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Parametric Study of Acceleration Effects on Burning Rates of Metallized Solid Propellants

Michael D. Fuchs* and Arie Peretz†
Armament Development Authority, Haifa, Israel
and
Y.M. Timnat‡
Technion-Israel Institute of Technology, Haifa, Israel

An experimental parametric study of the burning rate augmentation, resulting from operation in acceleration fields, of nine hydroxy terminated polybutadiene composite metallized solid propellants is described. The apparatus consists of a centrifuge and two identical slab test motors, each mounted at the end of a rotating arm. Experiments in the acceleration range 0-700g at pressures between 2.5 and 16 MPa were conducted. The effects of acceleration, combustion pressure, direction of the acceleration vector, base (static) burning rate, aluminum content and particle size, total solids content, and oxidizer particle size were investigated. The burning rate augmentation was found to be strongly affected by the acceleration level, the base burning rate, the angle between acceleration vector and normal to the surface, and the oxidizer particle size. An inconsistency in the effect of aluminum content and particle size was observed. A linear relationship between the acceleration-induced burning rate augmentation ratio and the reduced acceleration parameter, as suggested by Crowe, was established for the propellants tested. However, some deviations from Crowe's model, indicating the need for modification, were noted.

Introduction

SOLID propellant rocket motors, acting in acceleration fields, exhibit an increase in burning rate and undesirable residue retention. The successful design of motors, used for spin stabilization of rocket vehicles and space systems or for reduction of dispersion caused by thrust misalignment, demands quantitative knowledge of the response of available propellants to acceleration loads. Pressure buildup and slag formation in such motors may significantly affect engine performance and even lead to mission failure. Alternatively, information on the influence of propellant variables on burning rate augmentation and the amount of residue retained can help propellant formulators to provide suitable compositions for a given operational acceleration environment.

Many studies have been conducted during the past 20 years to determine the effects of acceleration loads on associated burning rate increase. Several models,[1-6] based on these studies, were suggested to describe the governing mechanisms and predict the sensitivity of different propellants to acceleration. All investigations concerned with metallized propellants have adopted a basic physical model, which assumes that burning rate augmentation is caused by increased heat transfer from burning metal particles and/or agglomerates, retained close to the propellant surface. The formation of pits on the surface was observed by many investigators by examination of quenched propellant grains. The transient phenomenon of unsteady burning rate increase, often observed experimentally,[7-10] is explained by the time-dependent size and shape of the particles, agglomerates, and pits. Acceleration-induced burning rate augmentation, observed in nonmetallized solid propellants, is attributed to increased heat transfer to the surface due to reacting ammonium perchlorate particles retained on the surface by the acceleration forces,[11] or due to a "compressed" gas phase reaction zone.[2] A critical review of the analytical models can be found in Ref. 12. Numerous studies have revealed that the acceleration-induced burning rate augmentation is affected by many parameters, the most important being the acceleration level a_g, the base (under no-acceleration conditions) burning rate r_0, the orientation angle ϕ (angle between the acceleration vector and the burning surface), the combustion pressure P_c, and the propellant composition (aluminum content and particle size, oxidizer particle size, type and amount of binder, kind and amount of additives, etc.).

The well-known "unified" model, suggested by Crowe[4] for metallized propellants, attempts to explain the burning rate increase for both transient and quasiequilibrium periods, assuming certain time-dependence of the agglomerate shape. The burning rate augmentation ratio (conventionally defined as the ratio of burning rate under acceleration conditions to base burning rate, r_g/r_0) is expressed in that model as a function of a grouping of ballistic parameters, called "the acceleration parameter." Making simplifying assumptions for the quasisteady case, Crowe was able to propose a simple relationship between the burning rate augmentation ratio of metallized propellants and a reduced acceleration parameter, B_r, defined as $B_r = (P_c a_g)^{1/4}/r_0$. (See preceding paragraph for nomenclature.) Crowe's model implies the existence of a threshold value of the reduced acceleration parameter, below which there is no effect of acceleration and above which the augmentation ratio varies almost linearly with B_r. Using certain empirical constants, allowed for by his model, Crowe was able to fit the experimental data of Willoughby et al.[13] and Northam[8] for aluminized PBAA and PBAN propellants with the above-mentioned relationship. According to Crowe, the same relationship with different empirical constants should apply to other composite propellants.

