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EVALUATION OF MAGNESIUM-ALUMINUM EUTECTIC TO IMPROVE COMBUSTION EFFICIENCY IN LOW BURNING-RATE PROPELLANTS

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16. Abstract

A previous investigation indicated that the combustion efficiency of low burning-rate propellants could be improved if the aluminum fuel was replaced by aluminum particles coated with a magnesium-aluminum eutectic alloy (ALCAL). The purpose of the present investigation was to evaluate the possibility of improving the combustion efficiency of these propellants by admixing the eutectic with the aluminum rather than coating the aluminum. Tests of three propellants similar in every respect except for the metal fuel were conducted in test motors with 4.54 kg (10 lbm) of propellant. The first propellant used aluminum fuel; the second contained aluminum admixed with magnesium-aluminum eutectic; the third used ALCAL. The test results show that the admixed fuel gave better low burning-rate combustion efficiency than the other two. The test results also showed that the ALCAL was deficient in that much, if not all, of the coating material could be found as the fine particles in a bimodal mix of aluminum and eutectic. The combustion efficiency of low burning-rate aluminized propellants can be significantly improved by mixing a small amount of magnesium-aluminum alloy with the aluminum fuel.

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EVALUATION OF MAGNESIUM-ALUMINUM EUTECTIC TO IMPROVE COMBUSTION EFFICIENCY IN LOW BURNING-RATE PROPELLANTS *

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SUMMARY

A previous investigation indicated that the combustion efficiency of low burning-rate propellants could be improved if the aluminum fuel was replaced by aluminum particles coated with a magnesium-aluminum eutectic alloy (ALCAL). The purpose of the present investigation was to evaluate the possibility of improving the combustion efficiency of these propellants by admixing the eutectic with the aluminum rather than coating the aluminum. Tests of three propellants similar in every respect except for the metal fuel were conducted in test motors with 4.54 kg (10 lbm) of propellant. The first propellant used aluminum fuel; the second contained aluminum admixed with magnesium-aluminum eutectic; the third used ALCAL. The test results show that the admixed fuel gave better low burning-rate combustion efficiency than the other two. The test results also showed that the ALCAL was deficient in that much, if not all, of the coating material could be found as the fine particles in a bimodal mix of aluminum and eutectic. The combustion efficiency of low burning-rate aluminized propellants can be significantly improved by mixing a small amount of magnesium-aluminum alloy with the aluminum fuel.

INTRODUCTION

Many solid-propellant rocket motors require low burning-rate propellants to minimize acceleration loads on the payload. In other vehicles the low rate is required to optimize energy management. The need for low burning rate often requires operation at low chamber pressures. Both of these parameters, low pressure and low burning rate, lead to combustion efficiency losses in high-energy aluminized solid propellants.

The investigation of reference 1 demonstrated that the combustion efficiency of low burning-rate (less than 0.51-cm/sec (0.2-in./sec)) propellants could be improved if the aluminum fuel was replaced by a processed aluminum commonly referred to as ALCAL –

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*Paper presented at the Ninth JANNAF Combustion Meeting, Monterey, Calif., Sept. 11-15, 1972.

aluminum particles coated with a magnesium-aluminum eutectic alloy estimated to be approximately 0.5 μm thick. The purpose of the present work was to evaluate an alternate method of improving the combustion efficiency of low-rate propellants operating at low chamber pressures. The alternate method chosen was to admix the magnesium-aluminum eutectic with the aluminum fuel rather than coat the aluminum. This method was chosen to determine whether the expensive coating procedure required to produce ALCAL is justified. During this investigation, the combustion efficiency of three propellants was evaluated in test motors that contained 4.54 kg (10 lbm) of propellant by weight. The propellant formulations were similar except for the metal fuel additive used: The control formulation used aluminum fuel; the second formulation used a mixture of aluminum and magnesium-aluminum eutectic; whereas the third formulation used ALCAL. In order to better characterize the metal fuels used, the additives were examined with the aid of a scanning electron microscope, X-ray emission analysis, and an atomic absorption spectrophotometer. This paper shows the results of the combustion efficiency tests and discusses these results in light of the detailed study of the fuel additives.

