Assume each drag plate has an area A and mass/area density σ. If the balance beam is of length $2D$ and its mass is negligible, the moment of inertia is

$$I = 2\sigma AD^2 \tag{4}$$

Lt P_D be the drag pressure (force per unit area) on each plate. The torque due to the full area of the fixed plate will be

$$\tau_0 = AP_D D \tag{5}$$

To be able to measure the drag force to a fractional precision ϵ, the system should be capable of sensing a net torque of

$$\delta\tau = \epsilon\tau_0 = \epsilon AP_D D \tag{6}$$

Let the torsional constant of the pivot wire be K. The balance must be adjustable to the null position to within an angle

$$\delta\phi = \delta\tau / K = \epsilon AP_D D / K \tag{7}$$

To maximize sensitivity, $\delta\phi$ should be as large as possible.

The actual nulling of the balance, by adjustment of the shutter aperture a, is done by a control loop. This loop must have the capability of steering the balance to the null position with zero steady-state error in a time short enough to allow measurements to be completed quickly. One such loop has been designed that settles the balance to the null position to within 0.1% of the input step magnitude in a time equal to

$$T_{0.1\%} = 27.6\sqrt{I/K} \tag{8}$$

Based upon these computations, a study has demonstrated the feasibility of the experiment. It has shown that a balance can be designed that is sensitive enough to distinguish between the molecule surface interaction mechanisms of interest, yet is responsive enough to allow measurements to be made in a relatively short time.

Four interaction mechanisms were considered. Of these, the hardest to distinguish were the thermal re-emission and the total-absorption models. It was determined that measurement of the relative drag force with an accuracy of 0.1% would allow these interaction mechanisms to be distinguished, hence

$$\epsilon = 10^{-3} \tag{9}$$

was chosen as the required fractional measurement precision of the apparatus.

The study showed that this precision is possible in a balance capable of performing measurements at 5-min. intervals if the drag plates are made of aluminum foil with a surface mass density of $\sigma = 0.01$ gm/cm^2, and the balance arms are $D = 5$ cm long. A zero-gravity taut band suspension system would be used with a torsional constant of $K = 0.035$ dyne cm/rad.

A number of technical concerns remain. These include the following.

1) To prevent inteference from the cloud of emitted and scattered molecules surrounding the spacecraft, the experiment must be deployed at the end of a boom. This cloud of molecules must be studied and modeled to determine the required boom length and the seriousness of the interference.

2) The shutter will have to be mounted so that "fringing" of the atmospheric beam due to thermal motion does not change the effective area. The trapping of molecules between the shutter and drag plate will also have to be eliminated. If this is impractical, an alternative approach is to dispense with the shutters altogether and allow the area of the fixed plate to vary by other means, such as using two movable overlapping plates.

3) Sun and albedo shields must be designed to remove the effects of radiation pressure.

4) Means must be provided to prevent forces due to charge buildup. At the least, the entire balance system will have to be grounded.

5) A more optimal control loop must be designed.

6) The possibility of resonance between the balance beam and spacecraft attitude excursions must be eliminated.

7) Active temperature control may be necessary.

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Effect of HMX on the Combustion Response Function

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Introduction

NITRAMINE propellants are of interest for rocket applications because of their potential for improved energy and smokeless combustion products, and recent studies have been devoted to understanding and improving their steady-state combustion characteristics.[1-4]

Rocket motors are, in general, principally concerned with steady-state performance, although anomalous combustion behavior can be brought about by unsteady processes occurring in combustion chambers. The most prevalent anomalous behavior is combustion instability. It is of particular concern in smokeless propellants because the absence of particulate combustion products deprives the combustion chamber of significant stabilization. There is extensive literature on the stability characteristics of homogeneous, nitrocellulose (NC) based solid propellants and inert binder propellants utilizing ammonium perchlorate (AP) as the oxidizer (e.g., Refs. 5 and 6). But little or no systematic information is available on the influence of nitramine oxidizers such as HMX (cyclotetramethylenetetranitramine) on driving propellant combustion instability. A series of T-burner combustion instability experiments were, therefore, carried out, the purpose of which was to determine the effect of replacing AP with HMX on the response function of inert binder (hydroxyterminated polybutadiene—HTPB) propellants, and of HMX addition on the response function of NC propellants.

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Propellant Selection

Standard thermochemical calculations and burning rate model calculations were performed to provide selection of the propellant formulations for the comparison experiments. In making these comparisons, it was desired to maintain propellant energy and burning rate reasonably constant within each group. Although differences can be corrected in the course of interpreting the response function, it was considered that excessive differences would render the comparisons less meaningful due to mechanistic bias.

AP and HMX produce different thermochemical effects in HTPB binder because AP is an oxidizer whereas HMX is an energetic monopropellant. HMX propellants tend to be low burning rate propellants, but significant burning rate control is available in AP propellants through particle size adjustment. Tradeoff study produced the two groups of selected HTPB propellants listed in Table 1: a low burning rate group (XA) and a high burning rate group (XB). It is difficult to match AP propellant burning rates with HMX alone, so the burning rate of formulation XA-3 is lower than desired for its group although its energy level is adequate. The two mixed oxidizer propellants are more closely related to their AP analogs in burning rate (including pressure exponent) and energy.

