

References

- ¹ Bertram, M. H., "Exploratory investigation of boundary-layer transition on a hollow cylinder at a Mach number of 6.9," NACA Rept. 1313 (1957); supersedes NACA TN 3546.
- ² Bertram, M. H., "Boundary-layer displacement effects in air at Mach numbers of 6.8 and 9.6," NASA TR R-22 (1959); supersedes NACA TN 4133.
- ³ Bertram, M. H. and Feller, W. V., "A simple method for determining heat transfer, skin friction, and boundary-layer thickness for hypersonic laminar boundary-layer flows in a pressure gradient," NASA Memo. 5-24-59L (1959).

- ⁴ Bogdonoff, S. M. and Vas, I. E., "Some experiments on hypersonic separated flows," ARS J. 32, 1564-1572 (1962).
- ⁵ Bertram, M. H. and Henderson, A., Jr., "Recent hypersonic studies of wings and bodies," ARS J. 31, 1129-1139 (1961).
- ⁶ Bertram, M. H. and Baradell, D. L., "A note on the sonic-wedge leading-edge approximation in hypersonic flow," J. Aeronaut. Sci. 24, 627-628 (1957).
- ⁷ Baradell, D. L. and Bertram, M. H., "The blunt plate in hypersonic flow," NASA TN D-408 (1960).
- ⁸ Thomann, H., "Measurements of heat transfer and recovery factor in regions of separated flow at a Mach number of 1.8," Aeronaut. Res. Inst. Sweden (FFA), Rept. 82 (1959).

Particulate Damping of Oscillatory Combustion

M. D. HORTON* AND M. R. MCGIE†

U. S. Naval Ordnance Test Station, China Lake, Calif.

An experiment is described in which the attenuation of oscillatory burning by aluminum is studied by means of a self-excited, one-dimensional oscillatory burner. Values of the response function of the combustion zone are presented for several variations of a composite propellant, which differ only in that some contain small amounts of aluminum. The data show that the addition of a small amount of aluminum to the propellant tested has little or no effect upon the response function of the flame (as defined by the Hart-McClure theory). These data show also that, for this experimental system, there is an increased acoustic damping that is caused by the presence of aluminum in the propellant. If this increased damping is ascribed to the formation of condensed Al_2O_3 droplets in the combustion gas, it is shown that the theory of Epstein and Carhart can explain the increased damping. As a function of frequency, the variables tested in the experimental program were three different aluminum additives, four concentrations of alumina, alumina as an additive, and the effect of pressure.

Nomenclature

- A_a = viscous attenuation length as defined by Eq. (4); this constant is positive for positive damping
- c = velocity of sound in combustion gas
- E = acoustic energy density
- f = frequency of oscillations during their growth, cps
- f_d = average frequency of oscillations during their decay, cps
- i = $-1^{1/2}$
- n_D = number of particles per unit volume with diameter D
- P = mean chamber pressure during firing in the burner
- p = instantaneous acoustic pressure
- p_0 = amplitude of pressure oscillations at arbitrary zero time
- r = linear burning rate of solid propellant
- R = radius of particle in combustion gas
- t = time
- u = fractional mass perturbation caused by fractional pressure perturbation ϵ
- y = reduced specific acoustic admittance of combustion zone
- Z = $(\omega R^2/2\nu)^{1/2}$
- α = constant that describes exponential change in amplitude of oscillations with time
- α_a = damping constant ascribed to particulate viscous damping; a negative value indicates positive damping
- α_c = growth rate constant due to oscillatory driving of combustion zone
- α_d = damping constant that includes all sources of damping

- α_D = damping constant that includes all sources of damping except that caused by the additive in question (Al or Al_2O_3)
- δ = ρ_0/ρ
- η = dynamic viscosity of combustion gas
- γ = ratio of heat capacities of combustion gas c_p/c_v
- ν = kinematic viscosity of combustion gas
- ρ = density of particles suspended in combustion gas
- ρ_0 = density of combustion gas in chamber
- ρ_s = density of propellant
- ω = angular frequency of oscillations
- u/ϵ = response function of combustion zone

Introduction

OSCILLATORY combustion, a problem that long has plagued the designers of rocket motors, owes its existence to the ability of the combustion process to couple with disturbances in the gas in such a way that a small perturbation can develop into high amplitude oscillations. These oscillations are usually in the normal acoustic modes of the rocket motor chamber. Oscillatory combustion, then, is the phenomenon in which the combustion chamber of a rocket motor exhibits the behavior of a self-excited oscillator. The balance of the paper will be devoted to the problem as it exists in solid propellant motors.

Over the years, various mechanical means have proved effective in increasing the acoustic losses in the rocket combustion chamber so that the oscillations are attenuated or eliminated. More recently, it has been found that various additives, such as aluminum, aluminum oxide, and silicon dioxide,¹ mixed into the propellant often will suppress the oscillations. By far the most important of these additives, because of its effectiveness and widespread use as a propellant fuel, is aluminum.

Received by ARS August 24, 1962; revision received April 15, 1963. The authors wish to acknowledge the financial support of the Special Projects Office of the Bureau of Naval Weapons, the technical support of E. W. Price, and the contribution of Billy G. Brown, who carefully made all the firings.

* Chemical Engineer, Research Department.

† Physicist, Research Department.

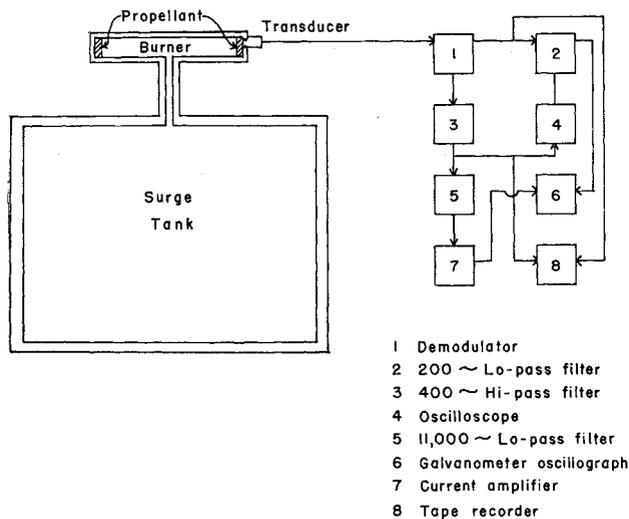


Fig. 1 Schematic diagram of burner and instrumentation

In spite of the general acceptance of aluminum as a suppressant of oscillatory combustion, the mechanism from which its effectiveness is derived has remained unknown. It is important that this mechanism be determined so that designers of rocket motors will know how best to apply this method of suppression to particular situations and so that the phenomenon of oscillatory combustion can be better understood. This paper describes an experiment designed to elucidate the mechanism by which aluminum suppresses oscillatory combustion and presents the results obtained in the experiment.

