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Development of a Laboratory-Scale System for Hybrid Rocket Motor Testing

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The results of efforts to establish a laboratory-scale setup for hot-fire testing of a modular hybrid rocket motor and experimental evaluation of the effect of several additives on the regression rates of hydroxyl-terminated–polybutadiene-based fuels are presented. Supercharged nitrous oxide was used as the oxidizer in all tests. The main objectives of the reported test-program phase were the design and buildup of the experimental facility and to sort out, by hot-fire tests, various fuel compositions with respect to the fuel regression rate and combustion–extinction ability at oxidizer shutoff. The cartridge-loaded fuel grains had an initial circular port diameter of 42 mm, a length of 400 mm, and a web thickness of 15 mm. Five fuel composition families with various additive contents of fine ammonium perchlorate, polystyrene, and a burning-rate catalyst were tested. The fuel regression rate increased with the increase in the ammonium perchlorate portion, but combustion extinguishment was not possible with high ammonium perchlorate content. A significant enhancement of the regression rate of up to 3.5 $\mathrm{mm/s}$ at an average oxidizer mass flux of about 140 $\mathrm{kg/m^2 \cdot s}$ (0.2 $\mathrm{lbm/in^2 \cdot s}$) was obtained with the addition of both fine ammonium perchlorate and large particles of polystyrene. Full combustion extinguishment and multipulse operation with an insignificant effect on the regression rate was demonstrated by the use of large particles of polystyrene additive and no addition of ammonium perchlorate.

I. Introduction

A HYBRID rocket motor is a chemical propulsion system in which the fuel and oxidizer are separately stored in different physical phases. Usually, a solid fuel and a liquid or gaseous oxidizer are used. During motor operation, the oxidizer is injected into a combustion chamber that contains the solid fuel grain. The combustion takes place in the turbulent boundary layer formed over the solid surface. In recent years, there has been an increased global interest in hybrid propulsion inspired by the success of projects, such as the privately funded SpaceShip One that used a hybrid rocket motor for propulsion into a high-altitude trajectory, and sounding rocket programs.

Hybrid propulsion systems offer several advantages over other chemical propulsion systems, such as greater safety, good storability, on–off and throttling capability, improved reliability, lower production cost, and a high potential for environmentally friendly exhaust products. Moreover, the addition of energetic ingredients in the solid fuel greatly increases the motor performance. Major drawbacks, however, include the low regression rate of conventional solid fuels, a lower system-density specific impulse, combustion efficiency problems, potentially shifting performance during steady-state operation and throttling, and reduced motor mass fraction. In addition, in some cases, combustion instability with pressure oscillations has been experienced.

Numerous theoretical and experimental studies, conducted worldwide, have approached the distinct features of hybrid rocket propulsion. Several concepts and methods, reported in the literature, have been proposed for increasing the fuel regression rate, which is a very important parameter in the design of hybrid motors. Pure (neat) commonly used polymeric fuels [e.g., crosslinked hydroxyl-terminated polybutadiene (HTPB)] exhibit low regression rates (around 1 $\mathrm{mm/s}$) with various oxidizers, such as liquid oxygen (LOX), gaseous oxygen (GOX), nitrogen–oxygen mixtures, nitrous oxide (N_2O), and hydrogen peroxide [1–13].

The effect of the addition of a small amount of solid oxidizer particles, mainly ammonium perchlorate (AP), in the solid fuel has been tested by several researchers. Obviously, such an inclusion may impair the safety advantage of hybrid motors. George et al. [4] used HTPB-based fuel grains with the addition of 7.55% AP in tests with GOX in small hybrid motors. The small increase in regression rates, as compared with pure HTPB, was found at oxidizer mass fluxes higher than about 100 $\mathrm{kg/m^2 \cdot s}$. It was postulated that this enhancement is caused by an additional heat source near the fuel surface resulting from the reaction of fuel vapor, AP decomposition products, and bulk turbulent eddy transport of oxygen across the flame front at a higher mass flux condition. Combustion extinguishment was achieved by nitrogen purge immediately after oxygen supply cutoff. Frederick et al. [8] systematically investigated the increase in the regression rate of HTPB-based fuels burning with GOX resulting from adding AP and a catalyst. A significant regression-rate augmentation of 447% compared with pure HTPB (the highest in their study) was obtained by adding 27.5% AP, with a 2-μ-diam particle size, combined with 2.5% ferric oxide (FO) as a catalyst. It was reported that, under the conditions tested, all formulations (with AP content ranging from 25 to 30%) extinguished with minor residual smoking when the GOX flow was stopped.

The effects of including metal and metal-compound particles in HTPB-based fuel grains, aimed at performance gains and enhanced regression rates, has been extensively investigated. It was expected that the inclusion of these energetic additives, fine aluminum particles in particular, would substantially increase the fuel regression rate due to higher thermal conductivity, reduced effective specific heat and decomposition energy, enhanced thermal radiation, and increased on-surface and near-surface heat release. Strand et al. [2] tested HTPB-based grains containing particulates of 40% aluminum

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and 30% coal and reported a small increase in regression rate. The small effect on the regression rate of 19.67% aluminum additive in HTPB grains was also reported by George et al. [4]. However, they obtained a regression-rate enhancement of more than 100% at and above an oxidizer mass flux of 30 $\mathrm{g/cm^2 \cdot s}$ for the combined effect of adding 6.15% AP and 18.46% aluminum in the HTPB fuel. Yi et al. [10] suggested the catalyzation of the decomposition/degradation of HTPB by metallic ions, released from metal compounds (mainly cupric oxide and copper chromite), added into the HTPB-based fuel. The firing tests with a mixture of GOX and nitrogen showed only a maximum increase of approximately 10% in the fuel regression rate for an addition of about 10% cupric oxide.