SYMBOLS

Values are given in both SI and U.S. Customary Units. The principal measurements and calculations were made in U.S. Customary Units.

A_t	throat area
C^*	characteristic exhaust velocity
g_o	conversion factor
p	chamber pressure
t	time
t_x	progressive to neutral burning transition point (see fig. 1)
w_p	propellant weight

Subscripts:

f	final
o	initial

APPARATUS AND PROPELLANTS

Test Motor

The ballistics of the three propellants were evaluated by using 15.24-cm (6.0-in.) inside diameter by 27.9 cm (11.0 in.) long, 2.54-cm (1.0-in.) web cylindrically perforated grains with nominal weights of 4.5 kg (10 lbm). One test firing was made with propellants from each batch to determine the propellant burning rate in the motor and the nozzle throat diameter required to yield a nominal burning rate of 0.254 cm/sec (0.10 in./sec) for the remaining tests.

Strand burning rates were determined by using the standard 0.635-cm (0.25-in.) square, restricted, cured propellant strands. No efforts were made to minimize heat losses at the low burning rates.

Propellants

An 84 weight percent solids, 19 percent metal, hydroxyl terminated polybutadiene (HTPB) propellant based on the R 45M binder system was used in all three formulations. The three formulations are listed in table I. Batch 72-16 contained 19 percent

TABLE I.- PROPELLANT FORMULATIONS

Ingredient	Size, μm	Batch 72-16	Batch 72-17	Batch 72-18
		Weight, percent		
AP[a]	400	46	46.00	46
AP	200	13	13.00	13
AP	20	6	6.00	6
Al	7	19	13.57	0
Mg-Al alloy[b]	3-5	0	5.43	0
ALCAL (7/71)[c]	15	0	0	19
Binder, curative, bonding agent	----	16	16.00	16

[a]AP denotes ammonium perchlorate.

[b]35%Mg-65%Al eutectic.

[c]Aluminum processed by Valley Metallurgical Processing Co., Inc.

Reynolds 400 Al and was the control formulation. Propellant batch 72-17 contained 5.43 percent 35-65 magnesium-aluminum alloy which gave a magnesium content of 1.9 weight percent. The alloy and the aluminum were mixed by tumbling these ingre-

dients for 1 hour in a twin-shell blender. The third batch 72-18 contained 19 percent ALCAL which when analyzed gave 0.323 weight percent magnesium and 18.677 weight percent aluminum in the propellant. The ALCAL was purchased from Valley Metallurgical Processing Co., Inc., and was processed through their coating apparatus as described in U.S. Patent No. 3,447,950. This material had been used in previous work (ref. 1) to assess its effectiveness as a means of improving the combustion efficiency of low-rate propellants. Since the ALCAL used in the present work came from a different batch than that used in reference 1, the propellants should be distinguished from each other. This is done by referring to the approximate date of processing. Thus the propellants of reference 1 used ALCAL (4/70); whereas the present test propellants used ALCAL (7/71).

Note also that the alloy is chemically compatible with the HTPB propellants being developed for low-rate applications. Previous experience indicates that some chemical compatibility problems can be encountered when the eutectic is used with acid-terminated propellants. These propellants developed small fissures when processed with normal curing agents. (See appendix A of ref. 1 for a discussion of this problem.)

DATA REDUCTION

Because the purpose of this program was to compare the combustion efficiencies of the three propellants, the characteristic exhaust velocity C^* and the burning rate were the only ballistic parameters evaluated. Owing to the deposition of oxide slag in the throat of the test motors at low-pressure levels, the throat area must be corrected to obtain accurate data for C^*.

