig) is sensitive to pressure; the dependence is given by

$$\bar{r} = bP^n = 0.002P^{0.90} \tag{1}$$

The importance of energy feedback from the gas phase for sustained combustion (dark zone) is implied, since, if solid phase exothermic reaction were important, the rate should be less dependent on pressure (low index). The importance of the other possible energy transfer processes mentioned has not been investigated in detail.

Initiation region

The transition from this quasi-steady, low-pressure reaction to rapid reaction (initiation) may occur in several ways: 1) thermal explosion of a condensed phase surface zone, and 2) runaway reaction in the gas phase either through a thermal mechanism or a branching chain mechanism. Heterogeneous reaction might also occur between gaseous decomposition products and a surface component.

Results of the linear pyrolysis experiments point to the occurrence of a thermal explosion "ignition" process. Cook[10] has shown that, for a thermal explosion mechanism, a relation of the form

$$\log\tau = (AE/RT_0) - \log\beta \tag{2}$$

should apply, where A and β are constants. Experimental data obey this relation (see Fig. 6). The observation of a temperature increase to values above the thermal block temperature further supports a thermal explosion mechanism. The deviation from exponential behavior may be the result of heat losses to the thermal block. Failure to observe a dependence on pressure or on oxygen concentration for pressure less than 30 psig suggests that the condensed phase is the site of thermal explosion. (For pressures greater than 30 psig, "ignition" delay at a given temperature depended inversely on pressure, suggesting a gas phase mechanism.) The occurrence of decomposition, as evidenced by pressure increase, before the appearance of luminous reaction at low pressures also supports a condensed phase rate determining mechanism. Since the observed base pressures between chuffs are less than 30 psig, a condensed phase mechanism for the initiation of chuffing is suggested.

The observation of intermittent burning in strands also suggests this mechanism, since the frequency of the phenomenon for strands burning in air is similar to that of strands burning with nitrogen flowing across the surface. For a gas phase process, one would predict nitrogen flow to cause cooling and dilution of gaseous combustion products and a resultant decrease in frequency.

On the basis of the data previously presented, an analytical model has been set up to explain the initiation of chuffing in burning propellant. Following Penner,[11] the combustion process is postulated to be controlled by a surface reaction that obeys an Arrhenius temperature dependence. It is further postulated that subsurface exothermic reactions will be relatively unimportant during most of the induction region; since this region follows a region of high-pressure burning, the temperature profile beneath the surface will be steep and not very deep.[4] The combustion process considered is the dark-zone reaction between chuffs. During most of this induction period, the reaction is assumed to be steady-state as evidenced by pressure measurements in rocket motors (pressure increase is initiated in a time that is short with respect to the induction time). The controlling relation may then be stated as

$$\bar{r} = Z'x \exp(-E'/RT_s) \tag{3}$$

As the reaction proceeds, the low burning rate allows heat to penetrate the surface and subsequent exothermic reactions begin, causing an acceleration in temperature until thermal explosion of the subsurface layer occurs. Considering this model analogous to a system consisting of a semi-infinite slab of a material contacting a heated surface, induction time to thermal explosion τ will be taken as given by Eq. (2) with T_0 now being identified with T_s. Equation (2) arises from solution of the differential equation describing heat conduction in a one-dimensional semi-infinite solid

$$\rho c\,\frac{\partial T}{\partial t} = k\,\frac{\partial^2 T}{\partial X^2} + \rho Q Z \exp\left(\frac{-E}{RT}\right) \tag{4}$$

For a reacting system, the term $(\rho c\bar{r})(\partial T/\partial X)$ should be included on the right-hand side of Eq. (4). Examination of the experimental data, however, indicates that the quasi-steady burning rate does not change with time (suggesting constant $\partial T/\partial X$) until the sudden exponential increase appears). To a first approximation, then, the term $k(\partial^2 T/\partial X^2) - (\rho c\bar{r})(\partial T/\partial X)$ will be set equal to zero, in which case an approximate solution of the remaining equation in the form of Eq. (2) may be obtained for the same boundary conditions.[12]

Eliminating T_s between Eqs. (2) and (3), and using the low-pressure quasi-steady burning rate expression given by Eq. (1), we obtain

$$\log\tau = \frac{AE}{E'}\log\frac{Z'x}{b} + \log\beta - \frac{AE}{E'}\,n\log P_i \tag{5}$$

