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Variable Thrust, Multiple Start Hybrid Motor Solutions for Missile and Space Applications

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ABSTRACT

Energy management in missile systems can provide substantial performance advantages, especially for modern missiles capable of all-aspect engagements. Energy management in upper stage propulsion systems allows for the same propulsion system to be used for a variety of payloads and orbits. The objectives of the study were to assess throttling capabilities and novel fuel concepts for hybrid motors. Experimental studies were conducted using 90% hydrogen peroxide (HP) with a variety of unique fuels in both direct injection and catalytic bed injection approaches. Performance efficiencies ranged from 91% to 100% and the combustion in all tests was smooth with the highest level of combustion roughness reaching only 0.6% of the steady state pressure. These hybrid motor tests also displayed the expected connection between the oxidizer flux level and the time required to ignite the fuel grain with higher flux levels resulting in lower ignition delays. Substantial throttling capabilities were demonstrated. Throttle-down tests analogous to a powered vertical landing exhibited a 10:1 throttling ratio with stable combustion across the entire range. Boost/Sustain/Boost thrust profiles representative of tactical solid rocket motors were tested with 75%, 50%, and lower sustain-to-boost chamber pressure ratios with rapid throttle-up achieved following the sustain period. To add multiple-start capability to a hybrid motor without reliance on a catalyst bed or separate ignition system, fuel grains catalytic with the oxidizer were investigated. Test fires of these fuel grains in the hybrid motor test article exhibited regression rates 2.5 times higher than the highest regression rates realized with the uncatalyzed polyethylene fuel grains.

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INTRODUCTION

Interceptor boost propulsion has traditionally been dominated by solid rocket systems due to their responsiveness and high mass fraction capabilities. However, increased costs of handling these flammable motors, the need to evolve more and more insensitive munitions, the static thrust profile created at propellant casting, and the inherent performance (Isp) limitations of solid propellants has motivated the interest in exploring alternate technologies. Hybrid propulsion devices have the potential to substantially increase the payload/range characteristics of modern missile systems due to a substantial advantage in specific impulse as compared to current solid propellant devices used in these applications. With the use of a variable position valve to control instantaneous oxidizer flow, additional energy management features can easily be incorporated in a hybrid system to permit a wide range of thrust variation/throttling. Further, the use of a hybrid system, with a liquid oxidizer and solid fuel, provides substantial safety and handling advantages that translate to reduced operations costs and limit exposure for military personnel. Because the fuel and oxidizer are not intimately mixed as in solid propellant formulations, hybrid propulsion devices are much less sensitive to adverse situations including exposure to external fires, bullet/fragment impact, electrostatic discharge, and inadvertent drop/impacts. For these reasons, they have the potential to better satisfy insensitive munitions characteristics that are highly desired for modern military propulsion systems.

Despite these advantages, hybrid systems have not seen a large number of applications in military propulsion systems, with the Sandpiper/HAST/Firebolt target vehicles being the lone military system fielded over the past 50 years. The main factors inhibiting the use of hybrid propulsion devices include the inherently low burning/regression rate of most common propellant combinations and the poor fuel utilization resulting from non-uniform regression of the surface or small variations in the local regression rate. Low regression rates necessitate large surface areas to produce the required thrust levels and this design requirement has typically been met by the use of multiport fuel chambers that are volumetrically inefficient. The oxidizer/fuel ratio of many of the prior propellant combinations was such that the fuel comprised roughly 1/3 of the total propellant mass and therefore poor packaging of the fuel grain results in substantial volumetric penalties to the system. In addition, when the fuel comprises a substantial fraction of the overall propellant, even small slivers translate to substantial impulse losses in the system. There have also been few published works on the abilities of hybrid rocket systems to function with reliable performance under throttled conditions. In the limit, a complete temporary shutdown (restart capability) would also be of potential interest in missile applications as well as in space motor applications where multiple burns are required for orbit insertion.

The goals of the present effort have been to demonstrate the feasibility of the throttling, restartable hybrid motor concept. To accomplish these goals, the specific objectives of the present study were:

1. To assess the potential weight and impulse advantages of hydrogen peroxide-based hybrids utilizing a catalytic fuel grain through performing systems studies and baselining concepts against current solid propulsion missile systems.
2. To experimentally determine the combustion performance and ignitability of catalytic fuel grains with various catalyst loadings for a hybrid motor using concentrated HP

3. To experimentally determine the combustion performance, ignitability, and throttling capability of a hybrid motor using concentrated HP and a catalyst bed

The following sections of this paper describe the efforts on just the experimental efforts aimed at demonstrating thottleability and restart characteristics of hybrid motors.

EXPERIMENTAL THROTTLING/RESTART STUDIES

Two test series were conducted as parts of this effort. In the first series of tests, a catalyst bed was placed upstream of the fuel section to directly feed decomposed HP gases to the fuel. The high decomposition temperature of rocket-grade HP permits for direct ignition of the fuel grain in this instance without the use of a separate ignition source. In the second series of tests, catalytic fuel grains were manufactured such that ignition could be attained with direct injection of liquid HP into the combustion chamber. Both approaches yielded successful ignition and reliable combustion.

Test Article Design

A nominal oxidizer flow rate of 0.5-lbm/s, significantly lower than the facility limit, was selected for the test article since this flow rate put the test article in the 100-lbf thrust class, a scale large enough to make the results relevant across a broad spectrum of thrust sizes. The Purdue-owned General Kinetics 2.9-in diameter catbed was selected for use in the experiment given it was large enough to handle the flow rate. A nominal fuel grain port diameter of 1.000-in was selected with a total web distance of 0.375-in, giving an outer diameter of the fuel grain 1.750-in. A modular fuel grain housing and combustion chamber were designed to accommodate a range of fuel grain lengths as shown in Figure 1. Two inch outer diameter paper phenolic, a readily available and low-cost material that has been used in prior hybrid motor firings at Purdue, was selected for the hybrid motor insulation. A dozen throats were machined from 2-in 0.0006-in grain graphite phenolic with two piston o-ring grooves on the circumference to seal the chamber. A Habonim control valve was selected that was capable of linearly varying the peroxide flow rate from 0.11-lbm/s at 20% open to 1.04-lbm/s at full open under expected operating pressures. Water flows of the control valve were conducted to verify ball position versus measured product of the discharge coefficient and effective flow area. Water flows also uncovered that the Habonim control valve required over 600-ms to fully open with a step function commanded "open" signal. Redundant head-end and a single aft-end pressure transducer were used to assess combustion performance. An image of the apparatus installed on the test stand within Purdue's Advanced Propellants and Combustion Lab (APCL) is provided in Figure 2.

