Aluminized Composite Solid-Propellant Burning Rates in Acceleration Fields

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The average burning rates of a parametric series of propellants were determined in acceleration fields up to 1000 *g* using a combustion bomb mounted on a centrifuge. The propellant strands were burned at 500, 1000, and 1500 psia with the acceleration field directed normal and into the burning surface. Acceleration caused a time-dependent increase of as much as 100% in the burning rate of relatively slow-burning aluminized propellants. The relative amount of burning-rate increase for the various propellants was strongly dependent on the amount of aluminum retained on the propellant surface during burning. The burning rates of two very fast-burning propellants were found to be essentially acceleration-independent.

I. Introduction

SOLID-PROPELLANT rocket motors are currently being used in applications which subject the metallized propellant grains to acceleration fields. The propellant burning rates increase appreciably when the acceleration field is imposed normal and into the burning surface.[1,2] Postfire inspections of motors containing metallized propellants have revealed the presence of metal and/or metal oxide residue in the motor cases. The propellant burning-rate increase and the retention of residue appear to be interrelated. The review and abstracting of the literature on the effects of acceleration on solid-propellant performance are presented in Refs. 3 and 4.

Although progress has been made toward an understanding of some aspects of burning-rate augmentation in acceleration fields, it was believed that additional experimental studies with well-controlled propellant parameters would yield valuable insight. A parametric series of aluminized propellants was formulated to establish the importance of some of the propellant parameters that could be controlled to minimize the effects of acceleration.

The objectives of this investigation were twofold. The first objective was to obtain the quantitative effect of acceleration on the burning rate of the propellants as a function of propellant composition, acceleration level, and time. The second objective was to obtain quantitative information on the amount of aluminum and/or aluminum oxide residue retained in the inhibitor case as a function of propellant composition, acceleration level, pressure level, and propellant burning rate.

II. Experimental Equipment and Procedures

The burning-rate experiments were conducted at the Naval Postgraduate School's (NPGS) Centrifuge Test Facility. Propellant samples were burned in a strand configuration in a combustion bomb mounted on the centrifuge. A 1565 in.^{3} combustion bomb and surge tank volume insured essentially constant pressure during burning (within 4% of the initial value). The use of relatively short strands, generally 2.25 in. or less, at a centrifuge radius of 3 ft limited the total acceleration change during burning to less than 7% of the original value. Detailed information concerning the centrifuge and related equipment is contained in Refs. 5 and 6.

The propellant samples were conditioned at 20°C in a refrigerator oven prior to burning. After preparations for an individual experiment were made, the propellant sample was removed from the oven, inserted in the combustion bomb, and ignited after being brought to the desired acceleration level. The propellant samples were ignited by a nichrome resistance wire and a small amount (approximately 50 mg) of black powder. The ignition wire was laid in a recessed notch filed in the propellant inhibiting case approximately $\frac{3}{32}$ in. from the propellant surface. This was done to avoid the difficulty Anderson experienced with broken ignition wires falling onto the burning surface of the propellant.[1]

The experiments were conducted with the acceleration vector directed normal and into the propellant burning surface. As the propellant strands burned, the pressure in the bomb increased 10 to 20 psi depending on the strand length. This pressure rise was sensed by a variable reluctance pressure transducer mounted on the centrifuge rotor arm over the center of rotation to minimize acceleration effects on the instrument. Pressure change in the combustion bomb and the output of a time mark generator were recorded on a Visicorder chart. The average burning rate of a propellant strand was calculated by dividing the initial strand length by the elapsed time of burning as determined from the pressure time trace. Pyrofuse timing wires (0.002 in. diam), spaced a known distance apart, were used as a secondary means of determining the burning rate in some of the experiments.

III. Propellants

A parametric series of six aluminized composite propellants was prepared by the Naval Weapons Center (NWC), China Lake, California. The formulations contained spherical ammonium perchlorate oxidizer (AP) and polybutadiene-acrylonitrile (PBAN) binder. Various amounts of either spheroidal aluminum powder (Al) or ground tabular alumina (Al_2O_3) were added. The weight ratio of AP to PBAN in every formulation was constant at 79 parts AP to 21 parts PBAN.