The pressure histories indicated that during these tests the nozzle throat area changed nearly linearly at first, followed by a time of nearly constant throat area. A typical pressure history is shown in figure 1. (The motors were designed to have neutral pressure histories with constant burning-rate propellants and with no throat deposition or erosion present.) The calculations for C^* in the data reduction program were modified to include the changing and constant throat areas. The pressure history was used to determine the time t_x (see fig. 1) where the throat-area calculations were adjusted. At time t_x the throat area was assumed equal to the final area. The equation for C^* for the two regions is

$$C^* = \frac{g_o\left(\overbrace{\int_{t_o}^{t_x} pA_t\,dt}^{\text{Region 1}} + \overbrace{A_{t_f}\int_{t_x}^{t_f} p\,dt}^{\text{Region 2}}\right)}{w_p}$$

where

$$A_t = A_{t_o} + \left(A_{t_f} - A_{t_o}\right)t/t_x$$

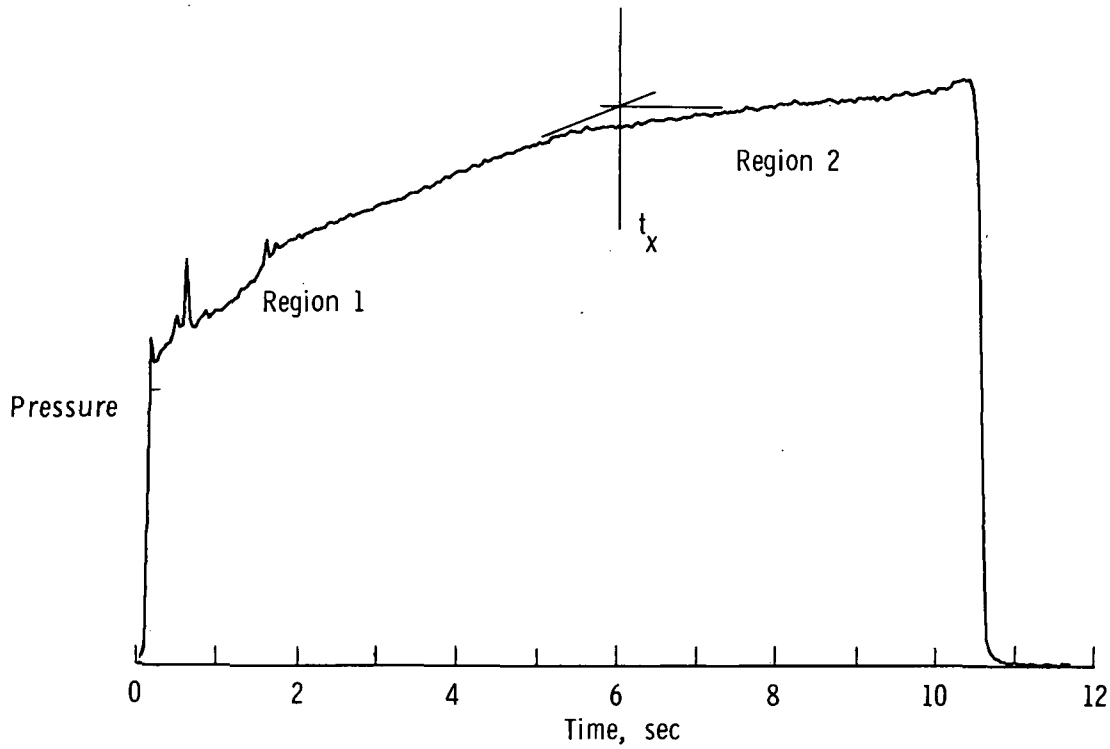


Figure 1.- Test motor pressure history.

The final throat area A_{t_f} was determined by removing the oxide slag from the throat after the test and measuring its thickness with micrometers. This technique was necessary because the oxide contracted from the throat during cooldown.

RESULTS AND DISCUSSION

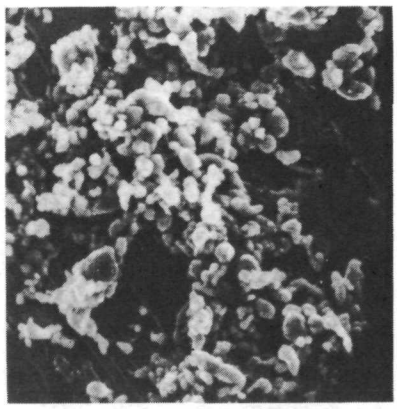
The strand burning-rate data and the motor test results were analyzed to determine differences in the three propellants containing the different fuel additives. The physical and chemical characteristics of the metal fuel additives were determined. These characteristics are presented, followed by a discussion of the rate data, and finally the combustion efficiency data.