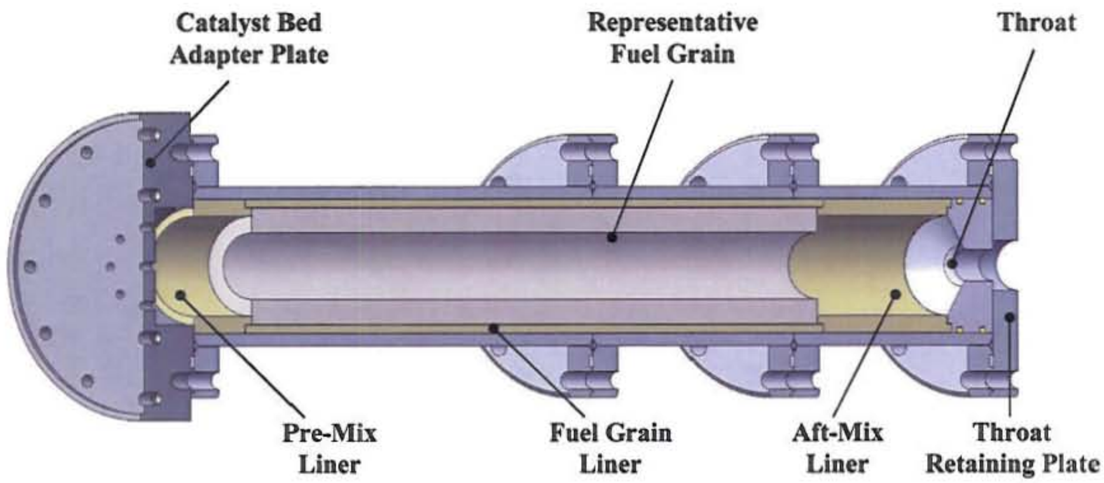


Figure 1: Representative Hybrid Motor Stack-Up

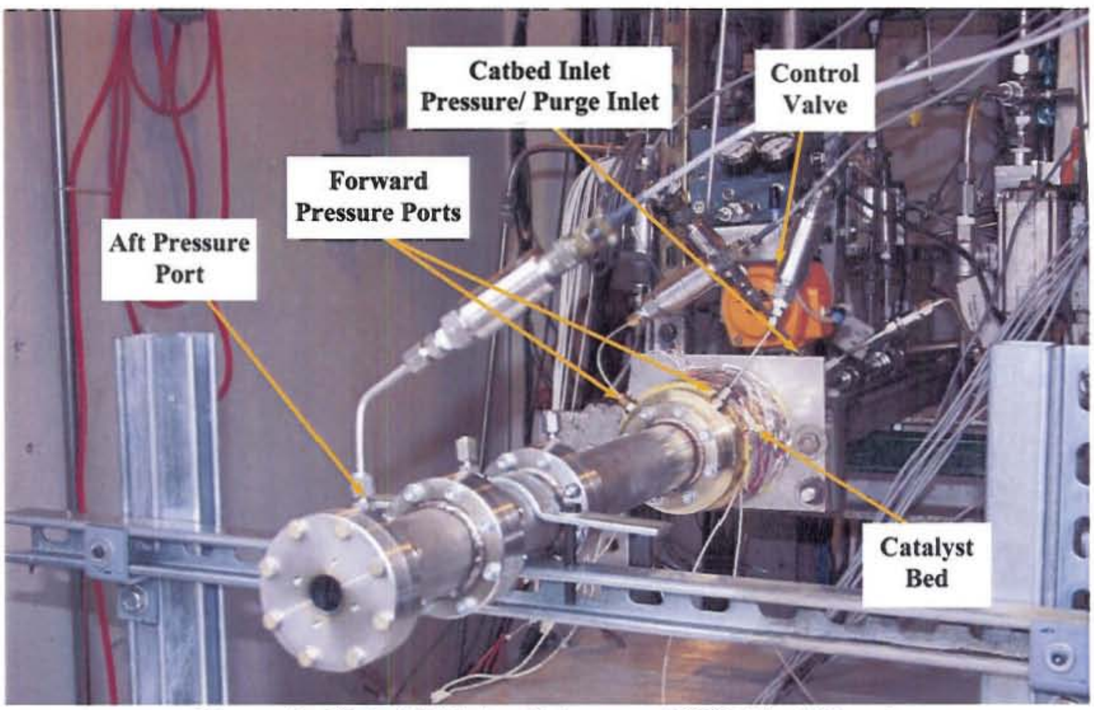


Figure 2: Hybrid Motor Setup on APCL Test Stand

1. Investigation of Catalyst Bed-Based Throttleable Hybrids

The initial series of tests focused on the catbed arrangement depicted in Figure 2. A set of steady-state test firings were conducted to establish the regression characteristics for this staged-decomposition/combustion configuration for which prior regression data are sparse at best. A cavitating venturi was used for flow measurement on this series of tests. Table 1 summarizes the desired operating conditions for these tests and Table 2 provides a summary of the resulting performance.

Table 1: Catalyst Bed-Based Hybrid Motor Steady-State Test Matrix

Test	Target Pc (psia)	Ox Flux ($lbm/in^2/s$)	Ox Mass Flow (lbm/s)	Fuel Port Dia. (in)	Init. Fuel Mass Flow (lbm/s)
Catbed-1	500	1.000	0.60	0.875	0.080
Catbed-2	500	0.600	0.47	1.000	0.063
Catbed-3	500	0.200	0.16	1.000	0.021
Catbed-4	260	0.300	0.24	1.000	0.045
Catbed-5	260	0.540	0.24	0.75	0.020

Table 2: Results Summary for Catalyst Bed Hybrid Performance Tests

Test Designation	Ave. Pc (psia)	Mixture Ratio	Ox Flux ($lbm/in^2/s$)	Ign. Delay (msec)	$\dot{r}$ (in/s)	η_{c^*} (%)	Pc Roughness
Catbed-1	530	6.8	0.65	449	0.041	100	0.6%
Catbed-2	450	6.7	0.40	818	0.031	91	0.4%
Catbed-3	461	6.1	0.15	2318	0.022	94	0.2%
Catbed-4	245	5.3	0.22	1907	0.022	92	0.4%
Catbed-5	253	4.9	0.33	1831	0.028	98	0.5%