This paper describes an experimental parametric study conducted to investigate the effects of the following

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*Internal Ballistics Group Leader, Propulsion Department. Member AIAA.

†Chief Research Engineer, Propulsion Department. Associate Fellow AIAA.

‡Professor, Department of Aeronautical Engineering. Member AIAA.

parameters on the acceleration-induced burning rate increase of propellants with hydroxy terminated polybutadiene (HTPB) binder: the acceleration level, the total amount of solids, the aluminum content and particle size, the oxidizer particle size, the base burning rate, the combustion pressure, and the angle between the acceleration vector and the normal to the burning surface. The results obtained are compared with Crowe's unified model for the quasisteady phase.

Experimental Apparatus

A test motor with a unidirectionally burning propellant slab (Fig. 1) was designed to investigate the augmentation phenomenon. A nearly uniform acceleration environment was obtained by minimizing the effects of burning surface regression and spin-induced vortex flow. The end-burning cylindrical propellant grain has an outer diameter of 10 cm and a web of 5 cm. This grain size was chosen in order to avoid edge effects, encountered with small propellant strands, and ignition transient phenomena, which may dominate thin-web slab combustion. Two ports, machined in an asbestos-phenolic insert, locate the grain and an igniter, as shown in Fig. 1. The igniter contains 7.5 g of 3A Magnesium-Teflon-Viton (MTV) pellets plus 3 g of 2L Boron-Potassium Nitrate ($BKNO_3$) pellets. Molybdenum nozzle inserts with various throat diameters were used to obtain the desired combustion pressure. The use of molybdenum assures a fixed throat area during the burning process.

The centrifuge, designed to provide the desired acceleration range, is shown in Fig. 2. It is capable of accelerating two test motors, each mounted at the end of a rotating arm, up to a radial acceleration of 2500*g* on the propellant burning surface, located at a distance of 56 cm from the axis. Ignition signals to the test motor igniters are transmitted through graphite contacts to copper slip rings mounted on the shaft and then through the rotating arms. Motor pressure is transmitted through stainless steel tubing, connected to a central bore at the end of the rotating shaft. Two stationary BLH pressure tansducers, each mounted at one end of the rotating shaft, measure the combustion pressure in the test motors.

The test motors were assembled on the centrifuge in a manner that eliminates speed variations due to motor thrust. Different orientations of the acceleration load with respect to the burning surface can be achieved by rotating the asbestos-phenolic insert within the motor case. At all orientations the acceleration vector is perpendicular to the thrust vector. The centrifuge is rotated by a 36-hp dc electric motor provided with a speed variator and a tachogenerator to keep a constant rotating speed during a test. A Milltronics noncontacting tachometer, capable of measuring up to 7200 pulses per minute, enables precise measurement and recording of the centrifuge spin rate. The two test motors are fired simultaneously after the centrifuge has reached the desired spin rate. Information obtained from the tachometer and the pressure transducers is recorded on a Sanborn recording system. More details on the experimental system can be found in Ref. 14.

Propellants Tested

Nine HTPB metallized composite propellant formulations were tested in this study. The baseline composition, used in most tests and designated propellant 5150, is a slow burning (base burning rate of 0.87 cm/s at 10 MPa with a pressure exponent of 0.35) HTPB propellant. It contains 15% binder and 70% bimodal ammonium perchlorate (the mass-median diameters of the particle sizes being 30% 9 μ and 70% 200 μ). The percentage of spherical aluminum power (16-18-μ Alcoa) in the baseline propellant is 15%.