It was found that the addition of meaningful quantities of HMX to an inert-plasticized NC binder produced considerable increases in propellant energy. Use of a relatively stable energetic plasticizer (trimethylolethanetrinitrate—TMETN) reduced the impact of HMX addition on propellant energy, and was considered more acceptable for research purposes than nitroglycerine. The resulting propellants comprise the third group (XC) listed in Table 1. There are two active binder propellants which do not contain HMX: XC-6 and XC-8. Propellant XC-7 consists of 40% fine HMX in the XC-6 binder formation. Therefore, propellants XC-6 and XC-7 maintain a constant binder, but at a disadvantage to the maintenance of energy and burning rate. Also, theremochemical calculations predict a small but finite amount of free carbon in the products of XC-6. Propellant XC-8 adjusts the binder ingredients in order to approach the energy and burn rate of the XC-7 propellant containing HMX. The essential difference between XC-8 and XC-7 is that nitrocellulose and TMETN, the energetic components of the binder, have been substituted for HMX. No free carbon is predicted in the products of XC-7 or XC-8. Relative to the HTPB series, all of these propellants are of lower energy and burn rate.

Experimental Results

Stability tests were carried out in 6.35-cm (2½-in.) diameter (i.d.) T-burners coupled directly to a surge tank. The propellant configuration used was a 0.95-cm (⅜-in.) thick disk. Data were obtained using the growth-decay technique.[7] Tests were conducted at nominal frequencies of 500, 900, and 1900 Hz and at pressures of 3.5 MPa (500 psi) and 7 MPa (1000 psi). For each propellant, two or more tests were performed at each condition.

HTPB Binder Propellants

The results for the low-rate and high-rate HTPB propellants are given in Figs. 1 and 2, respectively. The results are plotted as the sum of the measured growth and decay coefficients vs frequency. The propellants were all relatively stable in that the measured growth coefficients exceeded the decay coefficients only for the two high-rate propellants at the 1900 Hz, 3.5 MPa test condition. Such behavior may subject the absolute results to criticism, but the relative results are considered valid.

The low-rate XA-1 propellant was the weaker acoustic driver of the two propellants which did not contain HMX. The low rate results from the use of coarser particle sizes. Its results appear to be relatively independent of pressure. The minimum between 500 and 1800 Hz is considered real because only one test out of seven conducted at 900 Hz produced measurable acoustic driving.

The two low-rate propellants containing HMX (XA-2 and XA-3) exhibited unusual results. At 500 Hz, the pressure traces showed an immediate growth of oscillations following ignition to amplitudes of about 2% of the mean and then a slow decay over the duration of the burn. At 1900 Hz, the tests exhibited no oscillations at all. At 900 Hz, the 500 psi tests were like those at 500 Hz and the 1000 psi tests were like those at 1900 Hz.

Post-test examination of the XA-3 tests showed the T-burner to be full of a layered carbonaceous char. In the 1900 Hz tests, this char appeared to have been pulverized. For the lower HMX concentration XA-2 propellant, the char was less extensive, merely coating the wall of the T-burners rather than filling the interior. The char is presumed to be due to the fuel-rich nature of the two low-rate propellants containing HMX. Discovery of the char was somewhat supprising because it is not predicted by equilibrium thermochemistry. Another consequence of the char was that the burning rate was about 20% lower than expected. In any event, any contribution of HMX to stabilizing the combustion driving in these tests could not be distinguished from the mechanical suppression produced by the char.

The high-rate propellant data in Fig. 2 is more conclusive as to the role of HMX. These propellants did not produce char. Both XB-4 and XB-5 showed clear pressure and frequency effects, increasing in driving strength with decreasing pressure and increasing frequency. The XB-5 HMX-containing

Table 1 Propellant formulations for T-burner tests

	XA-1	XA-2	XA-3	XB-4	XB-5	XC-6	XC-7	XC-8
Wt. %								
AP (9 μm)	...	...	...	41.25	31.25	...	...	...
AP (50 μm)	40.00	20.00	...	...	...	...	...	...
AP (90 μm)	...	...	...	41.25	31.25	...	...	...
AP (200 μm)	40.00	20.00	...	...	...	...	...	...
HMX (4 μm)	...	20.00	40.00	...	22.50	...	40.00	...
HMX (15 μm)	...	20.00	40.00	...	...	...	...	...
R-45/HTPB	20.00	20.00	20.00	17.50	15.00	...	...	...
Nitrocellulose	...	...	...	...	...	10.00	5.99	35.00
TMETN	...	...	...	...	...	60.88	36.53	48.60
Polycaprolactone (PCP)	...	...	...	...	...	28.97	17.39	16.20
Stabilizers	...	...	...	...	...	0.15	0.09	0.20
Energy parameter $(T_F/M)^{1/2}$, $(\mathrm{K/mol})^{1/2}$	10.34	10.30	10.32	10.70	10.77	7.74	9.38	8.88
Burn rate @ 7 MPa, (cm/s)	0.66	0.53	0.41	1.22	1.09	0.28	0.38	0.43
Burn rate pressure exponent n	0.50	0.39	0.71	0.43	0.32	0.91	0.82	0.82