The AP size distributions were made as narrow as possible to study the effect of oxidizer particle size on burning-rate augmentation. Two different oxidizer particle size distributions were prepared by passing "as received" American Potash and Chemical Corporation TRONA AP through appropriate Tyler screens. The propellants all contained bimodal AP distributions. The coarse grind AP used was

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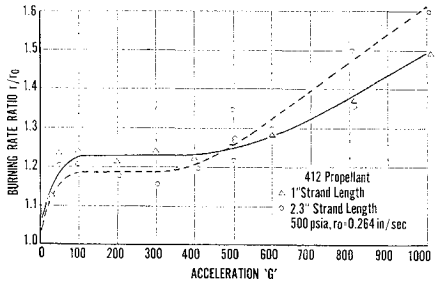

Fig. 1 Burning-rate vs acceleration for propellant P412 at 500 psia.

either 200μ mass mean diameter (mmd) or 94μ mmd material. In all the mixes the fine grind AP was American Potash as received 9μ mmd spheroidal AP. The aluminum additives used were Valley Metallurgical H-5 and H-30 spheroidal powders. The H-5 powder, 10.6μ mmd, was used as received. The H-30 powder was passed through a No. 325 (44μ) Tyler screen, which yielded a distribution with a 28μ mmd.

One propellant was formulated with aluminum oxide as the additive. The aluminum oxide was prepared by passing Aluminum Company of America ground tabular alumina T-61 −325 mesh through a No. 325 (44μ) Tyler screen. The resulting particle size distribution had a mmd of 9.3μ. The propellant formulations in the parametric series containing 94μ mmd AP were designated as the P410 series; those containing 200μ mmd AP were designated the P420 series.

The specific formulations were as follows: 1) P412: 19.95% PBAN, 58.22% 94μ AP, 16.83% 9μ AP, 5% H-30 (−325 Tyler) Al; 2) P413: 17.85% PBAN, 55.89% 94μ AP, 11.26% 9μ AP, 15% H-30 (−325 Tyler) Al; 3) P414: 19.95% PBAN, 57.73% 94μ AP, 17.32% 9μ AP, 5% T-61 (−325 Tyler) Al_2O_3; 4) P415: 17.85% PBAN, 40.00% 94μ AP, 27.15% 9μ AP, 15% H-30 (−325 Tyler) Al; 5) P421: 17.85% PBAN, 55.89% 200μ AP, 11.26% 9μ AP, 15% H-5 Al; 6) P423: 17.85% PBAN, 55.89% 200μ AP, 11.26% 9μ AP, 15% H-30 (−325 Tyler) Al.

Two fast-burning-rate propellants were supplied by the Thiokol Chemical Corporation. Although a detailed description of the propellants is classified, the propellants can be described in the following qualitative manner. The propellants contained a bimodal AP oxidizer distribution. The fine grind AP particle distribution had a very small mmd. The larger grind AP particle distribution had a somewhat larger mmd but qualitatively this distribution would be considered as a small mmd distribution. Both propellants contained a high percentage of as received Valley Metallurgical spheroidal aluminum powder. A hydrocarbon polymer binder and a burning-rate catalyst were also used in the formulations.

All propellant mixes were cast in blocks and then machined into 0.2-in. × 0.2-in. × 5-in. strands. The Thiokol propellant strands were 0.25 in. × 0.25 in. × 5 in. After the propellant strands were x-rayed to check for voids, they were inhibited using an unsaturated polyester cured with a peroxide. The propellant strands were cut to the desired length and measured with a micrometer. A cap of inhibiting material was then cast on one end of each sample. Thus, each strand was enclosed in a small end-burning motor with a port-to-throat area ratio of one. The propellant strands were prepared with a rigid inhibitor and end-closure for two reasons: to provide support for the viscoelastic propellant in the high acceleration environment, and to retain any nongaseous residue that might remain at the end of burning.

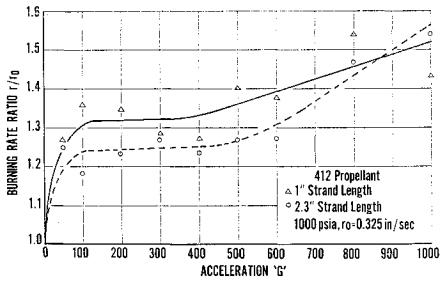

Fig. 2 Burning-rate ratio vs acceleration for propellant P412 at 1000 psia.

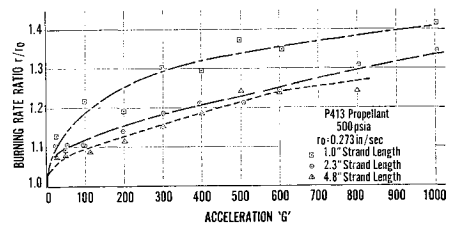

Fig. 3 Burning-rate ratio vs acceleration for propellant P413 at 500 psia.