Chiaverini et al. [6,7] conducted test firings of GOX with HTPB-based fuel grains containing either carbon black (CB) or up to 20% of ultrafine activated aluminum powder (UFAL) with a mean particle size in the range of 0.05 to 0.10 μ. They reported an increase by 70% in the fuel mass flux, which translates into around a 45% increase in the regression rate with an addition of 20% UFAL with respect to pure HTPB. That increase was attributed to higher heat release near the fuel surface and enhanced thermal radiation to the surface. The addition of CB powder had no noticeable effect on regression rate. A comprehensive survey of the effect of various additives in solid fuels for use in hybrid motors, including their influence on the regression rates, was conducted by Risha et al. [14]. Recently, the addition of metal hydrides to solid fuels, HTPB and paraffins in particular, was strongly promoted by Calabro et al. [15] They reported a significant increase in the regression rate by the inclusion of aluminum hydride (AlH_3, alane) in pure HTPB fuel.

The use of paraffin-based hybrid rocket fuels has been extensively studied in the past 15 years by research teams at Stanford University and NASA Ames Research Center [16–19]. These liquefying fuels form a hydrodynamically unstable liquid layer over their surface, and the entrainment of droplets from the liquid–gas interface yields regression rates that are three to four times higher than those obtained with the classical hybrid HTPB fuel using GOX as an oxidizer. The concept of blended fuels, which contain a mixture of two or more polymers, was also suggested in the past. For example, in a hybrid technology identification program aimed at the replacement of the space shuttle solid-propellant boosters with hybrid motors, a fuel composition containing HTPB, glycidyl azide polymer, and zinc was proposed [20].

The effect of the oxidizer injection characteristics on the fuel regression rate, at the forward part of the hybrid motor in particular, was studied and emphasized by Carmicino and Russo Sorge [21,22]. A unique vortex hybrid rocket engine, in which a swirl GOX injector (installed between the aft end of the HTPB grain and the nozzle inlet) generates a counterflowing vortex flowfield, was tested by Knuth et al. [23]. The highly increased heat flux to the fuel surface resulted in measured average regression rates up to seven times higher (1.19 mm/s) than those in similar classical hybrids using LOX and HTPB, as reported by a correlation in [1].

A perennial research program aimed at the acquisition of know how and establishment of a technological infrastructure for the testing and development of hybrid rocket motors was initiated in 2007 at the Manor-Advanced Defense Technologies Division of RAFAEL-Advanced Defense Systems, Ltd., Israel. This paper presents the activities conducted in the first phase of the program. The main objectives of this program phase were twofold: 1) design, buildup, and testing of a laboratory-scale and modular hybrid rocket–motor experimental facility; and 2) conduction of firing tests of small hybrid motors with a selected liquid oxidizer and various fuel compositions, with the focus on regression-rate enhancement and capability of combustion extinction at oxidizer flow shutoff.

II. Experimental Setup

A. Motor Configuration

The design of the test motor was performed with considerations of simplicity, low cost, and modularity in terms of the possibility of testing various fuel-grain compositions and chamber segment lengths, oxidizer injectors, instrumentation devices, and nozzle materials at a wide range of combustion-pressure levels. The motor and oxidizer feeding system were both placed on movable carts and connected between each other by flexible and detachable tubing. The motor assembly, schematically shown in Fig. 1, consisted of an injector head, a gaseous methane–oxygen igniter, a precombustion chamber, a combustion chamber containing the fuel grain, an aft combustion chamber, and a nozzle subassembly. The metallic motor parts were manufactured from a standard low-carbon steel. The precombustion and aft combustion sections were lined with silica–phenolic sleeves for thermal insulation.

The fuel grains had an initial circular port diameter of 42 mm, a length of 400 mm, and a web thickness of 15 mm. They were first cast into standard 3 in. polyvinyl chloride (PVC) tubes and, later, due to PVC residue burning at the end of the tests, into machined 2.7-mm-thick steel tubes. The loaded tubes were placed, freestanding (cartridge loaded), in the motor combustion chamber before test firings.

B. Oxidizer Feed System

The oxidizer feed system was designed for a maximum mass flow rate of 1 kg/s of liquid N_2O at room temperature. The system was supercharged up to 7 MPa by pressurized nitrogen that was supplied by a nitrogen bottle at a nominal pressure of 15 to 20 MPa and regulated to the feed pressure. The nitrogen pressurant was introduced into the N_2O tank through a port at the top of the tank, and the liquid N_2O was extracted by a siphon action from a separate port via a dip tube extending to the bottom of the tank. Two 40 liter oxidizer tanks were assembled on top of a mobile cart, and the fluid was delivered by a flexible $\frac{3}{4}$-in.-diam tube to the motor, which was placed in a separate test cell.