Now, if data from the thermal explosion experiments are applied to Eq. (2), AE = 26,900 cal/mole and $\log\beta = 11.94$. From the low-pressure burning rate relation, $n = 0.90$ and $b = 0.002$ in./sec. Values for the activation energy and frequency factor of the quasi-steady reaction between chuffs are estimated by a method based on Rice's[13] approach. Applying data for this propellant to Rice's method, and assuming a surface temperature of 250°C (this value, obtained by Klein[14] for a double-base propellant seems more reasonable than Rice's value), we obtain a value of E' = 14,300 cal/mole. To obtain a value for $Z'x$, an average low-pressure burning rate of 0.11 in./sec [from Eq. (1) and observed average values of P_i during chuffing] is used in Eq. (3). $Z'x = 9.22 \times 10^4$ in./sec results. Substituting the preceding numbers into Eq. (5), we obtain

$$\log\tau = 1.71 - 1.69\log P_i \tag{6}$$

This relation may be compared with the experimental relation

$$\log t_i = 1.24 - 1.62\log P_i \tag{7}$$

The constants in this equation are quite sensitive to the numerical values used for the various terms in Eq. (5). For example, when values of E' = 15,300 cal/mole and $Z'x = 15.20 \times 10^4$ cm/sec (requiring only a change of T_0 to 267°C) are used, the relation becomes

$$\log\tau = 1.22 - 1.58\log P_i \tag{8}$$

The required temperature adjustment is negligible compared with the accuracy of its experimental determination; the recent work of Sabadell[15] indicates the difficulties involved in obtaining reproducible results. Comparing Eqs. (7) and (8), we see that reasonable experimental agreement is obtained with the theory proposed for the values of the various constants used (see Fig. 7). Added support is thus given to a condensed phase thermal explosion initiation of chuffing.

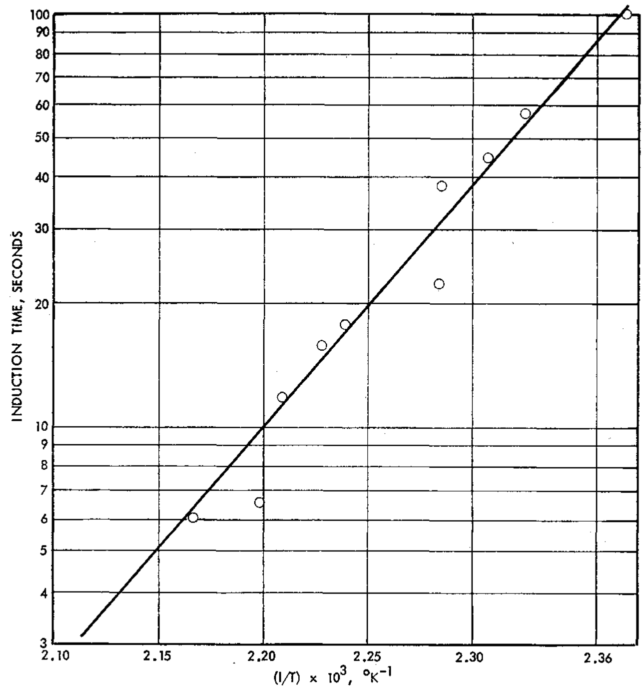

Fig. 6 Induction time-temperature relationship for a CMDB propellant.

Propagation region

The energy involved in the propagation region comes from several sources. During the low-rate induction region, subsurface heating occurs. The heated layer then burns rapidly during the propagation reaction. Reactive gases

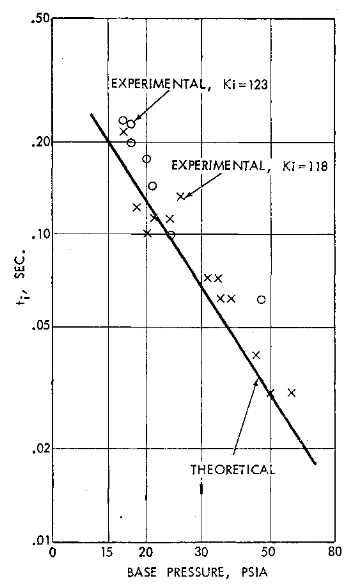

Fig. 7 Time between chuffs vs base pressure (prior to chuff).

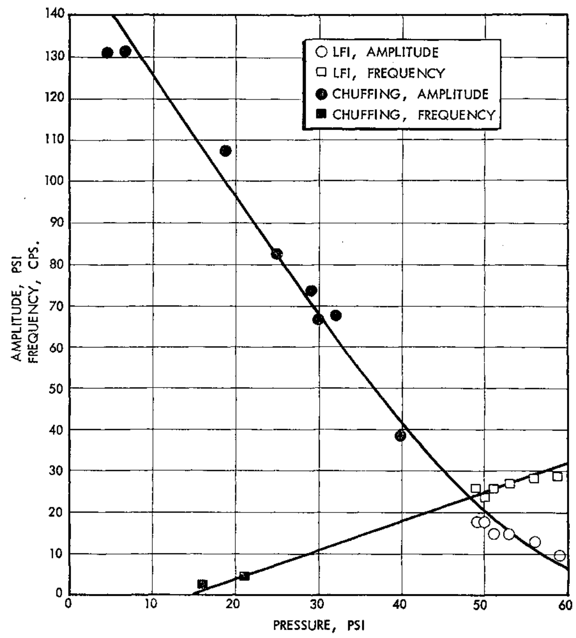

Fig. 8 Comparison of pressure dependence of frequency and amplitude of chuffing and LFI.

are also released during induction and may react further during propagation. The observation of nitrogen oxides at low pressures and their relative absence at higher pressures in combustion bomb experiments is an indication of this phenomenon. Crawford[1] observed the disappearance of nitrogen oxides after chuffing was initiated. During the induction reaction, surface temperatures are thought to be relatively low so that all components of typical CMDB propellants may not react. Thus, in metallized propellants, it is expected that metal particles (if the ignition temperature is greater than the dark-zone temperature) will accumulate on the surface, either as solid particles or as molten agglomerates, depending upon concentration and pressure. However, during the initiation reaction, the temperature will increase to the "ignition" temperature of the metal particles, and their reaction will contribute to the over-all pressure increase.