IV. Experimental Results and Discussion

The burning-rate data are presented as either the absolute burning rate, in in./sec., vs acceleration or the burning-rate ratio vs acceleration. The burning-rate ratio is defined as the burning rate at a given acceleration divided by the burning rate of the propellant with the centrifuge at rest. Each strand burning-rate datum point at a given acceleration represents the result of one experiment. The amounts of residue retained in the inhibitor cases of the propellants are presented for a particular propellant as a function of pressure and acceleration level. The curves drawn through the data points are considered indicative of the trend in the experimental data and are drawn to aid in comparison of the different propellants.

Burning-Rate Results

The burning-rate ratios vs acceleration for the parametric series propellants are presented in Figs. 1–12. The value of r_0 used to form the burning-rate ratio was the average of four burning rates obtained with the centrifuge at rest, two burning rates measured with 1.0-in. strands and two rates measured with the longer length strands.

The data indicate the following general characteristics of burning-rate ratio vs acceleration: 1) burning-rate ratio increases with acceleration level; 2) burning-rate ratio does not tend to a constant limiting value at high-acceleration levels; 3) burning-rate ratio for a given propellant exhibits no consistent pressure dependence (e.g., raising the pressure from 500 to 1000 psia resulted in higher burning ratios for P412, P413, and P421, and no measurable change in the values for P414, P415, and P423 propellants); 4) burning-rate ratio for a given pressure and acceleration level decreases with increasing strand length.

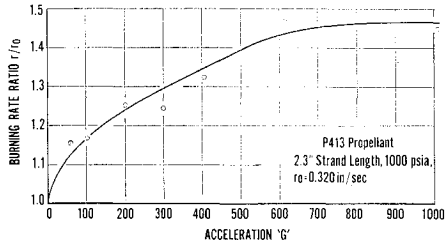

Fig. 4 Burning-rate ratio vs acceleration for propellant P413 at 1000 psia.

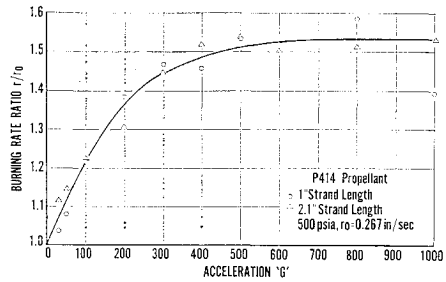

Fig. 5 Burning-rate ratio vs acceleration for propellant P414 at 500 psia.

There were exceptions to these general characteristics. The burning-rate ratios of P413 at 1000 psia (Fig. 4), P414 at 500 psia (Fig. 5), and P423 at 1000 psia (Fig. 12) did tend to a constant limiting value at high-acceleration levels. No decrease in burning-rate ratio with increasing strand length was observed for P414 (aluminum oxide additive) at 500 psia (Fig. 5) or for P412 (the only propellant with 5% aluminum additive) at 500 psia and acceleration levels greater than 500 g (Fig. 1).

The decrease in burning-rate ratio with increasing strand length indicates that a strand at a given acceleration and pressure level experiences a decreasing burning rate as the strand proceeds to burn. Data obtained from individual strands of P413 propellant equipped with timing wires confirmed the decrease in burning rate with time.

Residue Retention

The spent inhibitor cases were examined for possible residue to ascertain the relation between the quantity and nature of the propellant residue and the propellant composition, acceleration level, pressure level, and propellant burning rate. A carbonlike residue was found on the sides of the inhibitor cases at all acceleration levels. In addition, in most instances there was a metallike residue (having a cross-sectional area equal to the cross-sectional area of the corresponding propellant strand) which could be removed in one piece.

Anderson found the same type of residue cap and showed by x-ray diffraction and infrared spectrophotometer analyses that this residue was primarily aluminum oxide.[5] Northam reported that chemical analysis of the residue retained in slab-motor tests of aluminized propellants indicated that the amount of metallic aluminum in the residue increased from 3.4% at 80 g to 6.4% at 300 g.[2]

The amount of metallike residue retained for a given propellant was determined to be primarily a function of the acceleration level, strand length, and pressure level. Increasing the acceleration level increased the amount of residue. In general, the amount of residue was found to be directly proportional to the strand length. The exceptions were P412 and P421 above 400 g which retained three times as much residue when the strand length was increased by a

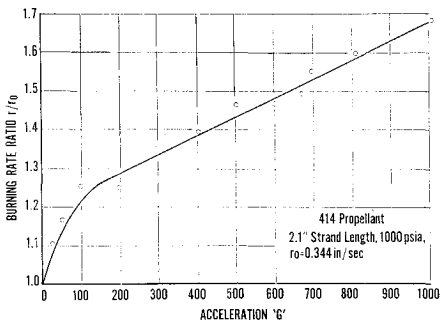

Fig. 6 Burning-rate ratio vs acceleration for propellant P414 at 1000 psia.