The oxidizer flow rate was controlled by a calibrated manual needle valve. The selection of the proper injection head for the testing was determined by the objectives of obtaining as fine a spray as possible and a low pressure drop across the injector. Three different types of injectors were considered for the tests:

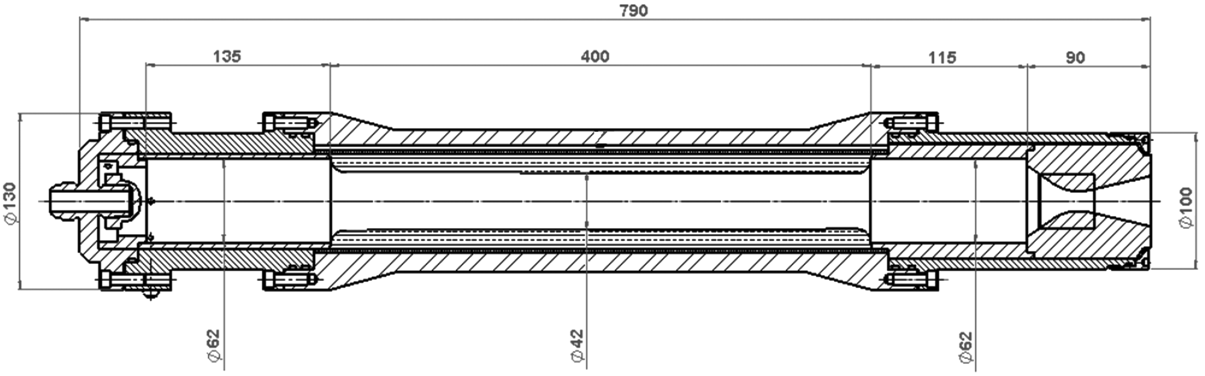


Fig. 1 Schematic motor layout with main dimensions (all in mm).

1) The first type was a self-impinging multidoublet injector with 42 orifices arranged in two concentric circles on the injector face. The design took into consideration the jet velocity, orifice diameter, and parameters of the liquid oxidizer. An impingement angle of 60° with an impingement distance of 4.5 mm was selected.

2) The second type was the impingement-on-pin injector, made by BETE Fog Nozzle, Inc. In this injector type, a laminar jet impinged on a target pin, generating fine fog. According to the manufacturer, it would produce a high percentage of droplets, in the 25 to 400 μ range, with water in a cone-shaped fog-spray pattern, with a spray angle of 90°. Six such injectors were welded to an injector plate.

3) The third type was the FogJet model FF fine-spray-nozzles injector, made by Spraying Systems Company. This was a one-piece multinozzle shower head that, according to the manufacturer, would produce a dense full-cone fogging spray of small-sized drops.

A front-face view of the three types of injectors that were tested is shown in Fig. 2. All injector types were subjected to cold-flow experiments with water for comparative visual evaluation of the issuing sprays, as observed in video-recording images, at liquid mass flow rates ranging from 0.3 to 0.8 kg/s. A pressure drop of 0.5 MPa was obtained for all injectors tested. The impingement-on-pin injectors exhibited the best results in terms of spray-pattern fineness, creating a mist of tiny droplets. Therefore, this injector type was selected for the hot-fire testing.

To clear the combustion chamber and feed lines of any leftover oxidizer, a purging system was installed using nitrogen gas. The oxidizer feed line and the motor were purged at the end of each hot-fire test.

C. Ignition System

Motor ignition was performed by a gaseous methane–oxygen igniter. Pressurized methane and oxygen, stored in standard gas bottles on the oxidizer cart, were injected into the fore end of the precombustion chamber and ignited by a standard car engine spark plug. The methane and oxygen mass flow rates were regulated by choked nozzles placed at the gas inlets to the motor. The upstream pressure in both gas lines was maintained at a constant level, using pressure regulators. A cross section of the ignition system setup is schematically shown in Fig. 3.

D. Nozzle Subassembly

Initial firing tests were conducted with a single-piece nozzle made of medium-density graphite. In later tests, a pyrolithic graphite nozzle throat insert (composed of three to four rings) or a tungsten insert were used to minimize nozzle throat erosion.

E. Instrumentation

The oxidizer mass flow and density were measured by a Coriolis mass flow rate gage model RFT3739 type D, made by Micro Motion, Inc. This method was chosen among numerous flow-metering methods because it could measure mass flow directly without the knowledge of fluid density. The gage also measured fluid density. Three pressure transducers made by Rosemount, Inc., were placed at different locations along the main oxidizer line. Two additional Rosemount pressure transducers were placed: one at the front end and the other at the aft end of the motor. Except for the oxidizer flow, which was controlled by a manual needle valve, all valves were pneumatically or electronically controlled. Motor thrust measurements were conducted using a load cell made by Lebow Company. The control and measuring devices were all connected to a control unit and activated by a preprogrammed sequence. Measured data were sampled at 1000 Hz. The instrumentation diagram is schematically shown in Fig. 4.

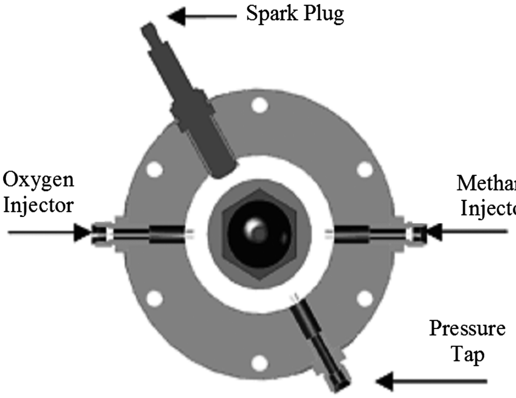


Fig. 3 Schematic cross section of ignition system setup.