High combustion efficiencies and smooth combustion was obtained across the series of tests. The measured regression rates were somewhat higher than those reported in prior literature[3] as the Pc level was higher than in those previous tests. Best fit of the limited data from these tests gave the following results for regression rate:

$$\dot{r} = 0.0568 G_{tot}^{0.63} \quad \text{for } P_C = 250\text{-psia}$$
$$\dot{r} = 0.0471 G_{tot}^{0.41} \quad \text{for } P_C = 500\text{-psia}$$

The exponent for the high pressure tests is considerably lower than that for other propellant combinations and radiation is believed to be important as Pc increases as noted previously by Wernimont[3]. Figure 3 summarizes the measured ignition delays associated with the catalyst bed steady-state evaluations. As with other prior hybrid tests, there is a substantial time required to heat the fuel grain surface to autoignition temperature. The higher pressure results are encouraging in reducing this requirement and thereby reducing the time under monopropellant operation.

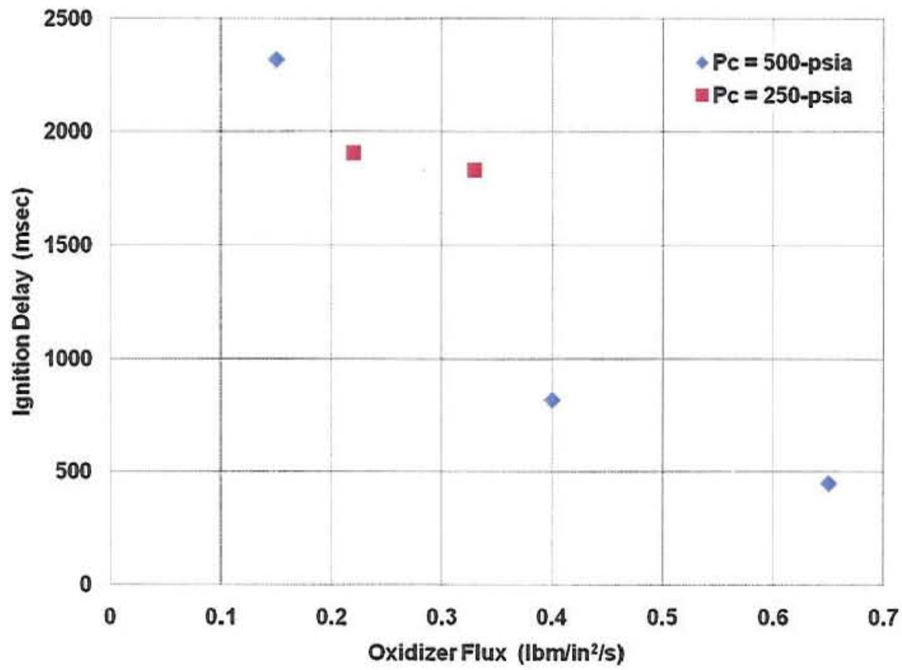


Figure 3: Catbed-Based Hybrid Motor Ignition Delay vs. Oxidizer Flux

The three throttling scenarios were considered:

1. Boost/Sustain/Boost. Simulating a tactical solid rocket motor profile with another boost at the end to demonstrate a "throttle up", this test profile starts with a nominal flow rate (boost), reduces flow rate to a fraction of the nominal value (sustain), and then returns to the nominal flow rate (boost).
2. Throttle Down. Representing a gradual reduction in thrust to decrease acceleration for an upper stage vehicle or for a soft landing in a vertical landing vehicle, this test profile starts at the nominal flow rate and then continuously decreases the flow rate throughout the test.
3. Optimum Mixture Ratio. With the increasing surface area of the fuel grain, the fuel flow rate changes throughout the test. This test profile increases or decreases the oxidizer flow rate to maintain the optimum mixture ratio throughout the burn.

Three tests were conducted for the Boost/Sustain/Boost scenario. Substantial experimentation was required to reconcile control valve performance due to nonlinearities in its effective discharge coefficient with valve position. The control valve achieved a 520-psia chamber pressure during the "Boost" phase and a 300-psia chamber pressure during the "Sustain" period, which is a low throttling level of only 56%. The plots of the chamber pressure and valve position for the third test are shown in Figure 4. Images taken from the three separate portions of the test fire are shown in Figure 5.

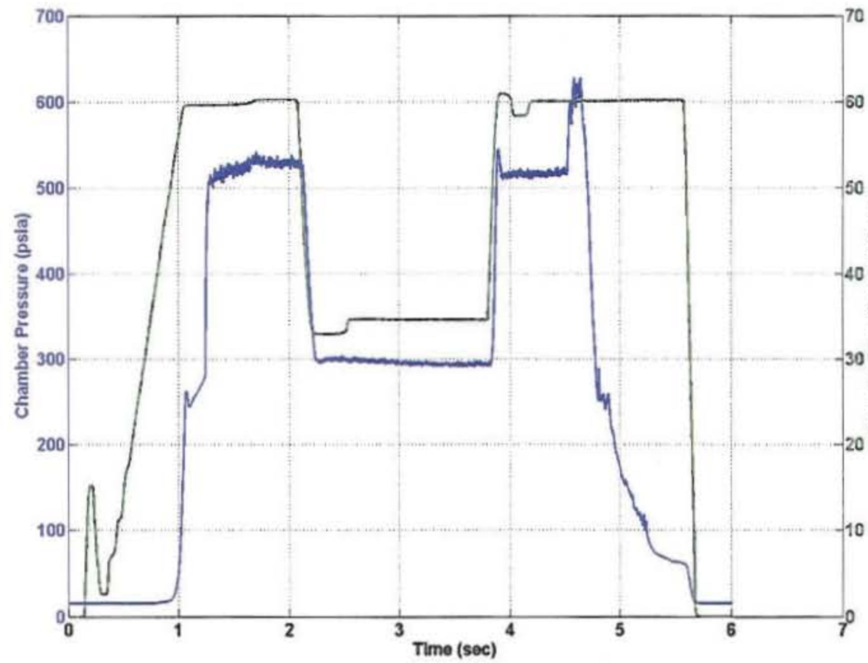
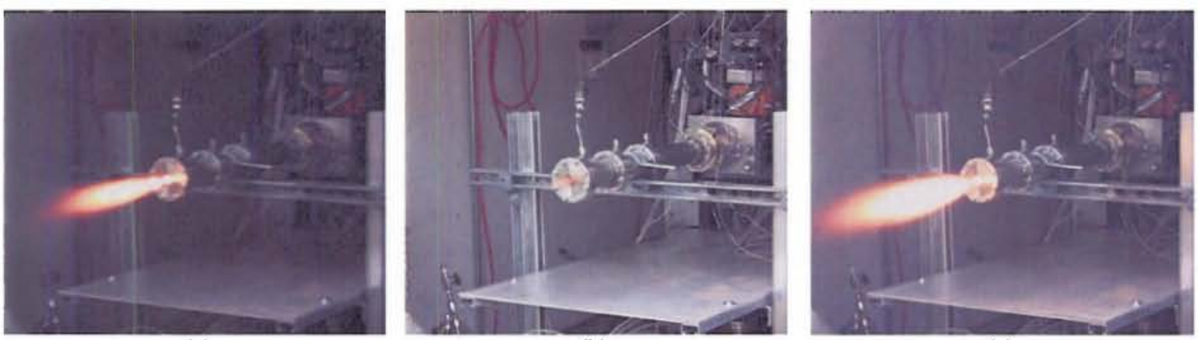