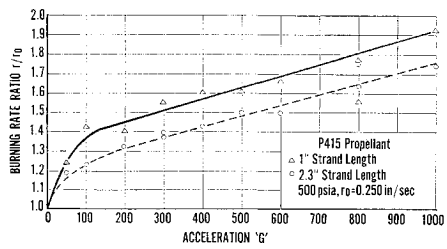

Fig. 7 Burning-rate ratio vs acceleration for propellant P415 at 500 psia.

factor of 2.3. Increasing the pressure resulted in more residue being retained in the inhibitor cases for propellants P415 and P423, and no change in the amount of residue retained for P412, P413, P414, and P421. Detailed information concerning the amount of residue retained in the inhibitor cases can be found in Ref. 7.

Figure 13 is a summary of residue data for 1.0-in. strand lengths burned at both pressure levels. A summary of burning rate vs acceleration data for 1.0-in. strand lengths is shown in Figs. 14 and 15. Examination of Figs. 13–15 indicates that no consistent trend exists for the amount of residue retained and the 0 g burning rate of a propellant. One might expect that the higher the burning rate, and hence the gas evolution from the propellant surface, the more aerodynamic drag would tend to remove the individual aluminum particles and any aluminum agglomerates from the propellant surface. The experimental results indicate that such a simple correlation is not valid.

The following observations regarding residue retention can be made based on the data shown in Fig. 13. Propellants P421 and P423 contain the same Al, AP, and PBAN weight percentages and the same AP particle size distributions. The only difference between the propellants is the Al particle size distribution. Propellant P421 contains 10.6 μ mmd aluminum whereas P423 contains 28 μ mmd aluminum. Propellant P421 retained the greatest amount of residue at both pressure levels. In contrast at 500 psia propellant P423 had the least residue retention of all six propellants. It appears that the size of the aluminum additive is an important parameter in controlling the amount of aluminum agglomeration and retention in an acceleration field: the smaller the aluminum additive size, the greater the amount of agglomeration, retention, and hence residue in a motor case. Data obtained in motor tests at United Technology Center (UTC) indicated the same trend.[8]

Propellants P413, P415, and P423 contain the same aluminum particle size distribution and weight percentages. Propellants P413 and P423 differ only in the particle size of the coarse oxidizer particles, P413 having the smaller size. The only difference between P413 and P415 is the weight percentage of the coarse and fine oxidizer. At 500 psia pressure there were significant differences in the amount of residue retained for these propellants. P413 retained approximately twice as much residue as did P415 which in turn retained approximately twice as much as did P423. When the strands were burned at 1000 psia, the differences in the amount of

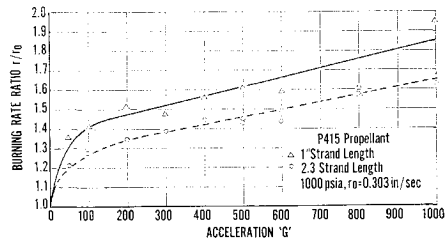

Fig. 8 Burning-rate ratio vs acceleration for propellant P415 at 1000 psia.

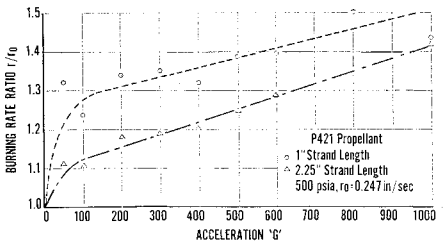

Fig. 9 Burning-rate ratio vs acceleration for propellant P421 at 500 psia.

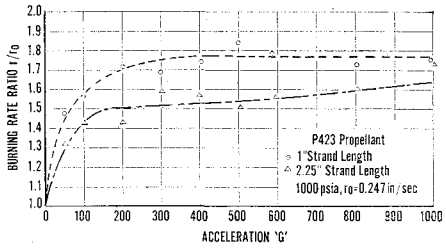

Fig. 12 Burning-rate ratio vs acceleration for propellant P423 at 1000 psia.

residue were not as well defined. P413 and P423 both retained a greater amount than did P415. However, the relative amounts retained by P413 and P423 varied with acceleration. Based on the behavior of these propellants, it seems that the amount of residue retained by bimodal propellants can be reduced by increasing the weight percentage of the fine size oxidizer and increasing the size of the coarse size oxidizer.