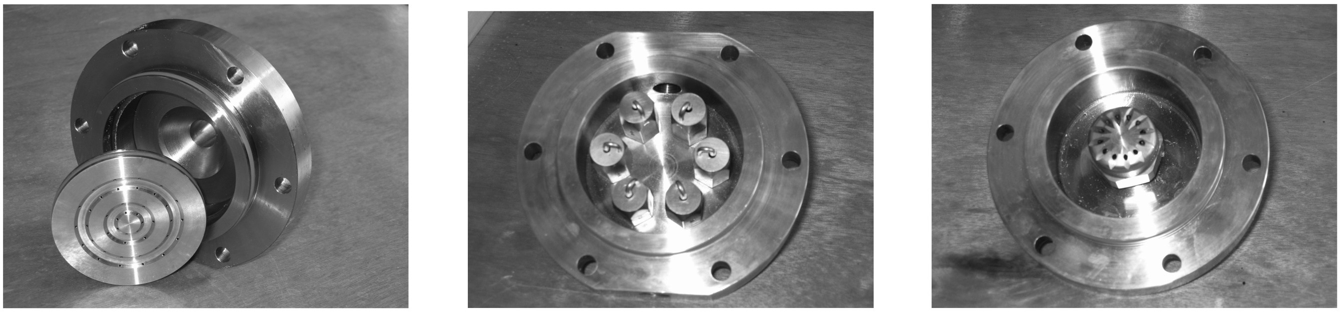
III. Oxidizer and Solid Fuels Tested

N_2O was selected as the oxidizer for this phase of the program because it met the following requirements:

1) It is safe and easy to handle and transfer.
2) It is inexpensive and commercially available.
3) It is nontoxic.
4) It is storable at room temperature.
5) It can be fed to the motor at high mass fluxes.

In addition, it is self pressurizing. At room temperature, N_2O is still below its critical point; hence, it is relatively simple to pressurize in the liquid phase. Moreover, the good record of using N_2O in the SpaceShip One project (before the recently reported accident) was also being considered.

Two approaches to the formulation of the tested fuel compositions and their combination were pursued. The first approach was the examination of a pothole or cratering concept, in which particles of a material with a decomposition or vaporization temperature much lower than that of HTPB are incorporated into the fuel. It has been assumed that potholes or craters created on the fuel surface in the combustion process would cause an effective surface regression rate that is significantly higher than that of pure HTPB. Polystyrene (PS) polymer (C_8H_8) was chosen as the test case. Fuel-rich propellants based on mixtures of HTPB and PS as fuels and AP as an oxidizer and burning-rate catalyst were reported to exhibit high burning rates in test firings of laboratory-scale rocket motors [24]. Thermal analysis of cured HTPB polymer shows a two-stage decomposition process



Multidoublet impingement **Six impingement-on-pin injectors** **FogJet shower head**

Fig. 2 Tested injector heads.

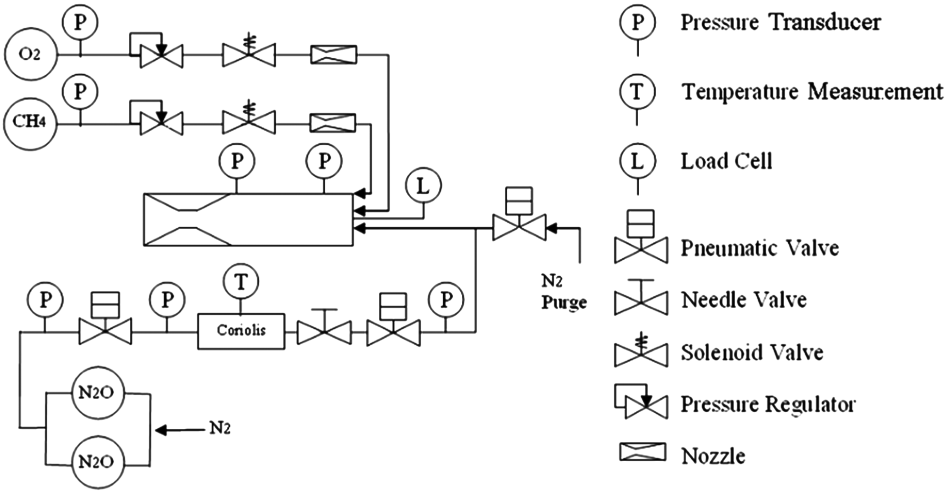


Fig. 4 Schematic instrumentation diagram of the test setup.

on heating [25]. The first stage, which is net exothermic, starts at about 320°C, and it is primarily depolymerization, cross linking, and cyclization. The second stage, which is net endothermic, takes place at a much higher temperature and primarily involves decomposition of the cyclized products [25]. Thermal analysis of PS shows the start of decomposition and weight loss at about 200°C. A melting point of 240°C for PS is mentioned in the database literature. According to Liljegren [24], larger PS particles partially decompose into styrene monomer at a relatively low temperature on the propellant surface, and that causes the particles to be ejected into the combustion-gas stream. It was therefore postulated in this study that a pothole effect may take place by the inclusion of PS particles in HTPB-based fuels and cause higher regression rates.

The second approach examined was the addition of fine AP particles and a burning-rate catalyst in the HTPB fuel, in the fashion proposed by Frederick et al. [8], but with a different oxidizer: N_2O in this case.

Five different composition families of HTPB-based solid fuels were tested with the goal of obtaining formulations with a relatively high regression rate and the ability of combustion extinction at oxidizer shutoff. All compositions contained a small amount (less than 1 wt %) of CB as an opacifying agent. Also, a conventional solid-propellant burning-rate catalyst, fine-particle FO, or Butacene was added to all formulations to enhance the regression rate. Trimethylol propane was also added to improve the mechanical properties of the fuel grains. Test firings with fuel grains made of HTPB with no AP and no PS additives were not conducted, but reference was made to the experimental regression-rate curves obtained by Doran et al., who tested an N_2O/pure-HTPB hybrid motor at various values of oxidizer mass flux [12]. Performance values for the N_2O/pure-HTPB hybrid motor can be found in the literature [1,5,26].