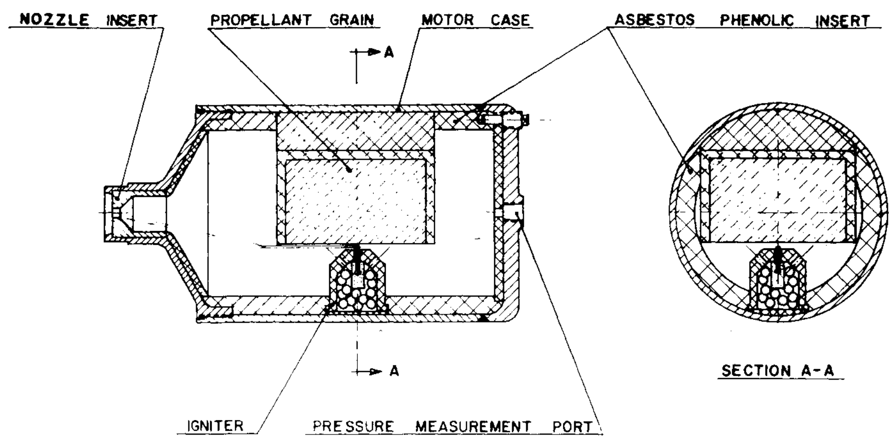

Fig. 1 Test motor.

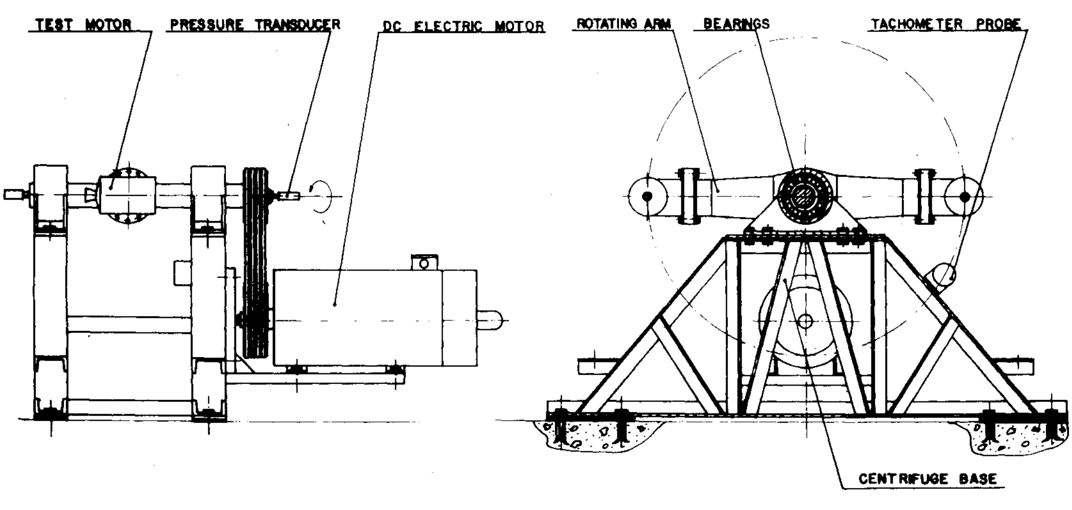

Fig. 2 Experimental setup.

The nine compositions tested to investigate the effect of various propellant formulation parameters on burning rate augmentation are listed in Table 1. Two compositions with 8 and 1% aluminum (propellants 5080 and 5010, respectively) and the same total amount of solids as the baseline propellant were tested to study the effect of aluminum content. Two other formulations with 0.75 and 2.0% Fe_2O_3 catalyst (propellants 5151 and 5152, respectively) were studied to investigate the influence of the base burning rate. In propellant 5153, the bimodal AP mass-median diameter (mmd) particle sizes were changed to 400/19 μ in order to determine the difference in augmentation caused by such a variation. Two additional aluminum mmd particle sizes (5 and 60 μ), propellants 5154 and 5155, respectively) were also used, as shown in Table 1, to investigate the effect of this parameter. Finally, propellant 8150, containing 88% of total solids (as compared with 85% for all other propellants) was tested. Based burning rate laws for all propellants are listed in Table 1.