Propellant P412 contained 5% 28μ mmd aluminum. The data in Fig. 13 indicate that the amount of residue retained by propellant P412 was less than the amount retained by the 15% aluminized propellants with the exception of P423 at 500 psia. Propellant P413 is the most similar in oxidizer particle size and weight percentage to P412. Since P412

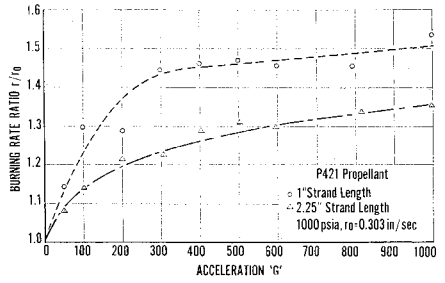

Fig. 10 Burning-rate ratio vs acceleration for propellant P421 at 1000 psia.

contained one-third as much aluminum as did P413, one might expect that P412 would retain a proportionally less amount of residue. Again the experimental results indicate that such a correlation oversimplifies the situation. It was found that P412 retained approximately one-half the amount of residue as did P413.

The amount of residue retained in the strand burning experiments on a percentage basis of original metal contained in the propellant was greater than that contained in Northam's slab-burning experiments[2] and UTC's motor experiments[8] by a factor of approximately two. The presence of the rigid inhibitor walls and the absence of a combustion gas flow parallel to the combustion surface probably accounted for the increase in residue as compared to slab and motor firings. For these reasons, it is not believed that strand

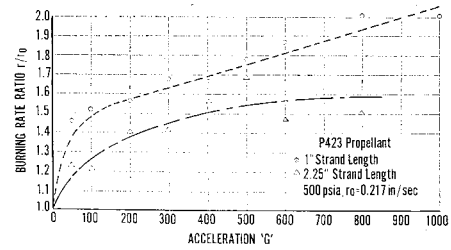

Fig. 11 Burning-rate ratio vs acceleration for propellant P423 at 500 psia.

residue retention data can be used to predict quantitative slagging information in actual spinning motors.

Burning-Rate Time Dependence

The experimental data indicate that there is a decrease in the burning rate as the strand proceeds to burn. The decrease can be explained if one postulates the possibility of at least two distinct modes of combustion. In the first postulated mode the aluminum agglomerates into discrete particles and interacts with the surface of the propellant at a finite number of points. The portion of the solid-propellant surface under an agglomerate now pyrolyzes at a faster rate than it did prior to the imposition of the agglomerate between the flame zone and the propellant surface. This increased pyrolysis rate is probably caused by the combination of the release of chemical energy of metal combustion and the increased heat transfer from the flame zone to the propellant surface through the low-thermal-resistance agglomerate.‡ An inverted cone-shaped pit with the agglomerate at the bottom is formed in the solid phase of the propellant. The rate at which the individual agglomerates in these pits proceed into the propellant solid phase controls the over-all burning rate of the propellant.

As the combusting aluminum agglomerate proceeds into the solid phase of the propellant additional fresh aluminum mass is added to the agglomerate. The rate at which an agglomerate acquires mass (the sum of the rate of addition of new aluminum and the rate of retention of aluminum oxide from the aluminum combustion surface reactions) is greater than the rate at which the agglomerate mass is reduced through vapor-phase aluminum combustion. Eventually the agglomerates become so large that they merge with agglomerates in adjacent pits. The surface of the propellant becomes covered with a continuous layer of aluminum and/or aluminum oxide and "floods." Once the surface of the propellant is flooded, a second slower postulated mode of com-

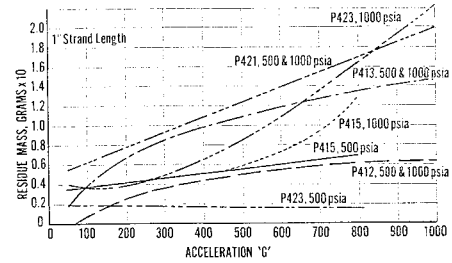

Fig. 13 Comparison of residue mass vs acceleration for 1-in. strand lengths.

‡ An analysis performed in Ref. 7 indicates that the heat-transfer rate from the flame zone to the propellant surface is increased by a factor of approximately 20 when the aluminum/aluminum-oxide agglomerate is retained on the propellant surface. The analysis also indicates that the chemical energy release rate from an agglomerate is of the same magnitude as the heat-transfer rate through an agglomerate.