Table 1 presents the range of major additive content in the tested composition families, as well as the corresponding ranges of average regression rate r_{av}, actual characteristic velocity c^*_{ac}, and c^* efficiency η_{c^*} obtained in the tests. The value of η_{c^*} is defined as the ratio of c^*_{ac} to the theoretical c^* as calculated by the NASA CEA (chemical equilibrium with applications) thermochemical code for the particular test conditions.

IV. Test Results

A qualitative testing approach was adopted for the first phase of the test program, with the goal of achieving the objectives defined in Sec. I. It was intended for the performance of the experimental setup to be checked out and the suitable-in-principle fuel compositions to be screened out, meeting the objective requirements by the previously mentioned approaches. An iterative calculation procedure was implemented before each test to determine oxidizer valve position and nozzle throat diameter, in order to obtain a combustion pressure of about 5 MPa at a constant oxidizer feed pressure of 7 MPa. Oxidizer mass flux values varied in the range of 100 to 400 $\mathrm{kg/m^2 \cdot s}$ (0.142 to 0.569 $\mathrm{lbm/in^2 \cdot s}$), yielding in most cases an oxidizer-to-fuel ratio higher than the stoichiometric.

A space-time-averaging approach was used for estimation of the fuel regression rate. First, for the circular port in this case, it was reasonably assumed that the regression rate was constant around the circumference of the port along the fuel grain. Second, the fuel mass consumption during the test was assumed to occur evenly over the entire port surface area. Pretest and posttest measurement of the port diameter at the grain ends revealed no noticeable differences in regression rates. Also, no fuel surface regression was observed on the endface surfaces of the grain. The average change in port radius that occurred during the test was determined from measurements of the initial and final masses of the fuel grain, as well as the precise values of grain length and fuel density. The burning time for a test was determined as the difference in time between the intersections of a constant-pressure line at 50% of the maximum pressure, with the pressure-time trace at pressure rise and tailoff. Altogether, 26 hot-fire tests were conducted: six with composition family 1 and five with each of the other fuel composition families. Burning time in the tests ranged from 4 to 15 s. Combustion efficiency ranged from 87 to 97%, depending on the fuel composition (see Table 1). No attempt was made to check test-to-test variability or derive standard deviation values and regression-rate laws, due to the small number of tests.

A generalized uncertainty analysis estimate was performed using the second-power equation in the single-sample-experiments method, according to Kline and McClintock [27]. The uncertainty interval in the calculated regression rates is based on the

Table 1 Tested HTPB-based fuel composition families and test results

Tested fuel composition family	AP additive 2.5 μ, wt %	PS additive, wt %	PS particle size, μ	c^*_{ac}, m/s	η_{c^*}	r_{av}, mm/s
1	20–40	20–40	10–100 (small)	1450–1490	0.87–0.96	1.0–1.5
2	20–40	20–40	400–800 (large)	1350–1360	0.89–0.95	2.0–3.5
3	20–40	——	——	1500–1510	0.96–0.97	1.2–1.4
4	——	20–40	400–800 (large)	1360–1400	0.90–0.92	1.0–1.2
5	10–20	40–60	100–400 (medium)	1340–1410	0.87–0.89	0.9–1.1

Table 2 Measurement uncertainties for regression-rate calculations

Measured Variable	Uncertainty	Units
Initial propellant mass	0.1	g
Final propellant mass	0.1	g
Initial port diameter	0.3	mm
Fuel-grain length	1.0	mm
Fuel-grain density	0.01	g/cm^3
Test burning time	0.1	s

measurement uncertainties for each of the independent variables, used to determine the regression rate in each test. These uncertainties, with odds of 20 to 1, are presented in Table 2. For a typical set of measured variables in a hot-fire test lasting 4 s with a fuel grain of family 4, the calculated regression rate was 1.07 mm/s ± 3.7%.

A. Fuel Composition Family 1:

This composition family was the starting point of the test program. It was based on testing HTPB–PS blended fuels with the addition of AP. The first series of tests was aimed at a runup and check of the test system and the testing procedure. Test results did not show a high regression rate as anticipated. The regression rates obtained were between 1 and 1.5 mm/s at 5 MPa and an average oxidizer flux range of 100 to 300 kg/m$^2 \cdot$ s (0.142 to 0.426 lbm/in$^2 \cdot$ s), slightly higher than those obtained by Doran et al. [12] with pure HTPB polymer fuel: 0.92 to 1.22 mm/s for N_2O mass flux ranging from 100 to 220 kg/m^2·s. The fuel did not extinguish at oxidizer flow cutoff. Significant smoldering with negligible thrust level continued for several minutes. Therefore, regression rates were calculated from full web burning tests only. The limited testing of an extruded PS fuel grain with an N_2O oxidizer in a subscale test facility by Doran et al. [12] should be noted. They reported an average regression rate of 0.82 mm/s at 4.2 MPa and an oxidizer flux of 39 kg/m$^2 \cdot$ s (0.0555 lbm/in$^2 \cdot$ s).