Fuel Additive Characterization

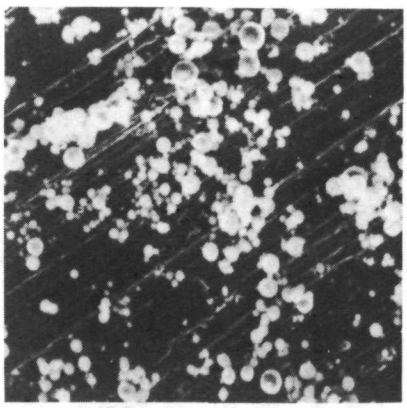
Samples of the fuel additives, aluminum, magnesium-aluminum eutectic, and ALCAL (7/71) were studied by using a scanning electron microscope; typical photomi-

crographs of these materials are shown in figures 2(a), 2(b), and 2(c), respectively. Figure 2(a) shows that the Al particles in the Reynolds 400 Al fuel have an irregular shape but generally have a unimodal size distribution. Figure 2(b) shows the spherical shape and fine particle size of the eutectic alloy. Since figures 2(a) and 2(b) are at the same magnification, the mixture shows mostly particles of a uniform size with a relatively narrow size distribution.

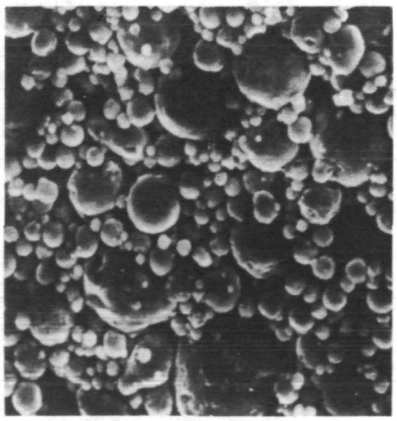
In contrast to figures 2(a) and 2(b), the ALCAL (7/71) in figure 2(c) shows a distinct bimodal distribution of coarse and fine particles. This distribution seemed anomalous since ALCAL is manufactured by coating 15 μm aluminum with a thin layer of eutectic. The initial size of the eutectic particles used in the coating process was 3 to 5 μm. A photomicrograph of this alloy is shown in figure 2(b). It was theorized that the coating process had been ineffective and that much of the eutectic coating material had not adhered



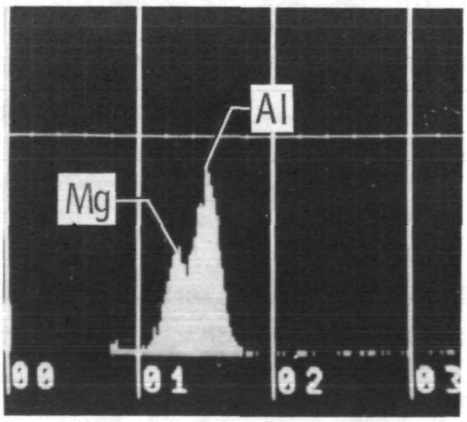
(a) 7 μm irregular Al (× 550).



(b) 3 to 5 μm Mg-Al eutectic (× 550).



(c) ALCAL (7/71) (× 550).



(d) X-ray scattering for small particle in (c).