Figure 4: Chamber Pressure and Valve Position during the Third Test of Catbed-6



(a) (b) (c)

Figure 5: Catalyst Bed Hybrid during the a) Boost, b) Sustain, and c) Boost

The Catbed-7 test was conducted to determine if a lower limit was evident in throttling the hybrid motor down to a barely choked chamber flow condition. The valve was programmed to open to 60% for 2 seconds, and then close fully over the next 10 seconds using a series of small discrete steps generated by the control program. Figure 6 depicts the measured chamber pressure history and valve position history for this test showing stable combustion at pressure as low as 55-psia, when the valve closed to almost 18%. With the initial chamber pressure at 515-psia, the Catbed-7 test achieved a throttling ratio of nearly 10:1. Deeper throttling may be possible; however, this would need to be investigated with a higher initial flow rate given the lower bound on measureable/attainable flow rates and with greater consideration given to the feed system design to maintain full lines at low flow rates. Also significant is the lack of appreciable combustion roughness at any level of the test.

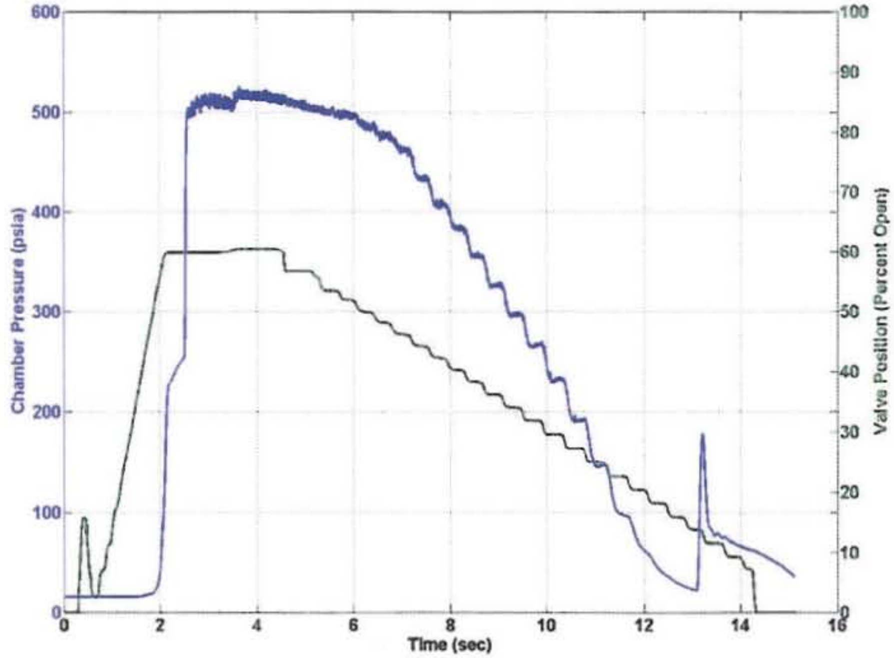


Figure 6: Chamber Pressure and Valve Position during the Catbed-7 Test

2. Investigation of Catalytic Fuel Grains for Hydrogen Peroxide Hybrids

The motivation behind the catalytic fuel grain advancement was an ignition device developed by one of the principals at IN Space LLC, Mr. Scott Meyer and another of our team members, Dr. Eric Wernimont of General Kinetics, Inc.[1] This ignition device, called a "consumable catalyst bed" or CCB, is a four to six inch length of fuel grain containing polyethylene and catalytic materials. The CCB reacts violently with concentrated hydrogen peroxide and subsequently ignites the fuel grain, which is typically polyethylene or HTPB. With proper injector and chamber design, the CCB has proved to be a reliable single-shot ignition source for hybrid motors successfully initiating hundreds of tests at Purdue University over the past decade and functioning at liquid oxidizer port fluxes in excess of 1.1 lbm/in^2-sec. An image of the CCB during a test firing of a poly(methyl methacrylate) (PMMA) fuel grain is shown in Figure 7.