Theory

Broadly speaking, an additive that suppresses oscillatory burning may be effective in either the propellant combustion zone, the bulk gas phase, or both. In the first case, the effect of the additive would be to reduce the driving, and the effect could be measured by the change in the response function or the acoustic admittance of the combustion zone. In the second case, the effect of the additive would be to increase the acoustic damping, and the effect could be measured as a change in the damping constant of the combustion products in the chamber. In the third case, of course, both the response function and the damping would be altered. In an experiment that permits the determination of the response function and damping constant, comparative testing of two propellants that differ only in that one contains aluminum will establish the effect of aluminum on driving and damping.

In order to introduce experimental and analytical simplicity, a one-dimensional burner was adopted for the experiment. The configuration, as shown in Fig. 1, is that of a cylindrical cavity bounded at both ends by disks of propellant which burn on the opposed inner faces only. Under the conditions of this experiment, it is found that oscillations occur only in longitudinal modes, and that longitudinal modes higher than the first are of negligibly low amplitudes. The disks of propellant are short enough so that their participation in the wave motion of the burner can be neglected. Because the flame zone is sufficiently thin compared to the wavelength of the first longitudinal mode gas oscillations, the flame can be considered as an acoustic boundary and can be characterized by an acoustic admittance. Thus the burner can be analyzed approximately as a one-dimensional acoustic system with distributed damping and with the driving concentrated at the end boundaries.

During the onset of oscillatory behavior in the experimental burner, the oscillations are in the linear regime, and the expression for the instantaneous acoustic pressure at the pres-

sure antinode (the surface of the thin propellant grains) is

$$p = p_0 e^{\alpha t} e^{i\omega t} \tag{1}$$

The real number α can represent not only a "growth constant" at the onset of the oscillations but also a "decay constant" when the oscillations decay in the linear regime after the propellant is consumed. For example, if α is considered as a sum of α_c , a combustion driving constant, and α_d , a damping constant, then, shortly after ignition, $p = p_0 e^{(\alpha_c + \alpha_d)t} e^{i\omega t}$, and, after burnout, $p = p_0 e^{\alpha_d t} e^{i\omega t}$. Note that α_d is a negative number and is assumed to be the same during the burn and after burnout—a gross assumption. The meaning and determination of the α 's are illustrated in Fig. 2, which shows a typical test record.

These exponential constants may be used to determine the real part of the acoustic admittance of the combustion zone which is a measure of the severity with which the combustion drives the oscillations. The real part of the reduced specific acoustic admittance of the combustion zone in terms of the growth-rate and decay-rate constants is approximately^{2, 3}

$$y = P\alpha_c / 4c\rho_s r f = (u/\epsilon) - (1/\gamma) \tag{2}$$

McClure et al.⁴ showed that Eq. (2), which neglects the mean flow of the combustion gas, for this case becomes approximately

$$u/\epsilon = P\alpha_c / 4c\rho_s r f \tag{3}$$

when the mean flow is considered.

Now consider two propellants that differ only in that one contains a small amount of aluminum. The quantities f and P are controlled experimentally, and it was observed that the addition of a small amount of aluminum to a propellant does not affect materially c, ρ_s , or r . Therefore, in order to measure the effect of aluminum on the response function of the combustion zone, one needs only to compare the α_c values of the two propellants. This may be done by measuring their respective growth constants ($\alpha_c + \alpha_d$) and decay constants (α_d) and then computing the values of α_c .

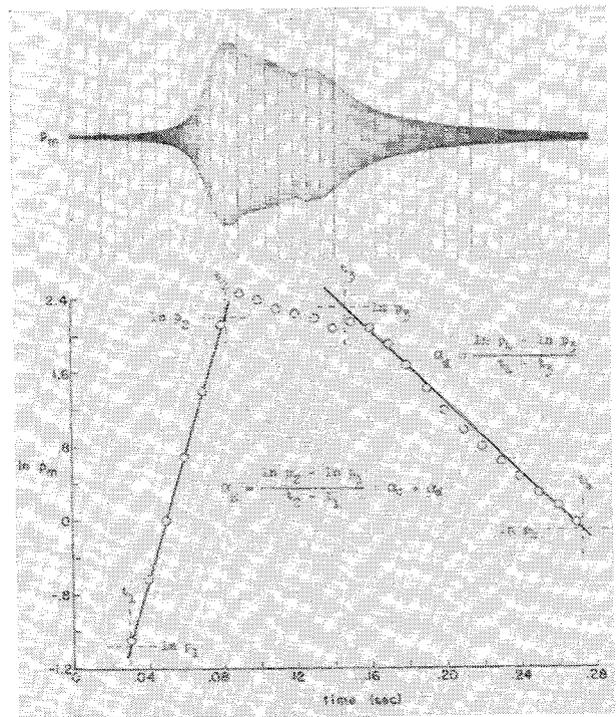


Fig. 2 Typical test record and its analysis. The natural logarithm of the amplitude of the pressure oscillations is plotted as a function of time, and the growth and decay constants ($\alpha_c + \alpha_d$ and α_d) are determined by taking appropriate slopes from the plot

If in comparing the two propellants it is found that the aluminum does not change α_c or $\rho_s c r$, then any reduction in the growth rate of the oscillations resulting from the addition of aluminum must be due to increased damping. To consider that special case, make the assumption that the oscillatory growth rate constant of the unaluminized propellant is $\alpha_c + \alpha_D$, whereas the oscillatory growth rate constant of the aluminized propellant under the same test conditions is $\alpha_c + \alpha_D + \alpha_a$. Thus, the implicit assumption is made that the aluminum adds a source of damping represented by α_a , whereas the aluminum does not influence any of the other damping mechanisms present. By subtracting the growth rate constant for the aluminized propellant from that of the unaluminized propellant, the damping constant can be measured.