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Figure 2.- Characteristics of metals used.

to the aluminum particles. This hypothesis was reinforced by studying the X-ray emission spectra from a number of fine and coarse particles in the ALCAL where the scanning electron microscope was used to focus an electron beam on single particles. A typical X-ray spectrum from a fine particle is shown in figure 2(d). The lower peak at 1.25 keV is characteristic of magnesium, and the higher peak at 1.5 keV is characteristic of aluminum. The spectra from the large particles showed no evidence of magnesium on the large particles. Thus, it was concluded that ALCAL (7/71) was most likely a bimodal mixture of large, nearly spherical, aluminum particles and fine, nearly spherical, eutectic particles. A sample of the ALCAL (4/70) material was also examined. The results were indistinguishable from those for ALCAL (7/71). Based on these two samples it is suggested that the coating process did not function as intended and that the eutectic did not coat the aluminum particles.

Since ALCAL (7/71) appeared to be a simple mixture of aluminum and eutectic and not aluminum particles with a 0.5-μm eutectic coating, it became necessary to determine the magnesium content of the mixture. This was done by using an atomic absorption spectrophotometer. The mixture was found to contain 1.7 percent magnesium from which the magnesium content of the propellant was calculated to be 0.323 percent.

Burning Rate

The strand burning-rate data for the three propellants are shown in figure 3 over a narrow pressure range. The data shown are the average rate for three runs at each pressure. The strand rate at 0.69 MN/m^2 (100 psia) for the formulation containing the admixed alloy was 5 percent greater than the aluminum control. This increase could have resulted either from the presence of the smaller eutectic particles and/or the enhanced ignition of the eutectic near the propellant surface. The strand rate for the propellant containing ALCAL (7/71) was 3 percent below the aluminum control. Since the presence of the magnesium should have increased the burning rate, it was concluded that this suppressed rate was due to the increased aluminum particle size. The motor burning rates were approximately 20 percent greater than the strand rates at the same pressure level. This difference, which is not uncommon with low burning-rate propellants, is thought to result from the increased heat loss in the strand burner at the low rates.

Combustion Efficiency

The results of the motor tests are shown in table II with the theoretical C^* and the C^* efficiency for each of the three propellants evaluated at the average chamber pressures from 0.43 to 0.55 MN/m^2 (62 to 80 psia). Note that the addition of these small quantities of magnesium causes less reduction in theoretical C^* than the 0.069 MN/m^2 (10 psia) change in pressure. The C^* efficiency (based on C^* calculated as discussed