Results and Discussion

Test motors with the propellants described were fired for various values of burning surface to throat area ratio, K_n, at normal to the surface accelerations ranging from zero (with the centrifuge at rest) up to 700g. The average burning rate at the various pressures and acceleration levels, r_g, is calculated by dividing the web thickness by the web burning time, determined from the measured pressure history. The average operating pressure is found by dividing the pressure integral by the motor burning time. All tests were conducted at a temperature of $25 \pm 3°C$. All pressure-time curves obtained had a shape close to rectangular. Thus, no ballistic evidence of an initial transient period with increased burning rate augmentation, reported by some investigators, was observed with this experimental configuration and the propellants tested. The short igniter action time (about 0.05 s) excludes any possibility of masking the transient phenomenon by the igniter. Transient period duration, as published,[8-10] is in the order of 2-3 s with the maximal burning rate augmentation taking place 1-1.5 s after ignition.

Effect of the Acceleration Level

Burning rates of the baseline propellant (most thoroughly investigated) as a function of combustion pressure for various acceleration levels are plotted in Fig. 3, using a mean least-squares fit for the experimental data. Above a certain threshold, the burning rate law is found to be strongly dependent on the magnitude of the acceleration. At a pressure of 10 MPa the burning rate increases from 0.87 cm/s without acceleration to 1.10 cm/s (augmentation factor of 1.26) for an acceleration of 100g and to 1.52 cm/s (factor of 1.75) at 700g. No noticeable effect of acceleration on the pressure exponent, n, has been observed for the range of parameters tested. A monotonic increase of burning rate with acceleration was observed also for all other propellants studied.

In view of the existing interest in low-level acceleration fields (e.g., low-spin stabilization of space vehicles), several propellant formulations were tested in acceleration fields of 10 and 50g. In these tests, a threshold acceleration, varying with propellant composition, below which very little or no effect is noted, was revealed.

Effect of the Combustion Pressure

Using three nozzles with different throat diameters, a pressure range of from 2.6 to 16 MPa was obtained with propellant 5150. Figure 4 depicts the variation of the augmentation ratio with acceleration load at pressure levels of 3, 7, and 10 MPa. The curves plotted are derived from the summary of experimental data shown in Fig. 3. At all three pressures, burning rate augmentation increases rapidly up to about 250g, after which the rate of increase is lower and becomes higher again beyond 500g. This kind of presentation eliminates the effect of pressure along a single curve and shows that the relationship $r_g/r_0 \sim a_g^{0.25}$, derived from Crowe's suggestion,[4] does not fit accurately enough the data obtained in this study over the entire range of parameters investigated.

Figure 5 shows the very small variation of the augmentation ratio with pressure for the baseline propellant at different acceleration levels. Indeed, Crowe's model suggests the relationship $r_g/g_0 \sim P_c^{0.25-n}$, which implies, in this case, that $r_g/r_0 \sim P_c^{-0.1}$. The experimental results of this study indicate that the pressure exponent in the above expression is really negative, while its absolute value lies between 0.02 and 0.03. Anderson and Reichenbach[15] reported that for both aluminized and nonaluminized polyurethane-AP propellants, burning rate augmentation increases considerably with pressure, whereas for nonaluminized PBAN-AP propellants, increasing pressure resulted in slightly lower augmentation. They reported anomalous behavior of an aluminized PBAN-AP propellant with regard to pressure and insignificant effect of pressure on the burning rate augmentation of analuminized CTPB-AP propellant. Willoughby et al.[3] also reported various trends of the combustion pressure effect as published by other investigators. In view of these reports, it has become quite obvious that the effect of pressure varies with the propellant type.