Two obvious sources of any increased gas phase damping which might be observed are 1) aluminum particles that act as distributed heat sources by burning at some distance from the propellant surface, and 2) the presence of any solid or liquid particles in the oscillating combustion gas. Assume that α_a is caused by the latter and see if such an assumption is reasonable.† The results of Epstein and Carhart⁶ may be taken and modified slightly to treat this case. These authors derive the formula

$$A_a = \frac{6\pi n_D R}{c} v (1 + Z) \times \left[\frac{16Z^4}{16Z^4 + 72\delta Z^3 + 81\delta^2(1 + 2Z + 2Z^2)} \right] \quad (4)$$

which describes a viscous attenuation coefficient for particles suspended in an oscillating gas.

To transform this damping constant from the present one that describes the fractional rate of energy dissipation as being $(dE/dT)/E = A_a c$ into one that describes the dissipation for a standing wave as being $(dE/dT)/E = 2\alpha_a$, the equality $-\alpha_a = A_a c/2$ may be used, which provides an attenuation coefficient in terms of time rather than distance. The negative sign is introduced because α_a is defined in such a manner that a negative α_a corresponds to positive damping. Inasmuch as a particle size distribution must be treated, and a damping coefficient with units of time is desired, Eq. (4) becomes

$$-\alpha_a = \sum \frac{3\pi n_D R v (1 + Z)}{c} \times \left[\frac{16Z^4}{16Z^4 + 72\delta Z^3 + 81\delta^2(1 + 2Z + 2Z^2)} \right] \quad (5)$$

In order to apply this expression to the experimental combustor, one would have to know the spatial and numerical distribution of n_D . Inasmuch as this information is lacking, some assumption must be made about n_D . Assume therefore that the combustion gases contain uniformly the aluminum oxide particles that could be recovered from the exhaust products of the burner.

Sehgal⁷ has determined experimentally the particle size distribution of combustion products of an aluminized, polyurethane-ammonium perchlorate composite propellant. He finds that the solid combustion products are composed almost entirely of small, spherical, aluminum-oxide particles. His data indicate that at 200 psi, the pressure used in this experiment, the particle diameters range from about 0.5 to 4 μ , with about 80% of the particles having diameters less than 1 μ . Since the propellant and burner used in this experiment were somewhat different from those used by Sehgal, there is no reason to believe that the aluminum oxide particle distributions were exactly the same in both cases. Therefore, an attempt to compute the predicted damping-frequency curve by the use

† The possible importance of particle damping has been discussed previously by Altman and Neustein in various reports from Aeronutronic and also by Bird et al.⁵

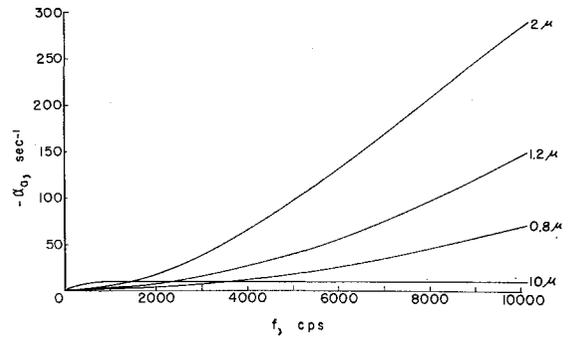


Fig. 3 Particulate damping constant as calculated by Eq. (5). The values used for the calculation were as follows: $\eta = 8 \times 10^{-4}$ poises, $\rho = 4$ g/cm³, $\rho_p = 0.002$ g/cm³, $c = 35,000$ in./sec, $R = 6 \times 10^{-5}$ cm, and $n_D = 1.1 \times 10^{17}$ particles/cm³. (This corresponds to the value obtained if the 1% aluminum reacts completely to form Al₂O₃ particles)

of Sehgal's exact particle size distribution data to evaluate Eq. (5) numerically is not justified. Instead, a diameter based on Sehgal's data simply will be chosen, and Eq. (5) will be used, although it should be recognized that the curve obtained in this manner probably is not realistic. Neither its shape nor its magnitude will be more than approximate. If 1.2 μ is used as the particle diameter, 4 g/cm³ as the density of the particles ρ , and the gas viscosity η is estimated to be 8×10^{-4} poises, the plot of α_a vs frequency shown in Fig. 3 is obtained for a gas that contains 2% Al₂O₃ particles. Also shown in the figure are theoretical damping curves for particle diameters of 0.8, 2, and 10 μ .

Because of the temperature oscillations that accompany the pressure oscillations in the burner, a small amount of damping is introduced by alternating heat transfer between the particles and the gas. Reference 7 also describes the damping constant for such a process, but, inasmuch as it is considerably smaller than the viscous damping constant, it will be neglected.

Experiment

In the experimental program, a side-vented cylindrical burner that used opposed, end-burning grains was used. The grains, which were 0.25-in. thick and 1.4-in. o.d., were bonded to the walls of the 1.5-in.-i.d. motor tubes with epoxy resin. The propellant surface was coated with a thin layer of pyrotechnic igniter paste, a resistance wire that was coated with the same igniter material was placed near each propellant surface, the leads were passed out through a pressure seal, and the burner then was assembled. After the pressure transducer was mounted in contact with the rear surface of one of the propellant grains and the burner was connected to a pressure surge tank, the tank was pressurized. The grains subsequently were ignited and the run made.

A schematic drawing of the burner and instrument system is shown in Fig. 1. The record of interest was that obtained by "band-passing" the signal from the first mode longitudinal oscillations to a galvanometer oscillograph, where it was recorded. An example of such a recording is shown in Fig. 2. The oscillograph record was used to determine the exponential growth and decay constants as indicated in the figure.

A polybutyl acrylic acid copolymer-ammonium perchlorate propellant was used as the base propellant in the program. The propellant was 80% NH₄ClO₄, 2% copper chromite, and 18% binder and curing agent. The same propellant that contained aluminum or aluminum oxide was used to evaluate the effect of the suppressant.