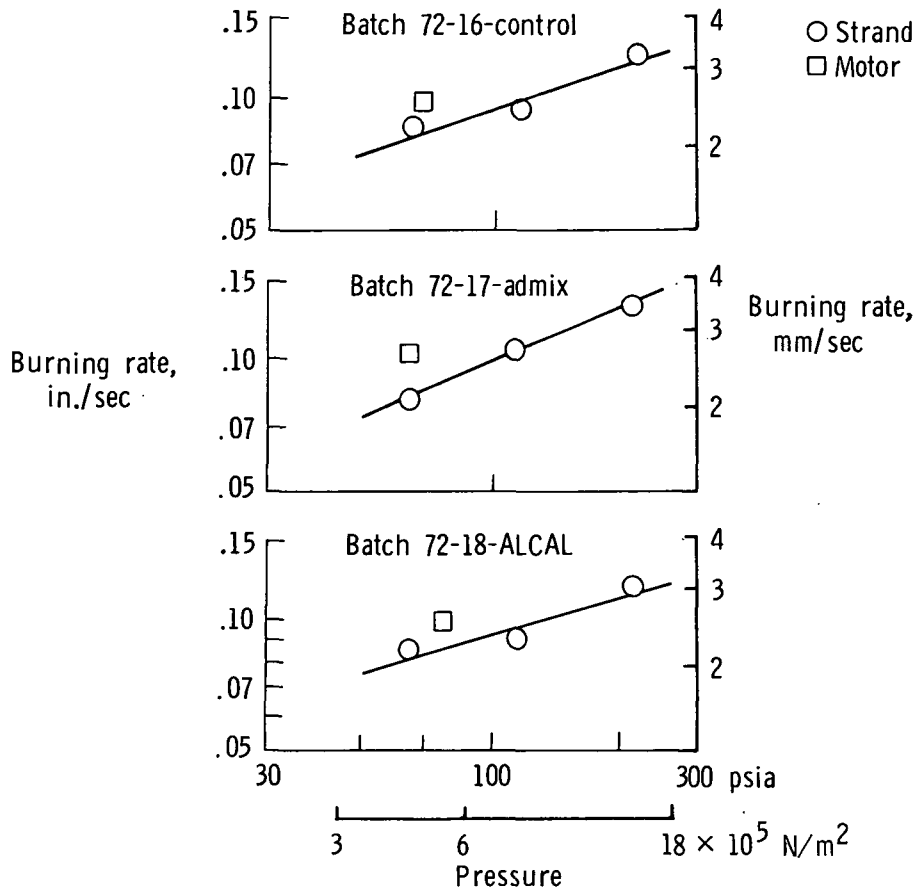

Figure 3.- Burning-rate data.

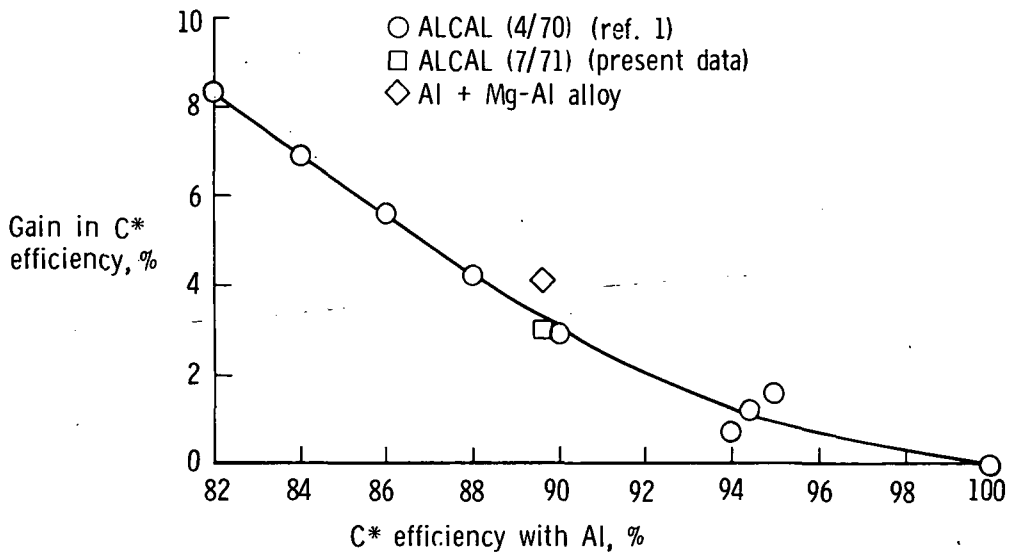

Figure 4.- Combustion efficiency gains with treated aluminum as a function of aluminum combustion efficiency at equal burning rates.

TABLE II.- MOTOR TEST RESULTS

Motor no.	p		Burning rate		C^*		C^*_{theor}		C^* efficiency, percent
	psia	N/m^2	in./sec	mm/sec	ft/sec	m/sec	ft/sec	m/sec	
72-16-1	69	4.76×10^5	0.0976	2.48	4486	1367			
-2	69	4.76	.0973	2.47	4476	1364			
-3	70	4.83	.1001	2.54	4656	1419			
-4	68	4.69	.0973	2.47	4572	1394			
-5	67	4.62	.0998	2.54	4608	1405			
-6	68	4.69	.0998	2.54	4594	1400			
Average	68.3	4.71×10^5	0.0987	2.51	4565	1391	5095	1553	89.6
72-17-1	67	4.62×10^5	0.105	2.67	4792	1461			
-2	65	4.48	.103	2.62	4789	1460			
-3	65	4.48	.103	2.62	4787	1459			
-4	65	4.48	.104	2.64	4735	1443			
-5	62	4.28	.103	2.62	4719	1438			
-6	64	4.41	.103	2.62	4700	1433			
Average	64.7	4.46×10^5	0.104	2.64	4753	1449	5073	1546	93.7
72-18-1	55	3.79×10^5	0.0860	2.18	4653	1418			
-2	77	5.31	.0988	2.51	4789	1460			
-3	Poor ignition								
-4	80	5.52	.101	2.57	4675	1424			
-5	79	5.45	.0986	2.50	4700	1432			
-6	78	5.38	.101	2.57	4720	1439			
Average[a]	78.5	5.41×10^5	0.0999	2.54	4721	1439	5084	1550	92.9