Effect of Orientation Angle

In order to investigate the effect of the orientation angle, ϕ, defined as the angle between the acceleration vector and the normal to the burning surface, the baseline propellant was tested at an acceleration level of 500g and orientation angles of 0, 10, 20, and 30 deg. The variation of r_g/r_0 with ϕ is shown in Fig. 6. The burning rate augmentation starts to decrease sharply when ϕ reached 10 deg and becomes negligible beyond 20 deg. This result is in general agreement with the findings of other investigators.[16] The knowledge of this effect is important in cases in which axial as well as radial acceleration exist.

Table 1 Composition data of propellants tested

Propellant designation	Total solids content %	Aluminum content %	Aluminum mmd μ	AP percentage %	AP fractions ratio %	AP mmd μ	Fe_2O_3 content %	Base burning rate law cm/s
5150	85	15	16	70	70/30	200/9	...	$0.389\ P^{0.35}$
5080	85	8	16	77	70/30	200/9	...	$0.445\ P^{0.35}$
5010	85	1	16	84	70/30	200/9	...	$0.445\ P^{0.35}$
5151	85	15	16	69.25	70/30	200/9	0.75	$0.530\ P^{0.40}$
5152	85	15	16	68	70/30	200/9	2.00	$0.533\ P^{0.46}$
5153	85	15	16	70	70/30	400/19	...	$0.262\ P^{0.50}$
5154	85	15	5	70	70/30	200/9	...	$0.418\ P^{0.32}$
5155	85	15	60	70	70/30	200/9	...	$0.492\ P^{0.40}$
8150	88	15	16	73	70/30	200/9	...	$0.442\ P^{0.42}$

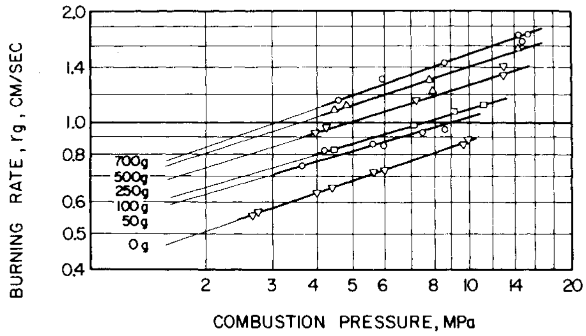

Fig. 3 Burning rate of baseline propellant vs combustion pressure at various acceleration levels.

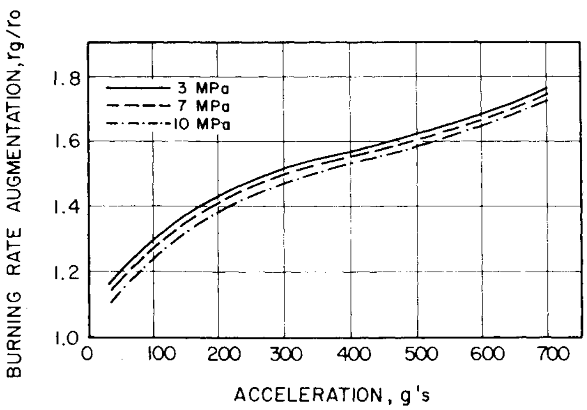

Fig. 4 Burning rate augmentation of propellant 5150 vs acceleration at various pressure levels.

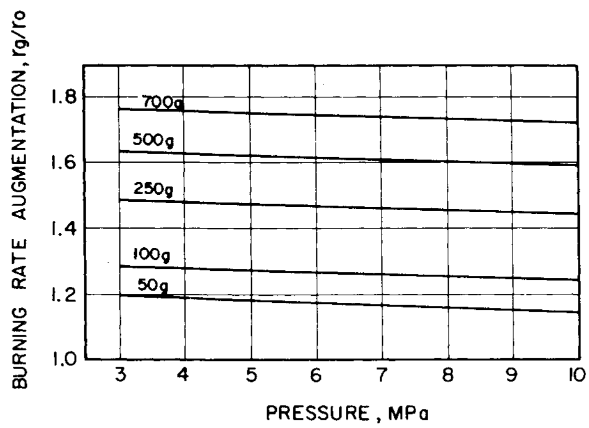

Fig. 5 Burning rate augmentation vs pressure for propellant 5150 at various acceleration levels.