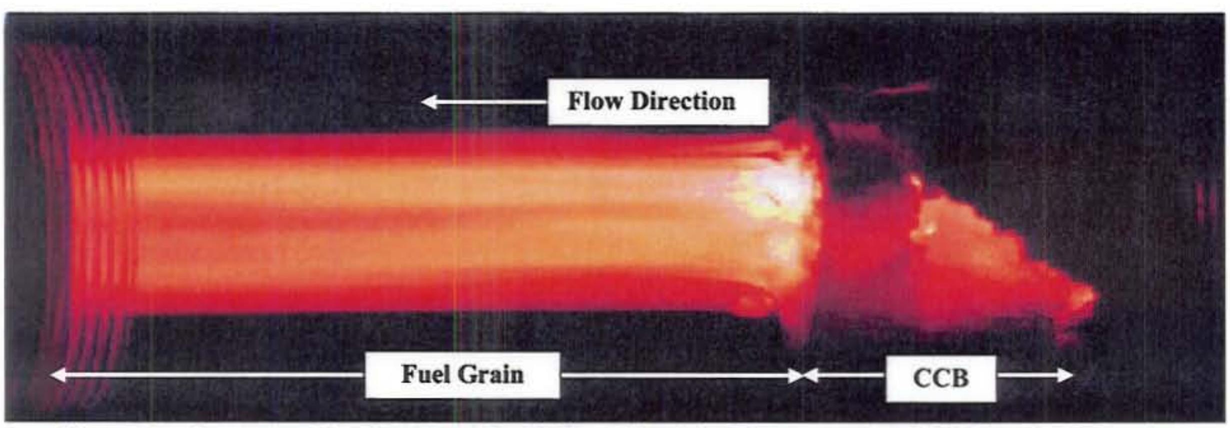


Figure 7: Consumable Catalyst Bed Visualized in Transparent PMMA Fuel Grain

To be able add multiple-start capability to a hybrid motor without reliance on a catalyst bed or torch ignition system, an entire fuel grain catalytic with the oxidizer was envisioned. The high reactivity of the liquid oxidizer with the fuel grain was also expected to lead to higher regression rates, which may serveto minimize fuel slivers. Nine candidate formulations were developed and evaluated in drop tests in order to assess reactivity with 90% HP. Table 2 summarizes the results of the catalytic screening tests of the fuel grain formulation samples. The results exhibit a fair degree of distribution between batches and even samples from the same batch achieved short splatter or ignition times on one test and none on the next. This variance between tests can be explained by the small area covered by a single droplet and the limited mixing possible with solid particles melted into a single piece when compared to a homogeneous liquid solution of catalyst and propellant.

Table 2: Summary of HP Catalytic Fuel Grain Formulation Screening

Formulation	Batch	Splatter Delay (msec)	Ignition Delay (msec)	Formulation	Batch	Splatter Delay (msec)	Ignition Delay (msec)
CFG-00	0.1	-	0.2	CFG-05	5.1	-	-
CFG-00	0.1	2.1	2.3	CFG-05	5.2	4.6	-
CFG-00	0.2	2.0	2.2	CFG-05	5.2	5.0	-
CFG-00	0.2	2.2	-	CFG-05	5.2	-	-
CFG-00	0.2	0.3	1.5	CFG-06	6.1	-	3.8
CFG-01	1.1	269.3	-	CFG-06	6.1	-	-
CFG-01	1.1	4.3	-	CFG-06	6.1	-	-
CFG-01	1.2	3.2	-	CFG-06	6.2	5.1	-
CFG-01	1.2	-	5.7	CFG-06	6.2	3.9	658.9
CFG-02	2.1	-	-	CFG-07	7.1	5.9	-
CFG-02	2.1	7.9	-	CFG-07	7.1	7.4	-
CFG-02	2.1	25.2	-	CFG-07	7.1	-	-
CFG-02	2.2	-	-	CFG-07	7.1	2.8	5.6
CFG-02	2.2	-	-	CFG-07	7.2	156.5	-
CFG-03	3.1	-	1.2	CFG-08	8.1	-	-
CFG-03	3.1	21.9	-	CFG-08	8.1	8.9	-
CFG-03	3.1	-	-	CFG-08	8.1	6.7	-
CFG-03	3.2	2.4	-	CFG-08	8.2	27.0	-
CFG-03	3.2	-	3.9	CFG-08	8.2	-	-
CFG-04	4.1	3.4	-	CFG-09	9.1	-	-
CFG-04	4.1	6.5	-	CFG-09	9.1	-	-
CFG-04	4.1	-	-	CFG-09	9.2	-	-
CFG-04	4.2	7.5	-	CFG-09	9.2	-	-
CFG-04	4.2	10.6	-	CFG-09	9.2	-	-
CFG-05	5.1	7.8	-				

Almost all samples caused the droplet to splatter within 10 msec of contact with a few outliers. Ignition events with the samples were far less common with only five of the ten formulations achieving any ignition and three of those achieving only one ignition event in four or five tests of the formulation. However, low splatter delays were seen as a good indication of reactivity and possible inclusion into motor tests even if ignition with the sample was not reached. The droplet splatter is the result of peroxide decomposition, which releases heat, and, in a motor configuration, ejected droplets are all but certain to make contact with additional catalytic propellant causing more splatter and decomposition. Given the time constraints of the Phase I study, only three formulations were selected for continued evaluation in motor firings. Those selected were the CFG-00, CFG-04, and CFG-06 formulations.

With a casting operation needed to generate the fuel grains, consideration was given to making a mandrel to produce a "star pattern" on the inner diameter rather than a straight cylindrical wall port. This star pattern, which is used on the CCB ignition devices, would significantly increase the inner wall surface area thereby aiding in ignition through providing more contact with the peroxide. A cylindrical port was ultimately selected for the mandrel since a more difficult ignition scenario provided a starker comparison between the formulations. Furthermore, demonstrating functionality with a cylindrical port geometry removes concern over whether or not a star pattern grain is required as in a re-ignition/relight scenario or when a simplified grain design is needed. Table 3 lists the physical properties of the catalytic fuel grains produced for hybrid motor testing.

Table 3: Physical Properties of the Catalytic Fuel Grains

CFG Test	Formulation	Grain Length (in)	Grain Mass (g)	Throat Dia. (in)	Port Pattern	Actual Density/ Ideal Density
1	CFG-00	3.70 / 3.87	162.63	0.457	Star/Circular	-
2	CFG-00	7.44	141.33	0.457	Circular	58.1%
3	CFG-04	8.88	111.87	0.458	Circular	47.8%
4	CFG-06	8.94	150.68	0.473	Circular	60.0%
5	CFG-00	7.97	135.82	0.475	Circular	60.0%
6	CFG-06	7.47	148.56	0.473	Circular	81.1%
7	CFG-06	7.44	147.19	0.492	Circular	80.1%
8	CFG-00	7.47	198.70	0.470	Circular	89.3%

Extensive reconfiguration of the test stand for conducting the hydrogen peroxide catalytic fuel grain tests was not required given that the test stand was already configured for the catalyst bed hybrid motor tests. An image of the setup is shown in Figure 8. The same motor hardware used for the catbed hybrid tests was employed for the catalytic fuel grain tests with the exception of the catalyst bed and transition plate. These were replaced by a forward flange housing a commerical off-the-shelf spray nozzle with the nozzle exit coplanar with the flange forming the headend of the combustion chamber. The spray nozzle was selected based on realizing flow rates from 0.093-lbm/s to over 0.46-lbm/s. Unlike the catbed hybrid motor configuration, the catalytic fuel grain tests did not use a pre-mix phenolic liner; the fuel grain and accompanying 1/8-in phenolic liner were flush with the chamber headend to ensure that all of the oxidizer flowed down the fuel grain port and did not pool on top of the fuel grain, which has previously led to hardstarts with the CCB ignition devices.