Figure 5 shows combustion pressure and thrust versus time traces of a motor test firing with a fuel grain of composition family 1. In this test, significant smoldering of the remaining fuel-grain residue followed the oxidizer flow cutoff. The sudden decrease in the pressure and thrust traces at about 4 s into the firing was caused by cracks in the medium-density-graphite nozzle throat insert, followed by small erosion, as revealed after the test. The low-frequency oscillations with peak-to-peak amplitudes of less than ±5%, shown in Fig. 5, are characteristic for the pressure versus time traces obtained in hot-fire tests with fuel composition families 1, 3, 4, and 5. Such low-frequency combustion instability encountered in hybrid motor testing has been reported by many researchers [1,5,8,12]. It is generally believed to be an oxidizer feed system-induced instability, caused mainly by one- or two-phase flow oscillations in the feed lines, sometimes combined with insufficient isolation from motor combustion processes (e.g., use of unchoked injector orifices), which is the case described here. In tests with fuel composition family 2, low-frequency pressure oscillations with a peak-to-peak amplitude of up to ±20% were obtained, which suggests that the feed system-induced instability was enhanced by the ejection and combustion of the large PS particles. Growth of the pressure oscillations was not observed in any test.

B. Fuel Composition Family 2:

In these formulations, an increase in the particle size of PS, as compared with composition family 1, was attempted in order to achieve a higher regression rate. Indeed, a high regression rate of up to 3.5 mm/s at 5.5 MPa and an approximately 140 kg/m$^2 \cdot$ s (0.2 lbm/in$^2 \cdot$ s) average oxidizer flux level was obtained. However, it was not possible to extinguish the fuel burning at oxidizer flow cutoff. Strand-burner tests of the fuel exhibited self-sustained combustion. Obviously, the inclusion of larger PS particles made a difference in regression rates, possibly by the previously mentioned mechanism in which the partially decomposed particles are ejected into the gas stream, creating a pothole effect. It is believed, in addition, that the effective mass fraction of AP on and near the fuel surface is increased due to the PS particle ejection that, in turn, contributes to regression-rate increase and self-sustained combustion at oxidizer flow shutoff.

C. Fuel Composition Family 3:

PS was removed from this composition family to obtain fuel combustion extinguishment and high fuel regression rates, in view of the test results reported in [8]. A fuel regression-rate range and fuel residue burning at oxidizer flow termination, similar to those acquired with composition family 1, were obtained. For about the same fuel formulations, the test results attained by Frederick et al. [8] could not be duplicated by replacing GOX with N_2O as the oxidizer. For example, at a 5.2 MPa chamber pressure and an oxidizer flux of 197 kg/m^2·s, an average fuel regression rate of 1.24 mm/s was obtained for 25% AP and 2.5% FO additions, as compared with

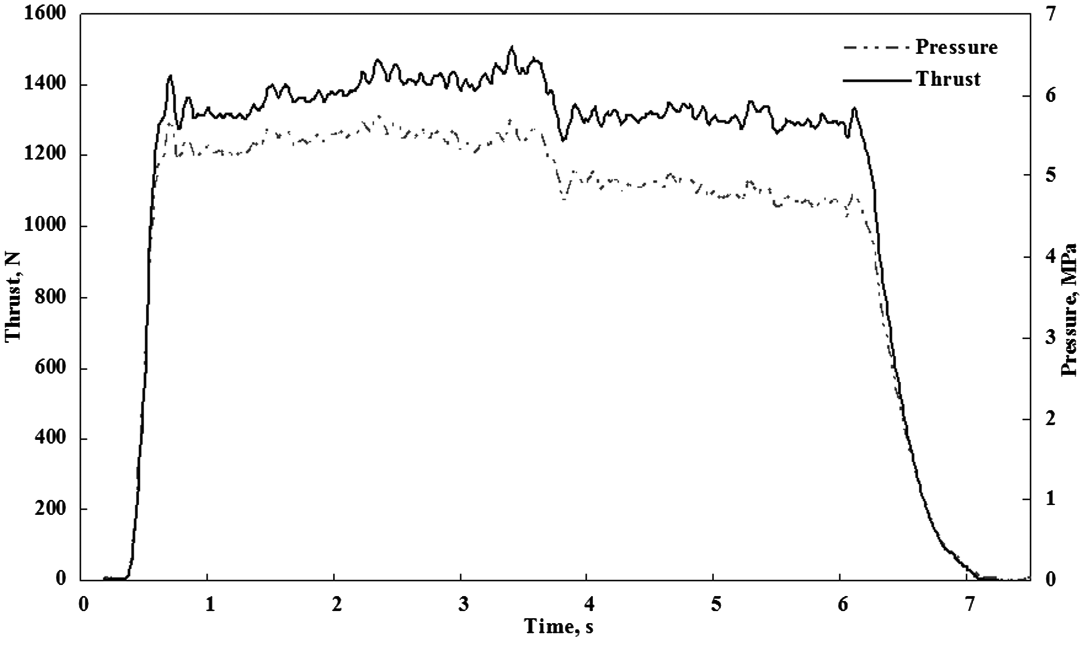


Fig. 5 Motor thrust and chamber pressure versus time experimental trace (fuel composition family 1).

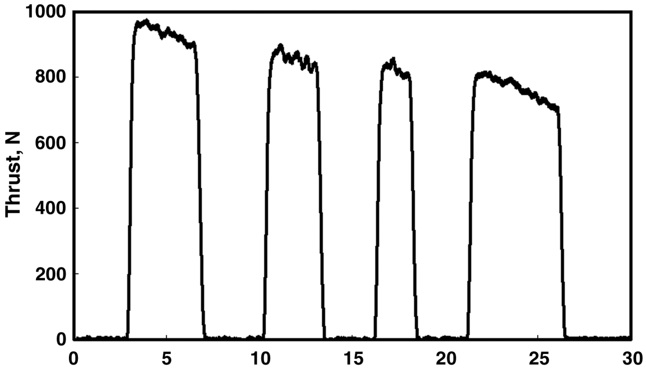


Fig. 6 Multipulse test (fuel composition family 4).