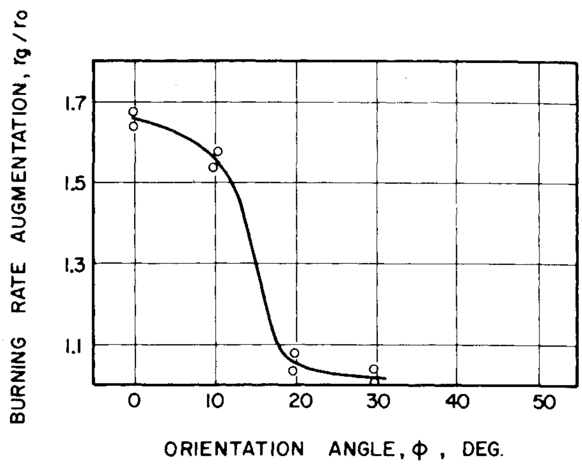

Fig. 6 Effect of orientation angle on r_g/r_0.

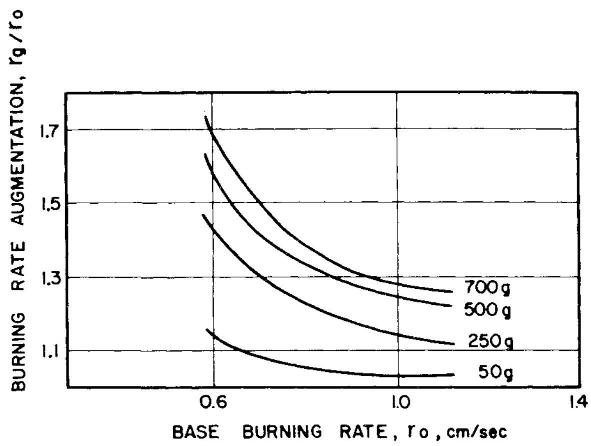

Fig. 7 Burning rate augmentation vs base burning rate (at 5 MPa).

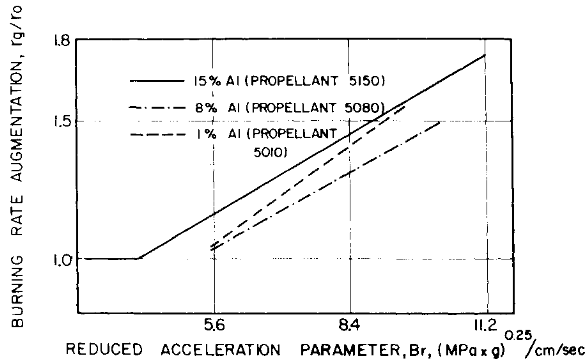

Fig. 8 Burning rate augmentation vs reduced acceleration parameter for 1, 8, and 15% Al propellants.

Effect of the Base Burning Rate

Burning rate augmentation vs base burning rate at constant pressure (5 MPa), total solids content (85%), aluminum percentage (15%), and aluminum mmd (16 μ) is plotted in Fig. 7, which shows that r_g/r_0 decreases with increasing r_0, as expected. This trend can be expressed as $r_g/r_0 \sim 1/r_0$, as proposed by Crowe's model.