Aluminum

To test the suppressive action of 5 μ aluminum (Metals Disintegrating 105 as received from the manufacturer), the

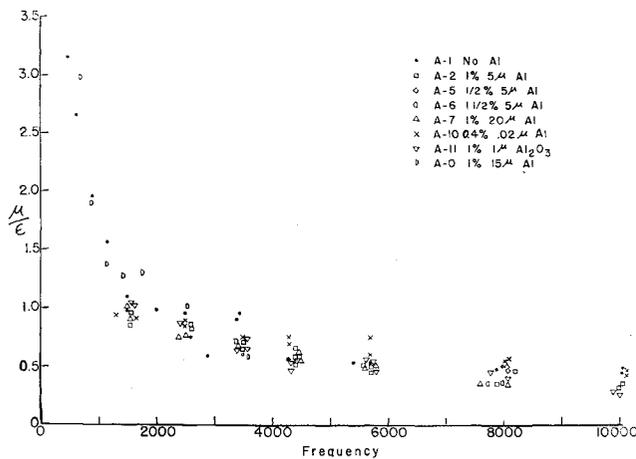


Fig. 4 Values of the response function vs frequency at 200 psig for the propellants tested

oscillatory characteristics of a propellant (designated as A-2) containing 1% of this aluminum were compared to those of the base propellant (A-1). With each of these propellants a series of firings was made at 200 psig, and during each series the motor lengths were varied suitably to produce frequencies from 500 to 10,000 cps.

From the pressure records of these firings, the exponential growth and decay constants were determined. Also determined from the pressure-time data were the burning rates of the propellants (0.37 in./sec.) and the speed of sound in the combustion gas (35,000 in./sec). The density of the propellants was 0.063 lb/in.³ These constants, along with Eq. (3), then were used to calculate the values of the response function of the combustion zone. These values are shown in Fig. 4 and also in Tables 1 and 2. In Fig. 5 are plotted values of the growth rate constant for the unaluminized propellant, and in Fig. 6 are plotted the values of the growth rate constant for the propellant containing 1% aluminum.

Examination of Fig. 4 shows that within the accuracy of the method the presence of aluminum has no effect on the response function of the propellant combustion zone. Thus, since the factor that multiplies α_c in Eq. (3) is experimentally the same for both propellants, α_c is unchanged; that is, the driving is unaffected by the presence of aluminum.

Table 1 A-1 propellant (no Al) at 200 psig

Test number	$(\alpha_c + \alpha_d)$, sec ⁻¹	f , cps ^a	$-\alpha_d$, sec ⁻¹	f_d , cps ^a	μ/ϵ
1658	121	3,456	26	2800	0.92
1659	59	2,900	31	2070	0.67
1664	50	1,500	34	800	1.21
1667	65	2,000	27	1210	0.99
1668	73	2,580	19	1600	0.77
1674	89	3,500	27	3000	0.71
1675	41	1,150	47	700	1.64
1677	23	900	59	575	1.96
1684	6	625	76	380	2.82
1685	6	490	70	320	3.34
1879	102	4,300	24	3250	0.63
1885	108	5,400	34	4000	0.57
1886	124	7,900	47	5600	0.47
1899	44	1,500	23	820	0.96
1900	72	2,500	36	1850	0.93
1901	96	3,400	36	2700	0.83
1902	97	4,400	28	3900	0.61
1903	120	5,700	36	4750	0.59
1904	138	8,000	55	6600	0.52
1905	160	10,100	68	8200	0.48
1973	130	10,200	76	7900	0.43

^a The first frequency, f , is measured during the growth of the oscillations and the second, f_d , during the decay.

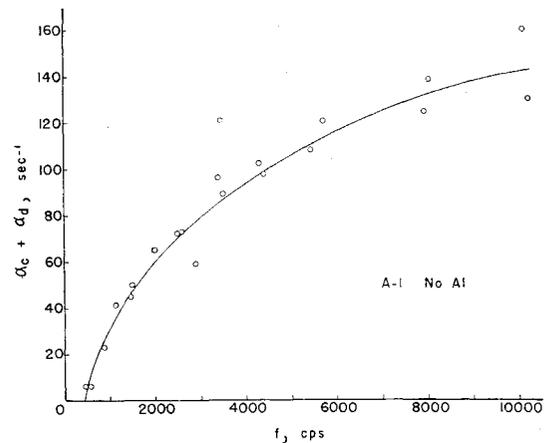


Fig. 5 Growth rate constants for the unaluminized propellant as a function of frequency at 200 psig

Since the driving is unaffected (or at least not greatly changed) by the presence of aluminum, the change in growth rate brought about by the addition of aluminum to the propellant must be due to increased damping, perhaps caused by suspended particles of aluminum or aluminum oxide in the combustion gas.

A curve of the damping predicted by Eq. (5) is plotted in Fig. 7. This curve is based upon an assumed uniform particle diameter of 1.2 μ , as estimated from Ref. 7. Also plotted in the figure is the experimentally determined decrease in growth rate due to aluminum addition which was determined from the difference in the smoothed curve data of Figs. 5 and 6. It is encouraging to note that this crude calculation of the damping yields values that are of the same order of magnitude as the experimental results. This order-of-magnitude calculation does not prove that the effectiveness of the aluminum is due to the viscous damping action of the alumina combustion products. From it, however, one may draw a rather strong inference that this is so. It should be noted that a known source of damping (alternating heat transfer to the particles) and a possible source of damping (the burning aluminum particles acting as distributed heat sources) have been neglected, and both might have to be considered in a more sophisticated treatment of the damping.

The somewhat roundabout method of determining α_d has been chosen for several reasons. A comparison of the damping after burnout of the different propellants would not be valid because the distribution of particles must be different during and after combustion. It is only through necessity

Table 2 A-2 propellant (1% 5 μ Al) at 200 psig

Test number	$(\alpha_c + \alpha_d)$, sec ⁻¹	f , cps	$-\alpha_d$, sec ⁻¹	f_d , cps	μ/ϵ
1888	37	10,200	128	8300	0.35
1889	60	8,200	104	6500	0.43
1890	70	5,600	66	5000	0.52
1891	54	4,400	62	3900	0.57
1892	66	3,500	50	3000	0.71
1893	59	2,600	46	2200	0.87
1894	28	1,530	40	1000	0.96
1914	52	2,600	50	2150	0.84
1916	50	4,400	61	3950	0.54
1919	48	7,900	74	6800	0.33
1920	59	4,400	64	3950	0.60
1921	74	5,700	63	5000	0.52
1922	21	1,550	41	1250	0.85
1923	46	3,500	59	3100	0.65
1928	56	5,700	64	4980	0.45
1992	54	10,000	96	8300	0.32
1993	67	4,400	70	3800	0.67

that the damping constants are used in the calculation of the response functions. Also, factors involved in the propellant burnout seem to cause the determination of the decay constant to be much less precise than the determination of the growth constant.