3.1 mm/s at lower pressure, as reported in [8]. However, it should be noted that Frederick et al. [8] used GOX as the oxidizer. N_2O, used in this study, has a positive heat of formation and decomposes exothermally, but its oxygen molecular mass content is only 36.4%. Hence, obviously, the heat flux to the fuel surface in the combustion chamber and, consequently, the fuel regression rate are lower than in the case of using GOX. It is believed that, for a similar fuel-grain composition containing AP, the much thicker thermal wave in the solid fuel, due to a lower regression rate in this case, prevents combustion extinguishment at oxidizer flow termination, in contrast to results reported by Frederick et al. [8].

D. Fuel Composition Family 4:

Full combustion extinguishment was achieved in tests with this composition family by completely removing AP from the fuel formulations. Regression rates of around 1.1 mm/s were obtained at pressure levels of 3–5 MPa and an average oxidizer flux range of 150 to 300 $kg/m^2 \cdot s$ (0.213 to 0.426 $lbm/in^2 \cdot s$). Multipulse operation of the test motor was performed to examine and demonstrate the stop–restart capability of the test system using the features of this composition family. Figure 6 shows a thrust versus time plot of such an experiment. Posttest examination of the extinguished grain surface revealed numerous small pits with an average diameter of around 0.5 mm randomly dispersed over the fuel surface. The lower than expected regression rate obtained in this case suggests that the presence of AP particles (i.e. AP monopropellant flame and HTPB–AP interaction) is necessary to promote the role of PS additive in HTPB-based fuels as a regression-rate enhancer in combustion with N_2O.

E. Fuel Composition Family 5:

This composition family was formulated with a higher PS content in a smaller particle size, a lower content of AP, and the addition of a Butacene catalyst. The test results revealed regression rates around 1 mm/s at pressure levels of 4 to 5 MPa and at an average oxidizer flux range of 100–250 $kg/m^2 \cdot s$ (0.142 to 0.355 $lbm/in^2 \cdot s$). Full flame extinction at oxidizer flow shutoff was obtained.

V. Conclusions

A laboratory-scale experimental setup was established and successfully used for controlled hot-fire testing of a small modular hybrid rocket motor. Supercharged N_2O, cartridge-loaded fuel grains, impingement-on-pin injectors, a gaseous methane–oxygen igniter, and a graphitic nozzle were used in the test program. Five different HTPB-based fuel composition families, which contained fine AP particles, polystyrene particles of various sizes, and a burning-rate catalyst as the major additives in various proportions, were tested.

It was generally found that an increase in the AP content yields an increase in the fuel regression rate, as expected. However, there is an upper limit of that content, somewhere between 15 and 40 wt %, depending on the fuel formulation and test conditions, above which combustion extinction at oxidizer flow shutoff is not possible. Full combustion extinguishment and multipulse operational capability with an insignificant effect on the regression rate was demonstrated by the addition of polystyrene with a large particle size and no addition of AP. A significant enhancement of the regression rate of up to 3.5 mm/s at 5.5 MPa and an average oxidizer mass flux of about 140 $kg/m^2 \cdot s$ (0.2 $lbm/in^2 \cdot s$) was obtained with the addition of both fine AP and large particles of polystyrene. It is postulated that the increase in the regression rate is caused by a pothole effect, due to the ejection of PS particles and/or PS decomposition products, promoted by additional heat release on or close to the fuel surface.

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References

[1] Sutton, G. P., *Rocket Propulsion Elements*, 6th ed., Wiley, New York, 1992, Chap. 15.

[2] Strand, L. D., Ray, R. L., and Cohen, N. S., “Hybrid Rocker Combustion Study,” AIAA Paper 1993-2412, 1993.

[3] Strand, L. D., Jones, M. D., Ray, R. L., and Cohen, N. S., “Characterization of Hybrid Rocket Internal Heat Flux and HTPB Fuel Pyrolysis,” AIAA Paper 1994-2876, 1994.

[4] George, P., Krishnan, S., Varkey, P. M., Ravindran, M., and Ramachandran, L., “Fuel Regression Rate in Hydroxyl-Terminated-Polybutadiene/Gaseous-Oxygen Hybrid Rocket Motors,” *Journal of Propulsion and Power*, Vol. 17, No. 1, 2001, pp. 35–42. doi:10.2514/2.5704

[5] Boardman, T. A., “Hybrid Propellant Rockets,” *Rocket Propulsion Elements*, 7th ed., Wiley, New York, 2001, pp. 579–607.

[6] Chiaverini, M. J., Harting, G. C., Lu, Y. C., Kuo, K. K., Peretz, A., Jones, S., Wygle, B., and Arves, J. P., “Pyrolysis Behavior of Hybrid Rocket Solid Fuels Under Rapid Heating Conditions,” *Journal of Propulsion and Power*, Vol. 15, No. 6, 1999, pp. 888–895. doi:10.2514/2.5512

[7] Chiaverini, M. J., Serin, N., Johnson, D. K., Lu, Y. C., Kuo, K. K., and Risha, G. A., “Regression Rate Behavior of Hybrid Rocket Solid Fuels,” *Journal of Propulsion and Power*, Vol. 16, No. 1, 2000, pp. 125–132. doi:10.2514/2.5541

[8] Frederick, R. A., Jr., Whitehead, J. J., Knox, L. R., and Moser, M. D., “Regression Rates Study of Mixed Hybrid Propellant,” *Journal of Propulsion and Power*, Vol. 23, No. 1, 2007, pp. 175–180. doi:10.2514/1.14327

[9] Chiaverini, M. J., Serin, N., Johnson, D. K., Lu, Y. C., and Kuo, K. K., “Instantaneous Regression Behavior of HTPB Solid Fuels Burning with GOX in a Simulated Hybrid Rocket Motor,” *Proceedings of the 4th International Symposium on Special Topics in Chemical Propulsion*, Begell House, New York, 1997, pp. 719–733.