Effects of the Aluminum Content and Particle Size

Burning rate augmentation vs the reduced acceleration parameter, B_r, for propellants 5150, 5080, and 5010, which differ only in the amount of aluminum (15, 8, and 1%, respectively), is shown in Fig. 8. It can be seen that the dependence of the augmentation factor upon the reduced acceleration parameter can be correlated by a linear function for the range of parameters investigated. This result is in good agreement with Crowe's model for the quasiequilibrium period, as supported by the experiments of Northam[8] and Willoughby et al.[13] with aluminized PBAA and PBAN propellants (the range of parameters covered in those tests was $0g < a_g < 650g$; $1.2\ \mathrm{MPa} < P_c < 9.7\ \mathrm{MPa}$; $0.4\ \mathrm{cm/s} < r_0 < 2.6\ \mathrm{cm/s}$). However, different empirical constants (slope and threshold value) for that relationship were obtained for the HTPB propellants in this study, as expected, by the use of a different binder. The highly aluminized composition (propellant 5150) is the most sensitive to acceleration effects, but propellant 5010 (1% Al) is more sensitive than propellant 5080 (8% Al) in the entire range of B_r studied. This inconsistency in the effect of metal content was previously reported by other investigators.[6,15]

This study also revealed an inconsistency in the effect of aluminum particle size. For the same value of B_r propellants 5154 and 5155 (5 and 60 μ, respectively) showed almost identical augmentation factors, while propellant 5150 (16 μ

mmd) exhibited higher r_g/r_0. The balance of forces (aerodynamic drag and centrifugal forces) acting on the 5- and 16 μ particles, emerging from the burning surface in a molten phase, indicates that for the entire range of acceleration levels tested, the 5 μ particles are blown away into the main flowfield, while the 16 μ particles remain near the burning surface, agglomerating and augmenting the burning rate, for acceleration levels higher than 50g. Various investigators reported agglomerate diameter up to 400 μ.[3,13] The large particle (60 μ) is ignited, while partially submerged, by the combustion products, thus limiting the agglomeration process. After emerging, the particle is held near the burning surface until its diameter reduces to a critical diameter, and then is blown away from the surface. The large agglomerates (originating from the 16 μ particles) release higher heat fluxes and are held longer near the surface, compared to the 60 μ particles, causing a higher burning rate augmentation.

Effect of the Total Solids Content

A single composition (propellant 8150), differing from the baseline propellant only in the amount of AP (73 vs 70%), was tested for the effect of total solids content. For $B_r = 12$ (MPa $\times g$)$^{1/4}$ $\times$ cm/s, propellant 8150 provided higher values

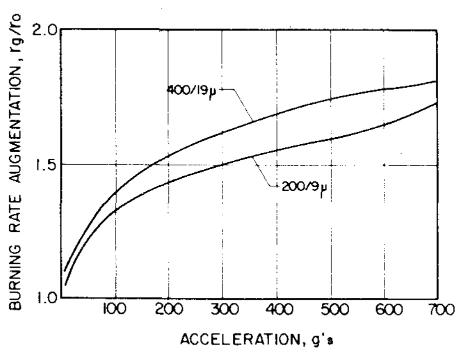

Fig. 9 Burning rate augmentation as a function of acceleration level for different oxidizer particle sizes.

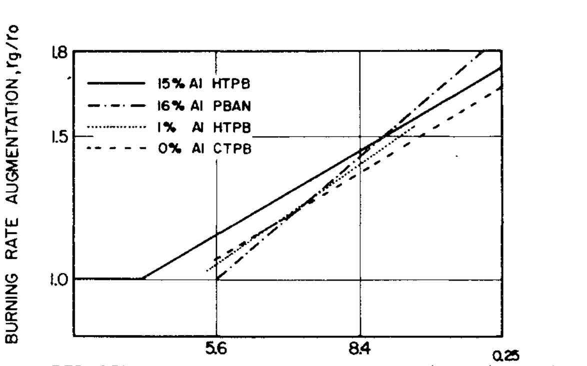

Fig. 10 Burning rate augmentation vs reduced acceleration parameter for propellants with different binders.