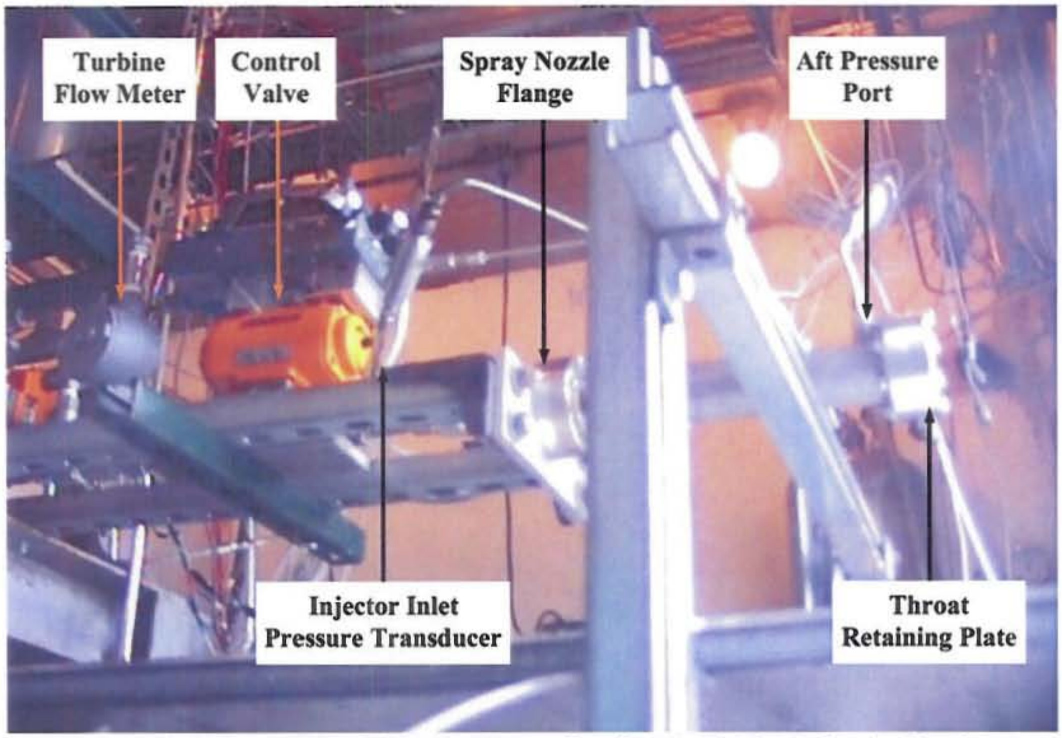


Figure 8: Setup of the Hybrid Motor for Catalytic Fuel Grain Testing

Tests of the catalytic grain formulations were conducted in the order listed in Table 4 summarizing the testing conditions. All fuel grains did achieve ignition with four of the eight tests experiencing a smooth startup transient. These tests included all of the CFG-06 formulation grains, pictured firing in Figure 9, and the first CFG-00 grain, which used a star pattern on the forward end of the fuel grain. However, the remaining four tests had hardstart ignition events resulting from a delayed ignition causing oxidizer to pool in the chamber, which then reacts suddenly and violently with fuel upon ignition. These tests included the CFG-00 formulations with a circular port only inner diameter and the grain made of the CFG-04 formulation.

Table 4: Test Summary for Catalytic Fuel Grain Tests

CFG Test	Formulation	Relative Valve Opening Speed	Flow Measurement Method	Ignition
1	CFG-00	Fast	Venturi	Smooth
2	CFG-00	Fast	Flow Meter	Hard Start
3	CFG-04	Slow	Flow Meter	Hard Start
4	CFG-06	Slow	Flow Meter	Smooth
5	CFG-00	Slow	Flow Meter	Hard Start
6	CFG-06	Slow	Venturi	Smooth
7	CFG-06	Fast	Venturi	Smooth
8	CFG-00	Fast	Venturi	Hard Start