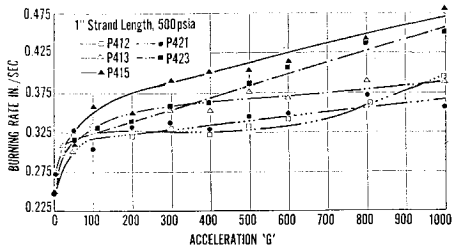

Fig. 14 Burning-rate vs acceleration for five aluminized propellants at 500 psia.

bustion begins. The propellant surface is now relatively smooth compared to its condition in mode one. The parent aluminum particles no longer agglomerate as the regressing propellant surface uncovers them, but rather these particles are individually encompassed by the molten aluminum and/or aluminum oxide flood layer. These particles are then converted to aluminum oxide as the hot oxidizer gases bubble through the flood layer. The propellant burning rate is no longer dependent on the rate at which individual agglomerates penetrate the propellant. The burning rate becomes controlled by the heat-transfer rate from the combustion processes taking place in the molten aluminum and/or aluminum oxide layer.

Crump[9] has taken high-speed motion pictures of the burning surface of aluminized propellants burning under standard acceleration conditions which tend to substantiate the postulated time dependent behavior outlined previously. The photographs indicate that individual aluminum particles in a rapid sequence ignite locally, melt, draw up to a large burning ball, and leave the burning surface as a large aluminum-aluminum oxide agglomerate. Experimental data reported by Northam[2] indicate that the application of an acceleration force promotes agglomeration and causes these agglomerates to pit the propellant surface. Photographs taken by NWC of an extinguished aluminized motor grain show a large number of cone-shaped pits present on the propellant surface.

The projected area of the largest pits found in Northam's slab burner tests and NWC's motor firings was approximately the same 0.04 in.^{2} cross-sectional area of the propellant strands studied during this investigation. Recent investigations at NPGS have been directed toward ascertaining the possible influence of strand cross-sectional area on burning rate. The results indicate that for combustion pressures above 500 psia the strand burning rate is independent of cross-sectional area for areas between 0.04 and 1.0 in.^{2} (Ref. 10).

Propellant surface "flooding" is evidenced by the residue cap found in the strand-burning experiments. In addition UTC has conducted motor experiments in which the residue formed a solid continuous layer.[8] The burning rate of the propellants decreased during the test firings. The UTC motors were fired at maximum accelerations of only 200 g and had web thicknesses of only 0.6 in. This indicates that the propellant surface can become flooded after only 0.6 in. of burning at acceleration levels below 200 g and that this flooding results in a decreased burning rate.

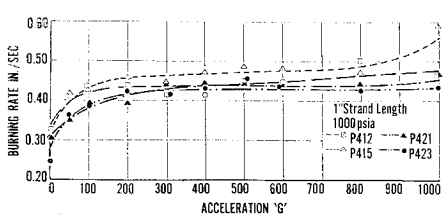

Fig. 15 Burning-rate vs acceleration for four aluminized propellants at 1000 psia.

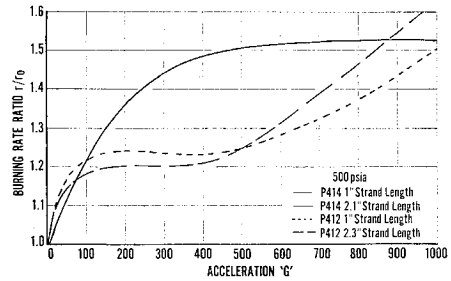

Fig. 16 Comparison of burning-rate ratio vs acceleration for propellants containing aluminum and aluminum oxide at 500 psia.

Aluminum Oxide Propellant Results

Anderson[1] found evidence that the heat-transfer mechanism may be important in determining the burning-rate behavior of metallized propellants in acceleration environments. He observed that the presence of a small amount of nichrome wire on a nonmetallized propellant surface caused the burning rate to increase more than could be accounted for by the chemical energy released by the combustion of the nichrome wire. Additional evidence that heat transfer may be important was obtained by UTC. Experiments conducted at UTC indicated that propellants containing the refractory metal tungsten exhibited burning-rate augmentation in acceleration fields.[11] Visual examination of the residue showed that no agglomeration had occurred and that there was no appreciable chemical reaction involving the tungsten.