Decay region

As the material accumulated during the induction reaction is removed through rapid reaction, the pressure decays until the characteristic low-pressure rate is again reached and the cycle begins again. Under certain aerothermodynamic conditions, the heat flux during a chuff is sufficient to establish normal combustion. Whether or not this flux is sufficient to establish steady-state conditions depends on motor parameters. Operating pressure and free volume seem especially important. Whenever the pressure and free volume, or a combination thereof, in an operating motor exceed critical values, chuffing ceases and steady-state combustion occurs.[5] Before these critical values are attained, heat transfer back to the surface during the "normal" combustion which occurs during chuffs is insufficient to maintain the surface enthalpy at a value high enough to maintain efficient combustion. Normally, a small perturbation in energy feedback would cause equilibrium to be re-established at some slightly lower pressure. The "equilibrium pressure" following a chuff, however, is much lower than expected for a small perturbation. Several mechanisms may be postulated to explain this observation. First, once inefficient combustion and associated pressure decay have begun, the pressure dependence of C_D for inefficient combustion will cause the pressure to decay to a value lower than it otherwise would. Second, during a region of pressure decay (in many instances, the peak pressure during a chuff is higher than design pressure) the temperature profile beneath the propellant surface may not have time to reach the steady-state, giving insufficient surface enthalpy for steady combustion. The theories of Sehgal and Strand[6] and Akiba and Tanno[7] are based on such an approach. As the free volume increases, the pressure decay rate of a chuff decreases until it is low enough for the temperature profile to follow the pressure change; steady combustion then occurs. Another possibility is that reactive species may be swept from the motor, or at least so far from the grain surface that energy feedback from the reaction is insufficient to maintain normal combustion. In ported grains, there may be a velocity effect on energy transfer. In either case, these effects will be eliminated by free-volume increase and chuffing will be terminated.

Low-Frequency Instability

The frequent occurrence of chuffing and LFI in the same motor firings, a transition from chuffing to LFI often observed, suggests a common mechanism. The similarity of the pressure dependence of the frequency and amplitude of chuffing to that of LFI supports this conclusion (see Fig. 8). The division of LFI into regions of study is not so easily accomplished as for chuffing. Definite pressure rise (propagation) and decay regions are present, but no separate induction region is discernible. It is postulated that the greater surface temperature (flame close to the surface at higher pressures of LFI) causes this region (induction) to become small with respect to the propagation and decay regions, so that induction of the next cycle occurs simultaneously with decay of the prior cycle. Since surface temperature increases with pressure the frequency of LFI subsequently increases; this phenomenon has been observed.[9] The dependence of the frequency of LFI in metallized propellant on the composition, concentration, and particle size of the metal was previously noted. These effects suggested the participation of the metal in the process, and it was postulated that LFI was associated with unsteady metal combustion at the propellant surface. Similar phenomena have been observed in nonmetallized systems[2, 3]; therefore, it seems likely that the metal just enhances rather than induces an inherent phenomenon. This enhancing effect may be discussed in terms of the previous thermal explosion theory.

The frequency of LFI will depend on surface temperature (analogous to inverse dependence of delay time of a chuff on temperature). The surface temperature of a metallized propellant will be influenced by the distance moved from the surface before a metal particle ignites and burns (assuming equal heats of combustion and flame temperatures). The frequency of LFI should be greater for a metal such as magnesium, which ignites close to the surface (shorter ignition delay time) than for one such as aluminum, which ignites farther from the surface. A decrease in particle diameter and the addition of "catalysts" should have the same effect on the enhancement of metal ignition. Preliminary experimental observations support these hypotheses. At pressures within which LFI is important, metal combustion is often incomplete. During the "induction" region of LFI, it is hypothesized that unburned metal collects on the propellant surface and burns during the propagation region, contributing greatly to the pressure increase. Increased metal concentration should cause an increase in amplitude. Since metal combustion efficiency improves with increasing pressure, the amplitude of LFI should decrease as pressure increases. Both these effects have been observed. The observed LFI data are thus seen to be consistent with a thermal explosion mechanism.

Conclusions

Chuffing and LFI in CMDB solid propellant rocket motors are interpreted to be initiated through a condensed phase thermal explosion mechanism, which is inherent in the propellant combustion process. Experimental data are shown to obey a theory developed on the basis of a thermal explosion mechanism.

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