[a]Includes tests 2, 4, 5, and 6 only.

previously) for the propellant containing 1.9 percent magnesium added by admixing the magnesium-aluminum eutectic with the aluminum fuel was 4.1 percent above that of the control propellant containing only aluminum. The efficiency improvement for the propellant made with the ALCAL (7/71) was 3.0 percent at a nominal burning rate of 0.254 cm/sec (0.1 in./sec) for both propellants. This propellant contained 0.323 percent magnesium. (The motor, no. 72-18-1, that was used to determine throat size to give a burning rate of 0.254 cm/sec (0.1 in./sec) was not used in these calculations.)

These C^* efficiency data are compared with the results of reference 1 in figure 4. The curve is a fairing of the data generated by using ALCAL (4/70). The ALCAL (7/71) data correlate well with the data of reference 1 as shown in figure 4, whereas the data from the propellant made with the admixed magnesium-aluminum eutectic showed a 0.8-percent increase above the correlation line.

Some of the improved combustion efficiency of the admixed fuel system (batch 72-17) over the ALCAL system (batch 72-18) might have resulted from the reduced aluminum size used for the admixed formulation. Part of this effect may also be attributed to the fact that the propellant with the admixed metal fuel contained 1.9 percent magnesium as compared with 0.323 percent magnesium in ALCAL (7/71).

Based on these results, it can be seen that the use of a magnesium-aluminum eutectic alloy admixed with the aluminum fuel additive of a low burning-rate propellant is an inexpensive and effective means of improving the combustion efficiency of this type of propellant. Further work is required to establish the relative importance of particle size and magnesium content and to define practical limits on the potential gain in C^* which can be achieved by this technique.

CONCLUDING REMARKS

The combustion efficiency, as indicated by C^* efficiency (characteristic exhaust velocity), was evaluated for three low burning-rate propellants which were similar except that they contained different aluminum fuel additives. The first propellant contained Reynolds 400 Al particles and was used as the control. The second propellant contained 1.9 percent magnesium obtained by admixing 35-65 magnesium-aluminum eutectic alloy with the Reynolds 400 Al. The third propellant contained 0.323 percent magnesium added by the use of specially processed aluminum (ALCAL).

The efficiency was measured in nominal ballistic test motors with 4.54 kg (10 lbm) grains at burning rates of 0.254 cm/sec (0.1 in./sec) with nominal chamber pressures of 0.43 to 0.55 MN/m^2 (62 to 80 psia). An 84 percent solids, 19 percent metal fuel, hydroxyl terminated polybutadiene (HTPB) propellant was used for the investigation.

The magnesium-aluminum eutectic alloy admixed with the aluminum fuel resulted in a 4.1-percent increase in C^* efficiency as compared with 3.0-percent increase in C^* for the ALCAL formulation.

Since the test results also showed that ALCAL, as processed on two separate occasions 15 months apart, consisted of a bimodal admixture of aluminum and eutectic, this difference in C^* efficiency must be attributed to the combined effects of particle size and magnesium content. The data are insufficient to permit any conclusions as to the relative importance of these parameters. The data are adequate, however, to show that the addition of a small quantity of magnesium in the form of an admixed eutectic alloy is a practical way to improve the efficiency of low burning-rate aluminized propellants.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., January 12, 1973.

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1. Cohen, N. S.; and Derr, R. L.: An Experimental Study of the Use of a Magnesium/Aluminum Eutectic Coating To Improve Aluminum Combustion Efficiency. Contract No. NAS 1-9182, Lockheed Propulsion Co., Nov. 1, 1970. (Available as NASA CR-111813.)

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