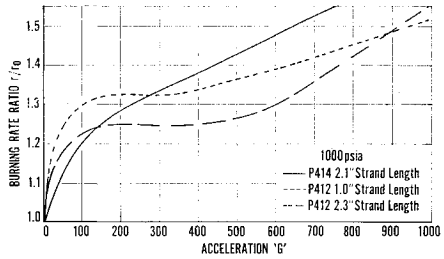

Fig. 17 Comparison of burning-rate ratio vs acceleration for propellants containing aluminum and aluminum oxide at 1000 psia.

Propellant P414 was formulated for comparison with propellant P412. The propellants differ primarily in that P414 contains 5% aluminum oxide as the additive instead of 5% aluminum. The formulation was conceived as an additional check on the possibility that heat transfer from the hot reaction gases through low-thermal-resistance agglomerates (as compared to the combustion gases) may be an important mechanism in the burning-rate augmentation.

A comparison of the results obtained for propellants P412 and P414 is graphically presented in Figs. 16–18. The data indicate that over most of the acceleration range the burning-

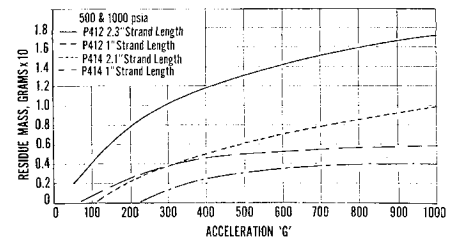

Fig. 18 Comparison of residue mass vs acceleration for propellants containing aluminum and aluminum oxide.

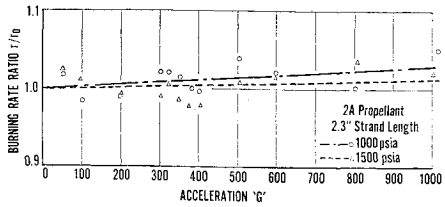

Fig. 19 Burning-rate ratio vs acceleration for propellant 2A.

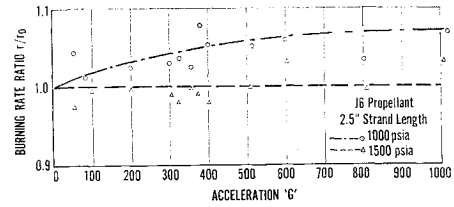

Fig. 20 Burning-rate ratio vs acceleration for propellant J6.

rate ratio of a propellant containing aluminum oxide (P414) was greater than that of a propellant containing aluminum (P412). It should be noted that the 0 g burning rates of P412 and P414 are within 5% of each other. This suggests that the aluminum oxide did not act as a burning-rate catalyst. Moreover, since the aluminum oxide was believed to be chemically inert, the acceleration-induced burning-rate increase of P414 could not have been caused by chemical energy release at the propellant surface. This strengthens the assumption that heat transfer may be a very important, if not the most important, mechanism of acceleration-induced burning-rate augmentation.

Additional evidence that indicates that conductive heat transfer takes place from the flame zone to the propellant surface through low-thermal-resistance agglomerates was found by Mann et al.[12] They used a small, refractory metal, counterflow, conductive heat exchanger positioned between the propellant surface and the flame zone to control the burning rate of nonmetallized propellants. Their results indicated that the basic propellant burning rate could be increased by a factor of up to seven. The data in Fig. 5 indicate that the burning rate of P414 propellant did not vary with strand length. This suggests that propellant P414 was able to sustain mode one combustion for the entire strand length. The residue mass of P414 was porous and of low bulk density. It appeared as though individual particles had been bonded together (possibly with residue from the fuel binder). This is in contrast to the residue from the aluminized propellants which was not porous and had the appearance of a liquid which had been cooled and solidified.

Fast-Burning-Rate Propellants

Two fast-burning-rate propellants supplied by the Thiokol Chemical Corporation were investigated at 1000 and 1500 psia. These propellants are designated 2A and J6. The only difference between the propellants was the size of the aluminum additive, propellant 2A having the larger size aluminum powder. Although the exact burning rates of the propellants are classified, it can be stated that the propellants burned at a rate very much higher than that of the propellants investigated in the basis parametric series.

Propellant J6 was photographed under standard acceleration conditions at 500 and 1000 psia by Crump of NWC using the high-speed motion picture technique outlined in Ref. 9. The motion pictures show that no aluminum agglomeration took place. The aluminum particles burned as individual particles at both pressure levels.