It is worth noting that the general sources of damping in these burners are poorly understood. However, whatever the unknowns and errors involved in the determination of the constants, it is the differences that are being evaluated. Since the unknowns and errors should be reasonably constant from one propellant to another, a comparative technique, such as is used here, hopefully should eliminate the unknowns and errors by subtraction.

Aluminum Concentration

In order to evaluate the effect upon oscillatory burning of the aluminum concentration in the propellant, the oscillatory behavior of the standard propellant (PBAA-NH₄ClO₄) was compared at 200 psig to that of the same propellant containing small amounts of 5 μ aluminum. For each of the aluminum concentration levels tested (0.0, 0.5, 1.0, and 1.5%), Fig. 4 shows that, at the same frequency, the aluminum had little or no effect upon the response function of the combustion zone. However, as Fig. 8 shows, the suppressant action of the aluminum is directly proportional to the concentration level. Inasmuch as there is a suppressant action and yet the response function is apparently unchanged, the damping must be increased. Equation (5) states that the damping is proportional to the number of particles in the gas and would explain the experimental results if one relies on the inference that has been made and makes the logical assumption that, at low concentration levels, the number of particles in the combustion gas is proportional to the aluminum concentration in the propellant.

Pressure

Sehgal⁷ has measured the effect of chamber pressure on the particle size of aluminum oxide produced by the combustion of an aluminized composite propellant. He found that the average particle size increased as the chamber pressure was increased. Since acoustic damping by particles is size-dependent, changes in pressure should change the damping. From Fig. 3 it can be seen that, at a given frequency, a small increase of particle diameter can either increase or decrease the damping, depending on whether the original diameter is less than or greater than an optimum value (about 3 μ). Earlier, it was estimated that the average aluminum oxide particle diameter produced by the aluminized propellant used in this investigation (A-2) was slightly greater than 1 μ at 200 psi. This diameter is below the optimum diameter over the frequency range tested. Therefore, if the estimated diameter is even approximately correct, and the deduced damping mecha-

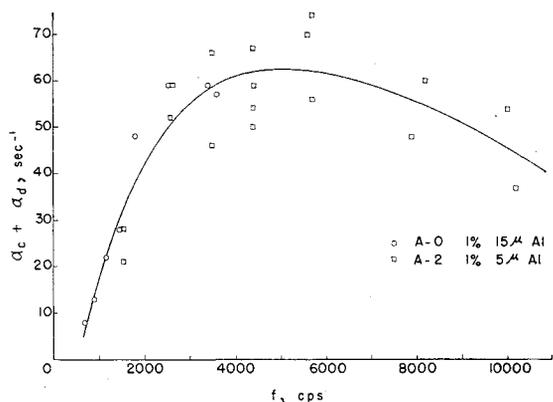


Fig. 6 Growth rate constants for an aluminized propellant (1% 5 μ Al) as a function of frequency at 200 psig

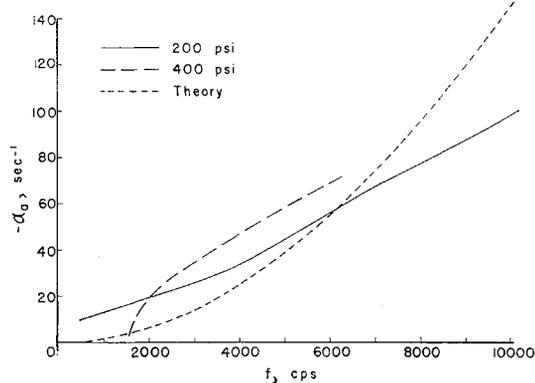


Fig. 7 Comparison between the damping constants as predicted by Eq. (5) and those determined experimentally. The 200 psig experimental points are determined by taking the differences between the "smoothed" data in Figs. 5 and 6, whereas the theoretical calculations use a diameter of 1.2 μ and the same values for viscosity, density, and weight fraction as are previously listed. The theoretical curve is calculated for a mean pressure of 200 psig

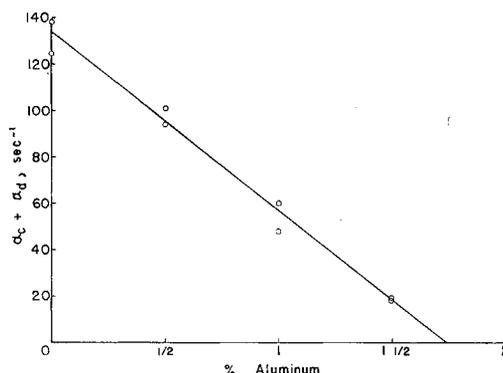


Fig. 8 Influence of aluminum (5 μ) concentration upon the growth rate of the oscillations at 200 psi and 8000 cps. The exponential growth rate constant of the oscillations is $\alpha_c + \alpha_d$

nism is the proper one, it would be expected that the damping would increase with increasing pressure, especially at higher frequencies.

In order to investigate the effect of pressure on damping, two comparative series of firings were made at a chamber pressure of 400 psig. The first series employed the reference propellant, and the second used the propellant containing 1% 5 μ aluminum (A-2). These were the same propellants as were used earlier to obtain a damping curve at 200 psig. Separate smooth curves were drawn through the growth rate points from the firings of unaluminized and aluminized propellants, and the difference between the smoothed curves is plotted in Fig. 7. These data, which scatter rather badly, are listed in Tables 3 and 4. The response function of the combustion zone was approximately the same for both propellants at 400 psig, as was true also at 200 psi, and so one again may interpret this difference curve as being a plot of the increased acoustic damping caused by the aluminum. If this interpretation is correct, it is evident that the damping was indeed greater at higher pressure and that the effect was more pronounced at higher frequencies. Because particle damping is strongly dependent on diameter, a slight increase in the diameters of any particles produced by the combustion process would account for any increase in damping.