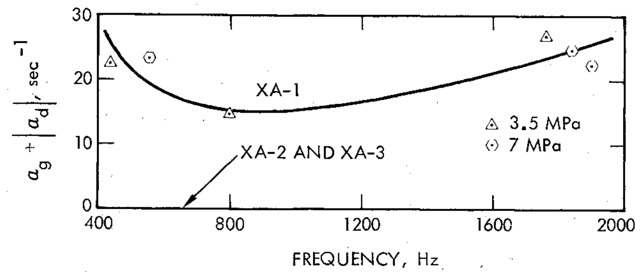

Fig. 1 T-burner results for low-rate HTPB propellants.

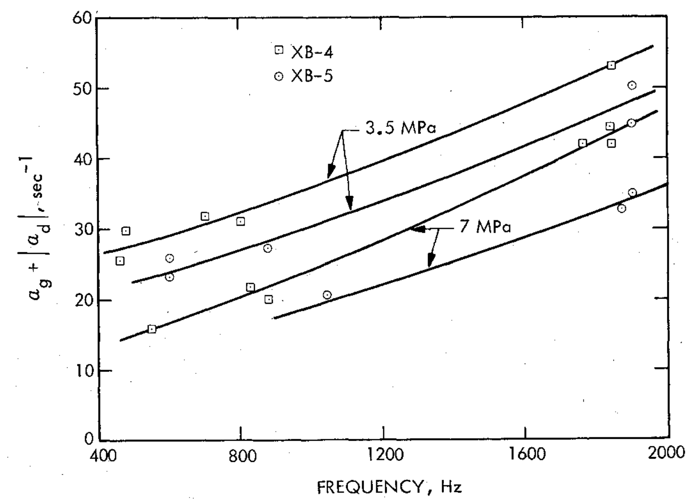

Fig. 2 T-burner results for high-rate HTPB propellants.

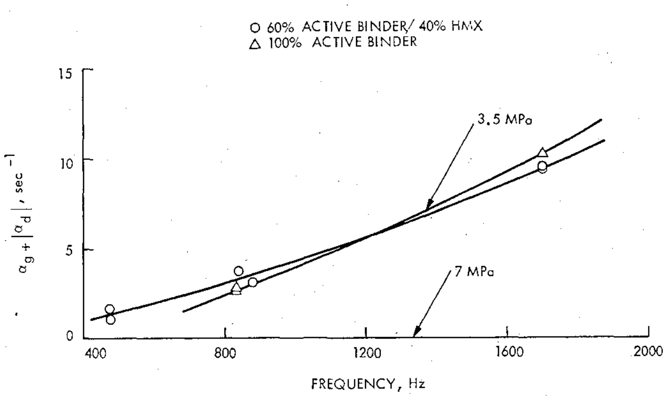

Fig. 3 T-burner results for active binder propellants.

propellant would not drive oscillations at all the 7 MPa-500 Hz test condition, and its data at 3.5 and 7 MPa fall below the respective data for the all-AP oxidizer XB-4 propellant. The measured damping coefficients at each frequency were about equal for the two propellants, indicating that the differences in acoustic driving are real.

Active Binder Propellants

The test results for the XC-7 and XC-8 propellants are given in Fig. 3. Unfortunately XC-6 produced an excessive amount of carbonaceous ash in the T-burner at all pressures tested, so that meaningful results could not be obtained. The ash filled the interior of the T-burner, far in excess of what would be expected from a predicted weight concentration of 0.4% of products. The ash material was also physically different from the layered char residues produced by the HMX/HTPB propellant.

The XC-7 and XC-8 propellants were both relatively stable in that no oscillations were driven over the frequency range tested at 7 MPa, and the measured growth coefficients at 3.5 MPa were quite small, the net growth coefficient exceeding the decay coefficient only at the 1900 Hz test frequency (and then only slightly). Post-test examination of hardware showed that the burning had been comparatively clean, so the measured stability is considered real. The results are qualitatively similar to the HTPB propellant results in that the driving was greater at 3.5 MPa than at 7 MPa and increased with increasing frequency.

The stability characteristics of XC-7 and XC-8 are nearly identical over the conditions tested. It appears to make very little difference whether or not the active binder contains HMX, as long as the energy and burn rate remain fairly constant. The active ingredients in these propellants are nitramine and nitrate ester compounds. These compounds have similar combustion chemistries, so that the similar combustion characteristics of these propellants are not surprising.

Conclusions

Over the pressure and frequency range tested (3.5-7 MPa, 500-2000 Hz) and for propellants having equivalent energy and burn rate, it is concluded that HMX produces less pressure-coupled acoustic driving than AP and that it is equivalent to NC/TMETN. Although ash produced by several of the propellants tested undoubtedly provided mechanical suppression, results from relatively clean-burning propellants allow the drawing of these conclusions. Formation of the carbonaceous combustion products indicates that binder decomposition does not follow equilibrium thermochemistry, and that this is aggravated by fuel-richness or the absence of AP.

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