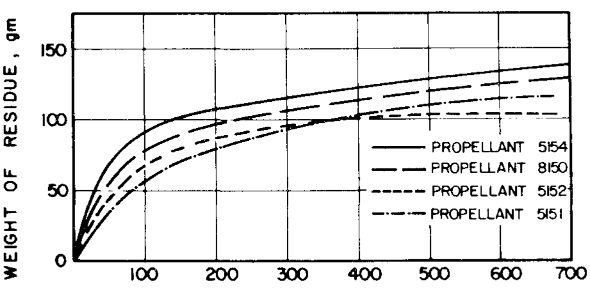

Fig. 11 Weight of residue vs acceleration level for various propellant compositions.

of r_g/r_0, whereas no noticeable difference was observed below that value of B_r.

Effect of the Oxidizer Particle Size

In order to investigate the effect of oxidizer particle size, a bimodal 400/19 μ AP formulation (propellant 5153) with a faction ratio of 70/30, respectively, was tested. The results obtained are compared with the baseline propellant in Fig. 9, showing r_g/r_0 vs acceleration level. As expected, the use of coarser AP increases the burning rate sensitivity to acceleration. Each "pocket" of the coarse oxidizer (400 μ) propellant contains a relatively larger amount of aluminum, as compared to "pocket" in the finer oxidizer (200 μ) propellant. Thus larger agglomerates, causing higher burning rate augmentation, emerge out of the coarse "pocket."

Effect of the Type of Binder

This effect was examined by comparing the results of this study of HTPB propellants with data on PBAN—and CTPB—based propellants published by other investigators.[8,13,17] Figure 10 shows the burning rate augmentation as a function of the reduced acceleration parameter for the three above-mentioned propellants. 16% Al PBAN propellant is compared with 15% Al HTPB (from this study), and 0% Al CTPB propellant is compared with 1% Al HTPB propellant (from this study). It may be concluded that within the range of B_r and propellant formulation parameters examined, the effect of binder type is not significant.

Residue Retention

Postfire inspection of the test motors revealed that in all experiments under acceleration, a black carbon-like residue, which could be removed in most cases in one piece, was found at the bottom of the inhibitor cap. An additional larger segment-like residue was found on the inner cylindrical surface of the asbestos phenolic insert between the propellant grain and the nozzle entrance. The amount of residue retained was found to increase slightly with pressure and strongly with acceleration level. Figure 11 shows the effect of acceleration on the total amount of residue retained in the motor for four 15% Al propellant compositions. The residue mass increases rapidly up to about 100g and then increases slowly towards the theoretically calculated total amount of condensed-phase matter in the combustion gases.

Concluding Remarks

A comprehensive experimental parametric study of the effect of acceleration on the burning rate of metallized HTPB solid propellants was conducted. The experiments were carried out in the centrifugal acceleration range 0-700g and at combustion pressure levels of from 2.5 to 16 MPa. The following conclusions were drawn from this study.

1) Linear relationships between the acceleration-induced burning rate augmentation ratio, r_g/r_0, and the reduced acceleration parameter, B_r (existing above certain threshold value of B_r), were established for nine HTPB metallized solid propellants.

2) Among the many parameters investigated, the most influential on r_g/r_0 were found to be the acceleration level, the base burning rate, the orientation angle, and the oxidizer particle size.

3) The combustion pressure, the total amount of solids, and the type of binder have no significant effect on the augmentation ratio within the range of parameters investigated.

4) An inconsistency in the effect of aluminum content and particle size was observed.

5) The results of this study follow, with certain deviations, the tendencies predicted by the analytical model of Crowe.[4] The data obtained in this investigation may be used to modify Crowe's model, or enable the establishment of more accurate predictions.

6) In the experiments with highly aluminized propellants, significant acceleration-dependent amounts of residue remained in the test motor.

7) The results of this study may be used as guidelines for model developers, spin motor designers, and propellant formulators.

Acknowledgments

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