Aluminum Particle Size

Other investigators have reported that, at the same concentration level, finer aluminum was a more effective suppress-

Table 3 A-1 propellant (no Al) at 400 psig

Test number	$(\alpha_c + \alpha_d)$, sec ⁻¹	f , cps	$-\alpha_d$, sec ⁻¹	f_d , sec ⁻¹	μ/ϵ
1707	53	3,000	51	2200	1.24
1710	55	3,500	50	2800	1.07
1711	40	2,550	50	1800	1.24
1712	38	1,950	36	1200	1.29
1933	66	5,600	45	4400	0.70
1934	62	4,350	34	3650	0.77
1935	60	3,500	35	2900	0.86
1936	48	2,500	27	2000	1.03
1937	11	1,550	15	910	0.59
1938	11	1,530	22	940	0.75
1939	38	2,500	19	1920	0.79
1941	66	4,400	40	3800	0.86
1942	81	5,800	38	4500	0.73
1950	56	3,350	29	2950	0.86
1955	29	1,850	16	1070	0.79
1956	71	5,600	41	4800	0.70
1975	90	10,100	82	8100	0.59
1976	81	8,100	70	6200	0.66
1977	84	9,000	67	6500	0.66
1978	81	9,900	92	7800	0.60

sant of oscillatory burning.^{8, 9} In order to study this phenomenon quantitatively, the oscillatory burning of four propellants was compared. The reference propellant (A-1) was the same as was discussed earlier, and the other propellants were the same as the reference propellant, except that the A-2 propellant contained 1% of 5 μ aluminum, the A-7 contained 1% of 20 μ aluminum (Linde spherical), and A-10 contained 0.4% of 0.02 μ aluminum (National Research Corporation ultra-fine). The growth and decay rate constants for these propellants which are plotted in Tables 1, 2, and 5-7 were determined at 200 psig and from 1500 and 10,000 cps.

Again, within the accuracy of the method, Fig. 4 shows that all of the propellants had the same response functions. Because the response functions of the propellants are the same, any change in the exponential growth rate of the oscillations plausibly is due to altered damping.

By the same technique as was described in the section on aluminum, the differences between the smoothed growth rate curves of the aluminized propellants and the unaluminized propellant were determined and are plotted in Fig. 9. This figure shows that the growth rates of the aluminized propellants are comparatively smaller than the unaluminized, and it is reasonable to ascribe the decreased growth rates to increased acoustic damping that is caused by the presence of alumina particles in the gas. Furthermore, it is observed that if this mechanism is correct, the damping decreases as a function of the initial particle size of the aluminum in the

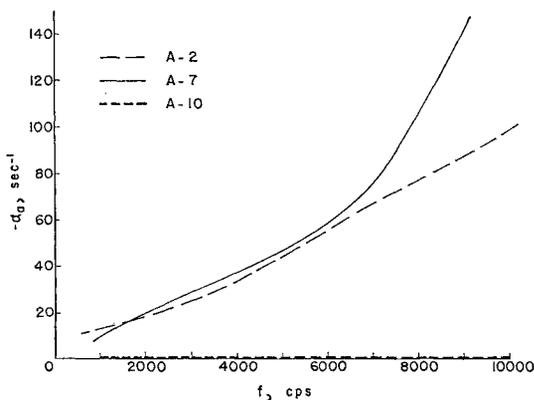


Fig. 9 Experimental damping of 20, 5, and 0.02 μ aluminum at the 1, 1, and 0.4% levels, respectively. Note that the 0.02 μ aluminum produces no damping

Table 4 A-2 propellant (1% 5 μ Al) at 400 psig

Test number	$(\alpha_c + \alpha_d)$, sec ⁻¹	f , cps	$-\alpha_d$, sec ⁻¹	f_d , sec ⁻¹	μ/ϵ
1924	14	2600	48	2300	0.86
1925	11	2600	43	2350	0.75
1995	21	5200	76	4950	0.57
1996	18	4300	80	3950	0.79
1997	24	3500	69	3175	0.84
1998	23	2300	46	2300	0.95
1999	11	1800	39	1550	0.95
2000	11	1550	37	1325	1.10
2005	23	2600	88	2300	1.32
2021	10	2450	46	2300	0.77
2022	12	3600	68	3200	0.71
2034	19	3400	54	3200	0.73
2036	8	5700	76	5000	0.53

propellant; at least this is so where there is a difference greater than experimental scatter.

Alumina

The postulate that aluminum suppresses oscillatory burning through the damping action of condensed phase particles in the combustion gas has been suggested by the foregoing results. However, because the aluminum undergoes a transition to aluminum oxide, all interpretations are somewhat speculative, as the spatial and numerical distribution of particle sizes is unknown. An attempt was made to eliminate this uncertainty by the use of aluminum oxide rather than aluminum as a propellant additive.

For the reference propellant and the A-11 propellant that contained 1% Al_2O_3 , comparative growth rates and response function values were obtained at 200 psig by the previously discussed method and are listed in Table 8. Again, both propellants had approximately the same response functions. The "damping" curve is taken (again as in the section on aluminum) from the difference in the smoothed growth rate curves and is shown in Fig. 10. Also shown in Fig. 10 are the damping curve calculated from Eq. (5) and the measured particle size distribution of the alumina that was mixed into the propellant. It is interesting to note that the damping theory calls for much more damping than actually was observed. The discrepancy between the theoretical and experimental damping may be due to the observed tendency of the unmixed alumina to agglomerate. If a significant portion of the alumina did not disperse during the mixing of the propellant, such a curve as was measured could be expected. Also, it is not inconceivable that the alumina agglomerated during the combustion process.