Propellants 2A and J6 exhibited little or no burning-rate augmentation at accelerations as high as 1018 g, as can be seen from Figs. 19 and 20. This negligible burning-rate augmentation can be explained by the following considerations. The small-size oxidizer particles contained in the propellant probably resulted in very little or no aluminum agglomeration as evidenced by the motion pictures of J6 propellant and in accordance with Crump's pocket model.[9] The high burning rate of the propellants produced a high gas velocity that provided the necessary aerodynamic drag to remove from the propellant surface whatever aluminum that did agglomerate. Since it is believed that the retention of aluminum agglomerates produces the burning-rate increase, the removal of these agglomerates results in little or no burning-rate augmentation.

The spent inhibitor cases were investigated for possible residue. The sides and bottoms of the cases were covered with the same type of black carbonlike residue found in the basic propellant series. The amount of this residue was less than that found for the basic series of propellants, being only enough to blacken the sides and bottoms of the cases. No single metallike residue cap was found in any of the inhibitor cases. However, the cases of the J6 propellant burned at accelerations greater than 200 g and a pressure of 1000 psia contained a number of discrete aluminum oxide particles. The amount of oxide residue increased from approximately 0.01 g at 200 g to approximately 0.05 g at 1000 g acceleration. Note that it was J6, the propellant with the small-size aluminum particles, which retained the aluminum oxide residue. This correlates with the results obtained for the basic series which indicate that it is propellants with small aluminum powder which have the tendency to retain the greatest amount of residue.

The data in Figs. 19 and 20 indicate that propellant J6 at 1000 psia exhibited the greatest sensitivity to acceleration. The fact that propellant J6 at 1000 psia retained traces of aluminum oxide residue again demonstrates the dependence of burning-rate augmentation on the retention of aluminum and/or aluminum oxide on the propellant surface.

V. Conclusions

The conclusions derived from the experimental program can be summarized as follows: 1) accelerations normal and into the burning surface of the nominal-burning-rate aluminized propellants were found to affect their burning rates; 2) the burning rate of an individual strand was found to decrease as the strand proceeded to burn; 3) the acceleration sensitivity of the aluminized propellants exhibited no consistent pressure dependence; 4) the primary factor affecting the relative acceleration sensitivities of the aluminized propellants was the amount of aluminum and/or aluminum oxide retained in the spent inhibitor cases.

There was an inverse relationship between the amount of burning-rate increase experienced by a propellant and the percentage of the original aluminum retained on the surface of the propellant. This inverse relationship can be explained by postulating at least two distinct burning-rate augmentation modes: 1) a relatively fast combustion mode in which distinct agglomerates determine the over-all propellant burning rate, and 2) a slower combustion mode in which the surface of the propellant is covered with a continuous flood layer. Those propellants which become flooded soon after ignition experience the least burning-rate increase and the greatest aluminum retention, whereas those propellants which tend to remain in the discrete agglomerate combustion mode after ignition experience the greatest burning-rate increase and the least aluminum retention.

The primary factor affecting aluminum retention was found to be the aluminum particle size. Increasing the aluminum size from 10.6 to 28μ mmd in otherwise similar

propellants was found to decrease the amount of aluminum retained on the propellant surface. It was also found that increasing the size of the coarse AP particles and increasing the weight percentage of the fine AP particles reduced the amount of aluminum retention. No consistent dependence on pressure or basic burning rate was found for the amount of aluminum retention.

A propellant formulated with aluminum oxide replacing aluminum was found to exhibit a greater acceleration sensitivity than the analogous aluminized propellant. This suggests that heat transfer is an important mechanism in the over-all augmentation phenomenon.

The agglomeration and retention of aluminum particles on the propellant surface appear to be the cause of the burning-rate augmentation of aluminized propellants. It appears that once the retention of agglomerated particles begins, the eventual result will be a continuous flood of the propellant surface with molten aluminum and/or aluminum oxide. The obvious and most basic method of controlling the burning-rate augmentation is to keep the aluminum from agglomerating.

The data obtained during the course of this investigation for the fast-burning-rate Thiokol propellants indicate that using very small oxidizer particles to discourage aluminum agglomeration, together with burning-rate catalysts to increase the basic burning rate of the propellant, is a very effective way of eliminating agglomeration and retention and thus controlling the burning-rate augmentation.

The results of this study suggest that any analytical model which attempts to describe the acceleration-dependent burning-rate behavior of aluminized propellants will have to account for the unsteady accumulation of aluminum and/or aluminum oxide on the surface of the propellant and the heat transfer from the flame zone to the propellant surface through the low-thermal-resistance agglomerates on the propellant surface. Investigations of a fundamental nature are required to gain a further understanding of the mechanisms involved.

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