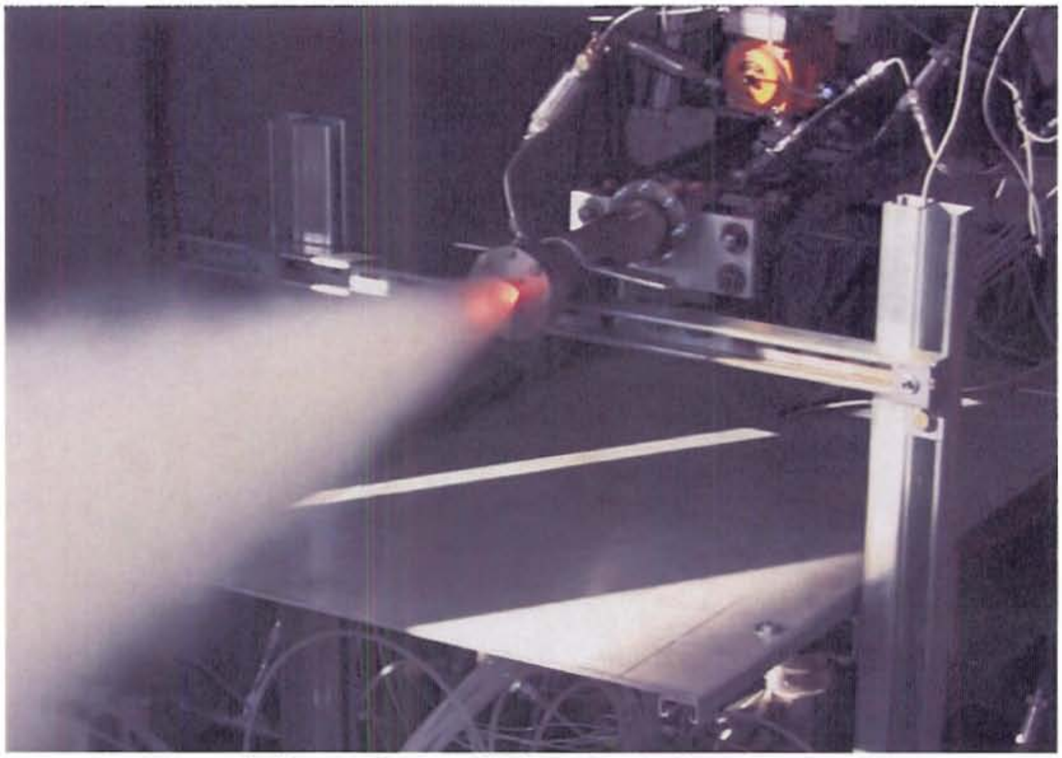


Figure 9: Image from a CFG-06 Grain Formulation Test

An example of injector inlet and chamber pressure traces during a smooth startup transient is displayed in Figure 10, which is a test of the CFG-06 formulation. There is no significant pressure overshoot in either the injector inlet or chamber pressure traces and both increase together. The sharp, 100-psia drop in the pressure traces approximately 3-sec after ignition is the result of the fuel being completely consumed. The reduced chamber pressure is the result of decomposing peroxide and burning phenolic insulator.

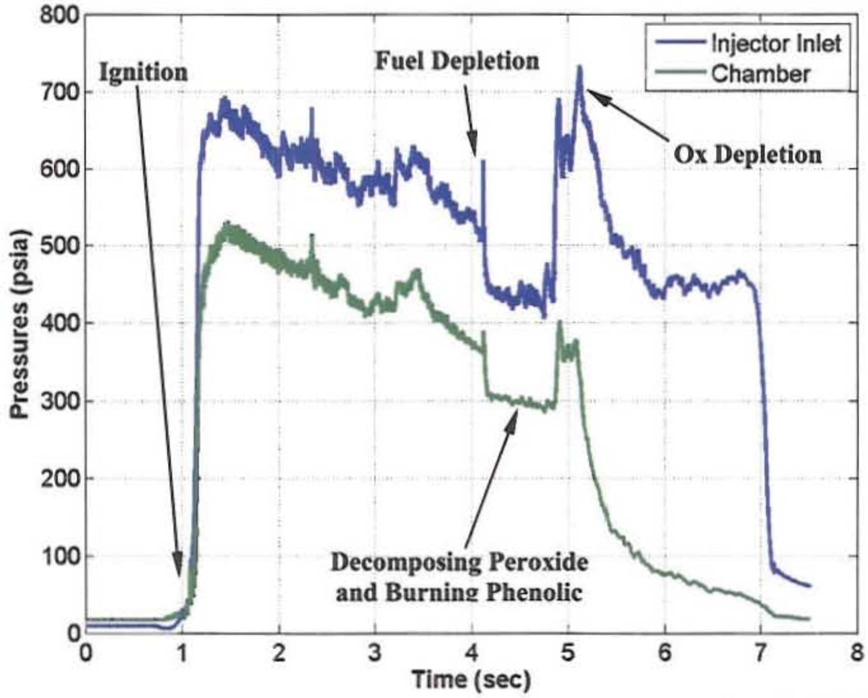


Figure 10: Injector Inlet and Chamber Pressures during Test 7 (CFG-06)

The results of the tests point strongly to the CFG-06 formulation as the best of the three for achieving a smooth startup transient with a circular port at the 1.0-lbm/in^2/s flux levels tested. Some variance in the startup sequences between tests makes a direct comparison of all tests difficult. The control valve opening speed was commanded by the LabVIEW control panel program, which was initially set to a fast opening time for the first two tests to evaluate a "slam" start. Following the hardstart of the second CFG-00 test, the opening time of the control valve was increased for the next four tests, including two of the three CFG-06 tests. The slower opening is beneficial from an ignition standpoint since the lower initial flow rate reduces the chance of quenching. The remaining two tests, including a CFG-06 grain, were conducted with a fast control valve opening time but a damaged turbine flow meter required the use of a cavitating venturi for measuring the flow rates of the test so the flow rates were limited during the startup of the last two tests. Therefore, the last CFG-06 test (Test 7) was not a direct comparison with the second CFG-00 test (Test 2). However, the CFG-06 formulation still appears best with regard to ignition considering that tests of CFG-00 (Test 8) and CFG-04 (Test 3) grains experienced a hardstart under the same or similar conditions.

Table 5 lists the average fuel grain regression rates achieved with the catalytic fuel grains having actual-to-ideal densities over 80%. The regression rates of these catalytic fuel grain tests were up to 2.5 times the highest of the regression rates realized with the catalyst bed-based hybrid motor tests. These results are particularly exciting since the high regression rates will not only result in fewer ports in the fuel grain to achieve high thrust levels but also significantly reduce the amount of performance-detracting fuel slivers. Regression rates were not determined for the less dense grains as the low densities were indicative of voids and loosely packed fuel and catalyst, which would make the results unrepresentative.

Table 5: Results Summary for Catalytic Fuel Grain Tests

CFG Test	Formulation	Ave. Pc (psia)	Mixture Ratio	Ox Flux (lbm/in²/s)	$\dot{r}$ (in/s)	η_{c^*} (%)	Pc Roughness
6	CFG-06	473	5.6	0.57	0.116	94	0.3%
7	CFG-06	472	5.6	0.48	0.107	95	4.0%
8	CFG-00	500	6.3	0.66	0.087	98	1.5%

The regression rates being significantly higher than anticipated also resulted in the mixture ratio of all the CFG tests being considerably lower than the desired 7.5. Additional testing to determine the regression rates at closer to optimum mixture ratios is needed; however, higher oxidizer and fuel flow rates would be expected in such testing, thus thicker web distances and, therefore, new hardware would be required. The high regression rates also made conducting throttling tests impractical due to the short test durations afforded by the 0.375-in web distance.

3. Investigation of Catalytic Fuel Grains for IRFNA Hybrids

The literature search revealed that there are numerous works that pertain to the development and study of hypergolic solid combinations for IRFNA dating back into the late 1950s. Early American efforts focused on amine fuels while a large amount of work was done in India in the 1970s and early 1980s.