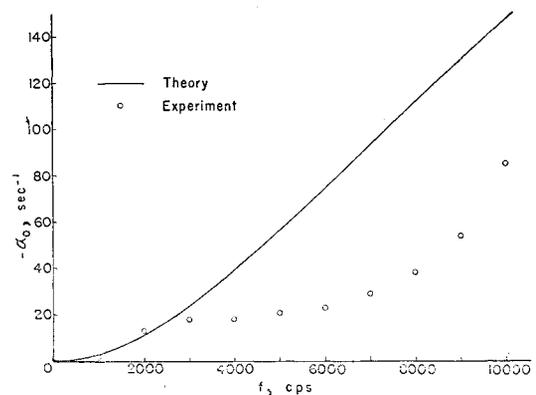


Fig. 10 Comparison between the theoretical and experimental damping constant for 1% alumina in the propellant. The theoretical curve was calculated from Eq. (5) and a measured particle size distribution of the alumina put into the propellant

Table 5 A-7 propellant (1% 20 μ Al) at 200 psig

Test number	$(\alpha_c + \alpha_d)$, sec ⁻¹	f , cps	$-\alpha_d$, sec ⁻¹	f_d , cps	μ/ϵ
2028	25	7600	99	6700	0.35
2029	56	5600	73	4800	0.50
2030	58	4400	61	3800	0.58
2031	56	3500	55	3200	0.68
2032	44	2400	37	2250	0.73
2033	30	1530	34	1050	0.90
2041	34	8100	95	6550	0.34
2042	62	5700	74	4700	0.51
2043	60	4400	62	3825	0.60
2045	47	2500	42	1980	0.77
2046	32	1500	38	980	1.01

Table 6 A-10 propellant (0.4% 0.02 μ Al) at 200 psig

Test number	$(\alpha_c + \alpha_d)$, sec ⁻¹	f , cps	$-\alpha_d$, sec ⁻¹	f_d	μ/ϵ
2053	138	10,200	86	7900	0.47
2054	139	10,100	73	7800	0.45
2055	145	8,100	74	6300	0.58
2065	136	8,050	65	6000	0.54
2057	117	5,700	46	4400	0.61
2058	124	5,700	54	4300	0.76
2059	106	4,300	46	3600	0.76
2060	101	4,300	39	3450	0.70
2062	90	3,500	34	2750	0.76
2063	80	2,500	24	1600	0.89
2064	74	2,500	25	1610	0.85
2065	48	1,530	16	850	0.90
2066	42	1,350	15	710	0.91

Table 7 A-0 propellant (1% 15 μ Al) at 200 psig

Test number	$(\alpha_c + \alpha_d)$, sec ⁻¹	f , cps	$-\alpha_d$, sec ⁻¹	f_d , cps	μ/ϵ
1841	57	3600	40	3000	0.57
1851	59	3400	57	2800	0.73
1852	59	2550	63	1900	1.03
1853	48	1800	61	1200	1.30
1854	28	1480	58	850	1.27
1855	22	1180	53	650	1.37
1856	13	900	67	500	1.91
1860	8	690	88	400	2.99

Discussion

There are two sources of uncertainty in the treatment of the data which deserve emphasis. The conclusion that all of the propellant variations have the same response function-frequency curves is contingent upon the assumption that the damping in the burner is the same before and after burnout. Furthermore, the frequency of the oscillations during the growth and decay is different, and this difference is not considered in the use of Eq. (3). Accordingly, the consideration of these factors requires that the conclusion be qualified. The qualified conclusion then is that the response functions of the propellants are approximately the same, and the greatest effect of the additives is in producing damping, which one infers as being due to viscous damping caused by particles in the gas.

So that these data may be presented in a complete form, the tables include values of the decay constants and the frequencies that were observed during these decays. These data will permit other investigators to apply theory more rigorously should it ever become desirable to do so.

In retrospect, the authors made a poor choice of propellants, because a good way to evaluate particle damping calls for measuring the particles in the exhaust and then using this measurement with Eq. (5) to calculate the damping. This calculated damping then could be compared to the experi-

mental value. However, the presence of 2% copper chromite in these propellants produces particles in the exhaust which make such a technique difficult to use. Future tests will employ collection techniques and different propellants.

A rather puzzling aspect of these results is that they seem to contradict earlier observations. Although the authors conclude that, in this case, the suppressive action of the additives is probably due to particle damping, others have arrived at a different conclusion. (See, for example, Ref. 8, which states that "There exists a considerable body of experimental observations to indicate that the site of the action of suppressants such as aluminum and aluminum oxide is in the active layer at the burning surface, in contrast to the possibility that they might function as attenuators of sound in the gas phase," and also Ref. 10). Because the present results are not proven to be applicable universally, this discrepancy truly may represent a complicated natural phenomenon. The authors feel, however, that a searching re-examination of the previous observations is in order.

The proportionality between the aluminum concentration in the propellant and the suppression of oscillatory burning also does not generally agree with the previous reports of researchers in the field,⁹ but there are reasons for the disagreement. Most, if not all, previous results have been expressed in terms of the maximum amplitude of oscillation, which is the pertinent variable to the rocket designer. The maximum amplitude of the oscillations is, however, fixed by the nonlinear aspects of the phenomenon, and the present results were obtained while the oscillations were in the linear regime (i.e., the present growth and decay measurements were taken at sufficiently low amplitudes that neither is a function of amplitude). Furthermore, the concentrations of aluminum used in this program were much lower than those generally considered. At higher concentrations of aluminum, the proportional relationship must fail, because the combustion of the aluminum is altered drastically by the lack of sufficient oxidizer in the propellant. Also, the present results are for one propellant only, and the conclusions drawn from this limited experiment need not apply in all cases.

The conclusion that the additives damp the oscillations by means of particles in the gas can be valid only if the size of the aluminum oxide particles produced by combustion is a function of the initial particle size of the aluminum. Sehgal did not find such a dependence, but his variation of the aluminum particle size was small.⁷ Again, the assumption is made that the alumina particles are on the small side of the optimum damping diameter (smaller than 3 μ).

To explain why smaller aluminum might produce smaller alumina particles, one must resort to speculation concerning the combustion of the aluminum particles. One might picture each burning particle of aluminum as being surrounded by a halo of aluminum oxide droplets that grow as the particle is

Table 8 A-11 propellant (1% Al₂O₃) at 200 psig

Test number	$(\alpha_c + \alpha_d)$, sec ⁻¹	f , cps	α_d , sec ⁻¹	f_d , cps	μ/ϵ
2113	41	1,525	34	1100	1.06
2114	58	3,450	46	2800	0.65
2115	76	4,400	32	3900	0.53
2116	90	5,700	29	4950	0.45
2129	34	1,500	36	1110	1.01
2130	68	2,530	33	2150	0.86
2131	68	3,500	38	2600	0.65
2132	70	4,350	26	3750	0.48
2133	98	5,700	46	4800	0.54
2134	101	7,800	68	6600	0.47
2135	61	10,100	61	7800	0.26
2137	57	9,900	76	8200	0.29
2139	77	3,550	43	2900	0.73
2162	88	5,700	58	4800	0.55
2163	88	8,100	63	6700	0.40

consumed. If this picture is correct, the experimental results follow, inasmuch as larger initial aluminum particles would produce larger aluminum oxide combustion products that would damp the oscillations more effectively.