[10] Yi, J., Wygle, B. S., Bates, R. W., Jones, M. D., and Ramohalli, K., “Hybrid Combustion With Metallized Fuels,” AIAA Paper 1993-2410, 1993.

[11] Galfetti, L., DeLuca, L. T., Grassi, P., Paravan, C., Luoni, V., Bandera, A., Colombo, G., DeCillia, L., Sempio, R., and Raina, H., “Combustion Behavior Investigation of Solid Fuels Using a Micro-Sized Hybrid Rocket Motor,” *Advancements in Energetic Materials and Chemical Propulsion*, edited by K. K. Kuo and K. Hori, Begell House, New York, 2008, pp. 199–213.

[12] Doran, E., Dyer, J., Lohner, K., Dunn, Z., Cantwell, B., and Zilliac, G., “Nitrous Oxide Hybrid Rocket Motor Fuel Regression Rate Characterization,” AIAA Paper 2007-5352, 2007.

[13] Farbar, E., Louwers, J., and Kaya, T., “Investigation of Metallized and Nonmetallized Hydroxyl-Terminated Polybutadien/Hydrogen Peroxide Hybrid Rockets,” *Journal of Propulsion and Power*, Vol. 23, No. 2, 2007, pp. 476–486. doi:10.2514/1.22091

[14] Risha, G. A., Evans, B. J., Boyer, E., and Kuo, K. K., “Metals, Energetic Additives, and Special Binders Used in Solid Fuels for Hybrid Rockets,” *Fundamentals of Hybrid Rocket Combustion and Propulsion*, edited by M. J. Chiaverini and K. K. Kuo, Vol. 218, Progress in Astronautics and Aeronautics, AIAA, New York, 2007, pp. 413–456.

[15] Calabro, M., DeLuca, L. T., Galfetti, L., Raina, H., and Perut, C., “Advanced Hybrid Solid Fuels,” *Proceedings of the 58th International*

Astronautical Congress, Vol. 9, Curran Assoc., Red Hook, NY, 2008, pp. 5722–5728.

[16] Karabeyoglu, M. A., Cantwell, B. J., and Altman, D., “Development and Testing of Paraffin-Based Hybrid Rocket Fuels,” AIAA Paper 2001-4503, 2001.

[17] Karabeyoglu, M. A., Altman, D., and Cantwell, B. J., “Combustion of Liquefying Hybrid Propellants, Part 1: General Theory,” *Journal of Propulsion and Power*, Vol. 18, No. 3, 2002, pp. 610–620. doi:10.2514/2.5975

[18] Karabeyoglu, M. A., and Cantwell, B. J., “Combustion of Liquefying Hybrid Propellants, Part 2: Stability of Liquid Films,” *Journal of Propulsion and Power*, Vol. 18, No. 3, 2002, pp. 621–630. doi:10.2514/2.5976

[19] Karabeyoglu, M. A., Zilliac, G., Cantwell, B. J., DeZilwa, S., and Castellucci, P., “Scale-Up Tests of High Regression Rate Paraffin-Based Hybrid Rocket Fuels,” *Journal of Propulsion and Power*, Vol. 20, No. 6, 2004, pp. 1037–1045. doi:10.2514/1.3340

[20] Claflin, S. E., and Beckman, A. W., “Hybrid Propulsion Technology Program: Final Report,” Vol. IV, NASA CR 183975, 1989.

[21] Carmicino, C., and Russo Sorge, A., “Role of Injection in Hybrid Rockets Regression Rate Behavior,” *Journal of Propulsion and Power*, Vol. 21, No. 4, 2005, pp. 606–612. doi:10.2514/1.9945

[22] Carmicino, C., and Russo Sorge, A., “Influence of a Conical Axial Injector on Hybrid Rocket Performance,” *Journal of Propulsion and Power*, Vol. 22, No. 5, 2006, pp. 984–995. doi:10.2514/1.19528

[23] Knuth, W. H., Chiaverini, M. J., Sauer, J. A., and Gramer, D. J., “Solid-Fuel Regression Rate Behavior of Vortex Hybrid Rocket Engines,” *Journal of Propulsion and Power*, Vol. 18, No. 3, 2002, pp. 600–609. doi:10.2514/2.5974

[24] Liljegren, T., “Fuel-Rich Propellants with Ammonium Perchlorate as Oxidizer and Mixtures of HTPB and Polystyrene as Fuel,” FOA (Swedish Research Institute) Rept. C 20395-01, Stockholm, Feb. 1981 (in Swedish).

[25] Lu, Y. C., and Kuo, K. K., “Thermal Decomposition Study of Hydroxyl-Terminated Polybutadiene (HTPB) Fuel,” *Thermochimica Acta*, Vol. 275, No. 2, 1996, pp. 181–191. doi:10.1016/0040-6031(95)02726-2

[26] Arves, J. P., Jones, H. S., Kline, K., Smith, K., Slack, T., and Bales, T., “Development of N_2O/HTPB Hybrid Rocket Motor,” AIAA Paper 1997-2803, 1997.

[27] Kline, S. J., and McClintock, F. A., “Describing Uncertainties in Single-Sample Experiments,” *Mechanical Engineering*, Vol. 75, Jan. 1953, pp. 3–8.

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