Jain et al[5] studied hypergolic ignition of solid hydrozones with "pure" nitric acid (91.3% HNO_3, 7.3% NO_2, 1.33% H_2O) and RFNA (73% nitric acid, 24% NO2, 2.7% water). Ignition delays were measured using drop tests with typical delays in the 60-300 msec range. These delay times are likely too long for true hypergolicity, but may still be viable in a throttled system if one presumes the motor can be started at a very low flow. The best compound tested was p-hydroxybenzaldehyde-dimethylhydrazone that exhibited ignition delays of 37 and 103 msec with pure nitric acid and RFNA respectively.

Munjal and colleagues at Birla Institute of Technology studied nitric acid hybrids for a number of years. Reference 6 provides a study of ignition delays of various formaldehyde fuels with fuming nitric acid. A simple drop test was conducted with varying amounts of fuel with a fixed amount of oxidizer. Long ignition delays, ranging from 300 msec to several seconds were measured with these materials. Temperature effects were studied over a small range from 10 – 25°C and the ignition delays roughly doubled for the 10°C case as compared to the room temperature 25°C case. Additives were evaluated to reduce ignition delays showing dramatic effects. Ammonium vanadate, ammonium dichromate, potassium dichromate, potassium permanganate and vanadium pentoxide all showed success in accelerating the formaldehyde-based fuels and reduced ignition delays by as much as an order of magnitude and to levels as low as 100 msec. Additive concentration was 4.5 g per 100 cc of nitric acid. A related study[7] shows that alcohol fuels become hypergolic with nitric acid if potassium permanganate is added to the oxidizer at levels as high as 20%. Reference 8 provides a study along a similar vein with potassium perchlorate particle size being varied to reduce ignition delay. It is likely undesirable to add materials to the oxidizer as the overall storability and corrosivity may be affected.

Other works[9,10] from the Birla Institute of Technology provide regression rate data for nitric acid/aniline formaldehyde hybrids. The fuel powder in the Reference 9 studies was pressed into grains of 30 mm i.d., 60 mm. o.d. and 80 mm length giving a very small length-to-diameter

(L/D) fuel grain. Fuel density was 2.53 g/cc. The ammonium vanadate catalyst was added to the oxidizer at the 1% level to improve hypergolicity. Magnesium loadings as high as 11% were considered within the pressed fuel grains. Combustion tests were done at horrendously low flux levels (less than 0.1 lbm/in2-s) and chamber pressures near 200 psi. Regression rates for the unloaded fuel were near 3 mm/s while the higher metal loadings increased regression rates by as much as 25%.

Reference 10 provides a comparable study with 22 mm i.d., 50 mm o.d. and 270 mm length grains that are more reasonable in L/D. In this study, the catalysts ammonium vanadate and potassium permanganate were added to the fuel powder at the 5% and 2% levels prior to pressing. Tests were conducted at low pressures (less than 70 psi) and very low flux levels (less than 0.1 lbm/in2-s) and regression rates in the range of 0.2 – 0.6 mm/s were obtained. The academic work at the Birla Institute apparently spurred some interest within the Indian defense establishment as documented in References 11 and 12. Reference 11 provides a summary of mid 1970s work at the Indian Defence R&D Laboratory on aniline furfuraldehyde fuel claimed to be hypergolic with a number of storable oxidizers including RFNA. A detailed procedure is provided to the mechanism used to mix and solidify the fuel grain that contained 1% potassium chromate as a regression catalyst. Other catalyst materials were also evaluated. The authors claim that for amine-based solids an ignition delay of less than 500 msec is "very good". Ignition delays were measured in a Pino-type apparatus that includes injection holes to simulate an injector. Ignition delays less than 100 msec were measured using ammonium dichromate and potassium permanganate catalysts. Delays were reduced further by dissolving some of the catalyst in the oxidizer as detailed in the other studies above.

Reference 12 hails from the Indian Institute of Armament Studies with a similar study of Pinoapparatus ignition delays for a variety of fuels. The effect of magnesium loading on the ignition delay was investigated; an optimal magnesium loading of 50 – 70% was noted for most of the fuels tested. With very large ignition delays (over 1 sec in many cases) for most fuels, the best performers were hydrazine and glyoxal condensate (1:1), p-phenylenediamine and glyoxal condensate (1:1) and m-phenylenediamine and glyoxal condensate (1:1), all of which featured ignition delays of less than 100 msec for a variety of metal fuel loadings.

Due to time and funding limitations associated with the Phase I SBIR that sponsored the study, limited evaluations were conducted with the IRFNA oxidizer. It would be beneficial to explore this alternative in the future as IRFNA is a viable storable oxidizer for some applications.

CONCLUSIONS AND RECOMMENDATIONS

Experimental studies successfully demonstrated restartability and throttleability for hybrid rockets utilizing hydrogen peroxide as oxidizer. Both catalytic bed and catalytic fuel grain alternatives produced excellent combustion characteristics. Throttling tests demonstrated a 10:1 throttling range, which was limited by the facility and hardware as constructed, with smooth combustion over the entire test. Deeper throttling may be possible. Boost/Sustain/Boost mission profiles were tested with sustain portions reaching 75%, 50%, and lower of the boost period chamber pressure. These tests also exhibited rapid transition between the phases as would be required in a tactical missile system. Testing has also verified that a slow throttle up from the nominal flow rate is possible to maintain the optimum mixture ratio providing higher specific impulse performance as the fuel grain burns back.

New regression rate correlations have been calculated for a hybrid motor using a catalyst bed to decompose 90% hydrogen peroxide and a polyethylene fuel grain at 250-psia and 500-psia chamber pressure conditions. These regression rates are 50% and 20% higher, respectively, than previous studies using a different ignition method. These tests demonstrated smooth, stable combustion at characteristic velocity efficiencies up to 100%. Also, the delay in fuel grain ignition was shown to be related to the oxidizer flux with the higher fluxes achieving lower ignition delays.

A variety of catalytic fuel grains were developed for use with high concentration hydrogen peroxide. These fuel grains achieved regression rates 2.5 times that of the highest regression rate reached in the tests of the uncatalyzed fuel grains used in the catalyst bed-based hybrid experiments. In addition to simplifying grains in future motor designs, these high regression rates will serve to minimize fuel slivering. One fuel grain, designated CFG-06, performed remarkably well through repeated and smooth ignition with a simple cylindrical center port grain. Not having to increase the surface area of the catalytic fuel grain through star-shaped patterns in order to aide in ignition indicates that multiple starts are possible without the need to consider whether burn back of the grain has resulted in sufficient surface area to relight.

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