Thus, the 20 μ aluminum would produce the largest aluminum oxide droplets and show the largest damping, as the experimental results show. The exploratory firings employing 15 μ aluminum were not carried out at high frequencies, and so it is difficult to use them in the comparison. The damping of the 5 μ aluminum would be expected to show the experimentally observed intermediate value. Finally, one would expect the ultrafine aluminum to produce ultrafine alumina droplets that would not damp the oscillations significantly, and such were the experimental observations.

The fact that the ultrafine aluminum did not affect the oscillations at all suggests that the active site of the aluminum is not in the combustion zone. This is so because the large surface area of the ultrafine aluminum should maximize any chemical effects of the aluminum in the combustion zone were there any present. The lack of an effect clearly is not due to the low aluminum concentration, inasmuch as Fig. 2 shows that the influence of 0.5% coarser aluminum is easily measurable.

Speculation

It is possible to speculate extensively about the relation between the results of this program and the problem of oscillatory burning as it occurs in rocket motors. A feature that necessarily complicates the comparison is that the zone in which aluminum combustion takes place may be several inches thick. Thus in the combustion chamber there is a spatial distribution of particle sizes, with the combustion products being present at distances far from the burning surface and the original aluminum being predominant very near the propellant surface.

In the end burner, the damping due to the presence of the original aluminum particles scarcely would be noticed, because not only would they be a small fraction of the total particles present, but also they would be located near the velocity node, where the velocity oscillations would be small.

In an operational rocket motor where propellant forms the chamber walls and the aluminum reaction zone is three-dimensional, the original aluminum particles could contribute to the damping. The difference in the aluminum reaction zones might explain why finer aluminum is a better suppressant in a rocket motor,⁹ whereas the converse is true in the burner.

The scaling laws pertaining to the oscillatory combustion in a given motor are rather complicated. Therefore, the only speculation that will be made at this time is that, if other losses are neglected and the response function of the propellant is a weak function of frequency, longer motors that employ aluminized propellant should be more prone to show longitudinal oscillatory burning. This is because a longer motor has a lower first mode longitudinal frequency, and the damping for a given particle size decreases with frequency. That this conjecture may be reasonable is illustrated by Ref. 11, which illustrates a case where a high concentration of aluminum proved unable to eliminate low-frequency longitudinal oscillatory burning.

Because increasing pressure increases the size of the Al_2O_3 particles formed⁷ and decreases the driving of the combustion zone,^{2, 3} aluminum should seem to be much more effective at higher pressures. This can be true only if the damping mechanism is correct, and if the aluminum particles produced are smaller than the optimum diameter.

The general explanation for the damping of oscillations by particle-producing additives may be that it is the size of a particle in the gas and not its chemical composition which determines its efficiency in eliminating oscillatory burning. This might account for the hodgepodge of results that have accumulated with the firing of propellants containing different additives whose combustion product particle sizes and distributions are unknown.

Summary

By means of a comparison technique, it has been shown that the addition of aluminum or aluminum oxide to a propellant (PBAA-NH₄ClO₄) does not alter greatly the response function of the combustion zone. It further is shown that, under reasonable assumptions, the increased damping attributable to these additives may be explained by means of particle damping theory.

The additive damping is shown experimentally to increase with frequency, mean chamber pressure, aluminum concentration, and aluminum particle size.

References

- 1 McClure, F. T., Angelus, T. A., Berl, W. G., Freen, L., Jr., Hart, R. W., Landsbaum, E. M., Price, E. W., Shuey, H. M., and Summerfield, M., "A general review of our state of knowledge," First Report of the Working Group on Solid Propellant Combustion Instability, Appl. Phys. Lab., Johns Hopkins Univ., Rept. 371-1 (July 1960).
- 2 Strittmater, R., Watermeier, L., and Pfaff, S., "Virtual specific acoustic admittance measurements of burning solid propellant surfaces by a resonant tube technique," Ninth International Symposium on Combustion, Cornell Univ., Ithaca, N. Y. (August 31, 1962).
- 3 Horton, M. D. and Price, E. W., "Dynamic characteristic of solid propellant combustion," Ninth International Symposium on Combustion, Cornell Univ., Ithaca, N. Y. (August 31, 1962).
- 4 McClure, F. T., Hart, R. W., and Cantrell, R. H., "Interaction between sound and flow: stability of T-burners," AIAA J. 1, 586-590 (1963).
- 5 Bird, J. F., McClure, F. T., and Hart, R. W., "Acoustic instability in the transverse modes of solid propellant rockets," Appl. Phys. Lab. Rept. TG 335-8, Johns Hopkins Univ. (June 1961).
- 6 Epstein, P. A. and Carhart, R. R., "The absorption of sound in suspensions and emulsions, I: Water fog in air," J. Acoust. Soc. Am. 25, 553-565 (1953).
- 7 Sehgal, R., "An experimental investigation of a gas-particle system," Jet Propulsion Lab., Pasadena, Calif., Rept. 32-238 (March 16, 1962).
- 8 McClure, F. T., Angelus, T. A., Cheng, A., Cheung, H., Green, L., Jr., Hart, R. W., Nachbar, W., Price, E. W., Regan, N. W., Summerfield, M., Torda, T. P., and Watermeier, R., "Panel discussion on 'Solid propellant combustion instability,'" *Eighth Symposium (International) on Combustion* (Williams and Wilkins Co., Baltimore, Md., 1962), p. 908.
- 9 Price, E. W., "Review of experimental research on combustion instability of solid propellants," *Progress in Astronautics and Rocketry: Solid Propellant Rocket Research*, edited by M. Summerfield (Academic Press Inc., New York, 1960), Vol. 1, pp. 568-602.
- 10 Price, E. W., "Combustion instability in solid propellant rocket motors," *Astronaut. Acta* V, 63-72 (1959).
- 11 Dickinson, L. A. and Jackson, F., "Combustion in solid propellant rocket engines," *Fifth AGARD Combustion and Propulsion Colloquium, Braunschweig, Germany, April 9-13, 1962* (Pergamon Press, London, 1962), pp. E1-E14.